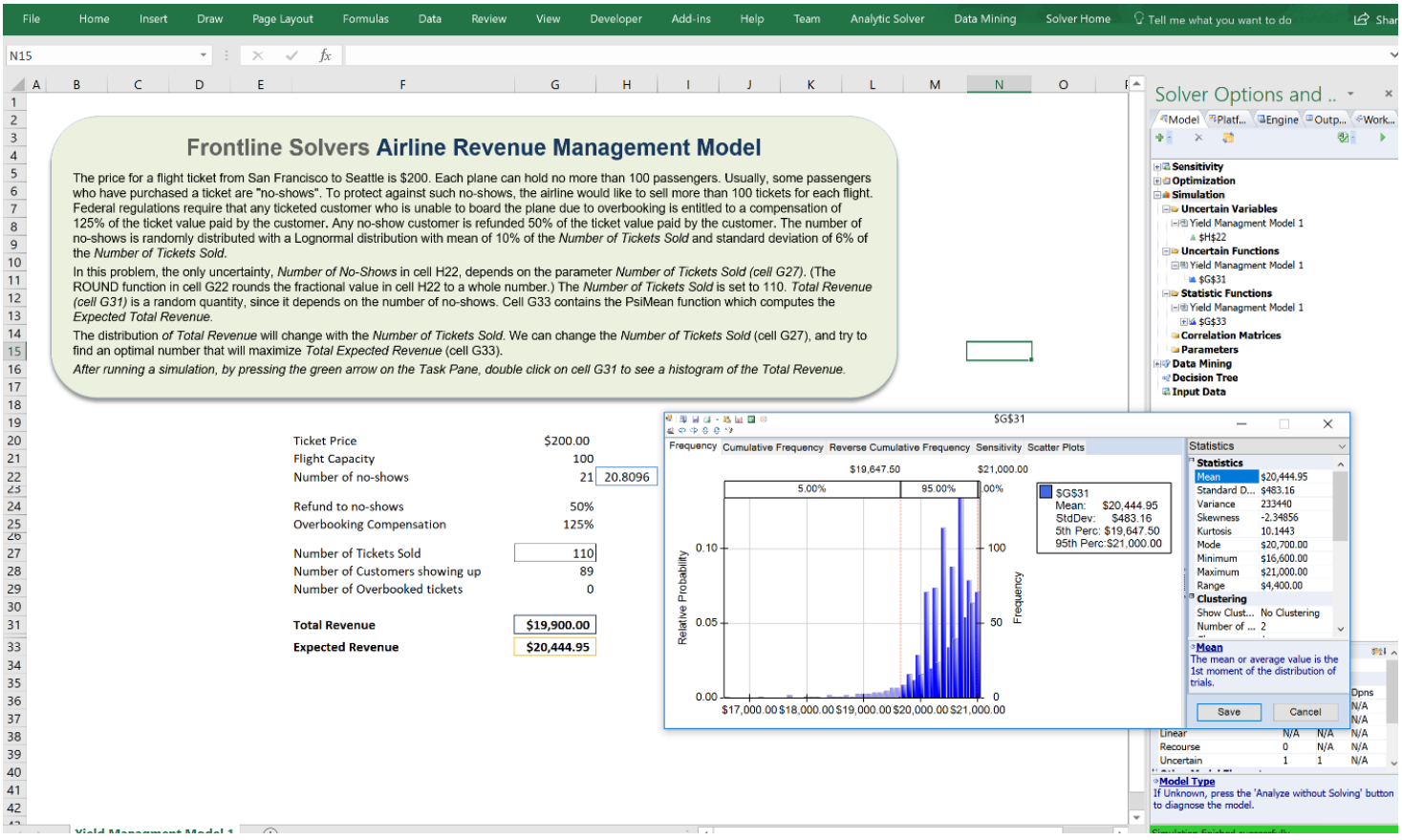
Version 2020 **For Use With Excel 2010-2019**

FRONTLINE solvers

Analytic Solver Optimization
Analytic Solver Simulation
User Guide



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Thanks to Dan Fylstra and the Frontline Systems development team for a 25-year cumulative effort to build the best possible optimization and simulation software for Microsoft Excel. Thanks to Frontline's customers who have built many thousands of successful applications, and have given us many suggestions for improvements.

Earlier versions of Risk Solver Pro and Risk Solver Platform have benefited from reviews, critiques, and suggestions from several risk analysis experts:

- Sam Savage (Stanford Univ. and AnalyCorp Inc.) for Probability Management concepts including SIPs, SLURPs, DISTs, and Certified Distributions.
- Sam Sugiyama (EC Risk USA & Europe LLC) for evaluation of advanced distributions, correlations, and alternate parameters for continuous distributions.
- Savvakis C. Savvides for global bounds, censor bounds, base case values, the Normal Skewed distribution and new risk measures.

How to Order

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Start Here: V2020 Essentials

Getting the Most from This User Guide

Desktop and Cloud Versions

Analytic Solver V2020 comes in two versions: **Analytic Solver Desktop** – a traditional "COM add-in" that works only in Microsoft Excel for Windows PCs (desktops and laptops), and **Analytic Solver Cloud** – a modern "Office add-in" that works in Excel for Windows and Excel for Macintosh (desktops and laptops), and also in Excel for the Web using browsers such as Chrome, FireFox and Safari. Your license gives you access to both versions, and your Excel workbooks and optimization, simulation and data mining models work in both versions, no matter where you save them (though OneDrive is most convenient).

Your license also gives you access in 2020 1H to Frontline Systems' website **AnalyticSolver.com** – a third way to create and solve models, if you don't have an Office 365 subscription and you don't have a Windows PC. But we *highly* recommend an **Office 365 subscription** to make your work easier and faster.

Installing the Software

Read the chapter "Installation and Add-Ins" for complete information on installing Analytic Solver Cloud and (if you wish) Analytic Solver Desktop. This chapter also explains how the Cloud and Desktop versions interact when both are installed, and how to install and uninstall both versions.

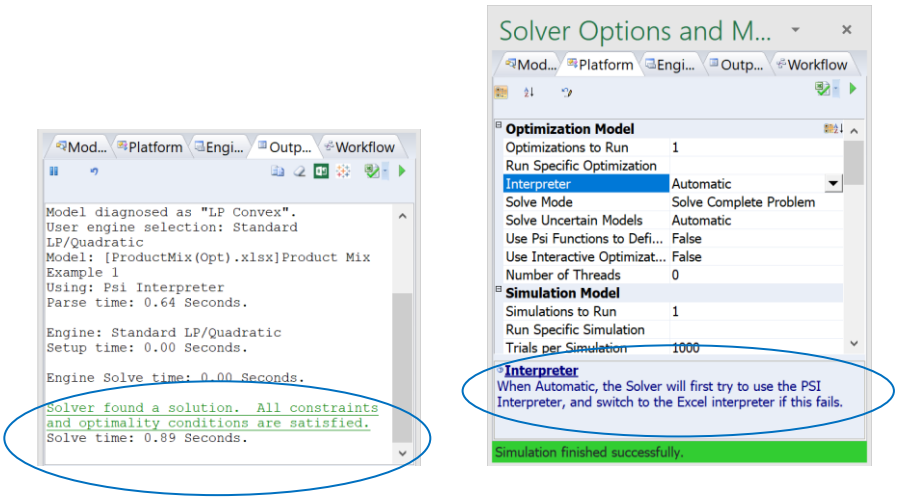
In brief, to add **Analytic Solver Cloud** version to your copy of Excel, you use the Excel Ribbon option **Insert – Get Add-ins** – no Setup program download or installation is required. To install **Analytic Solver Desktop** on Windows PCs, visit https://analyticsolver.com, login using the same email and password you used to register on Solver.com, download and run the SolverSetup program.

Understanding License and Upgrade Options

Frontline Solvers V2020 feature a revised, simpler product line that gives you access to **all** features, **all** the time for small models, and a new licensing system, tied to **you** and usable on more than one computer. Read about this in the chapter "Help, Support, Licenses and Product Versions."

Getting Help Quickly

Choose Help on the Ribbon. You'll see several options, starting with **Help – Help Center**. Support Live Chat, Example Models, and User Guides are also available here. In Analytic Solver Desktop (only) you can also get quick online Help by clicking any underlined caption or message in the Task Pane.



Finding the Examples

Use Help – Examples on the Analytic Solver or Data Mining Ribbon to open a list of example optimization and simulation models, and example data sets for data mining, that you can open by clicking hyperlinks. See the chapter "Help, Support, Licenses and Product Subsets" for details. Some of these examples are used and described in the **Examples** chapters.

Using Existing Models

Open your existing workbook, developed in any previous version of Frontline Solvers or the standard Excel Solver. Your model should appear in the Task Pane; just click the Optimize or Simulate button. Read **Automatic Mode and Solution Time** in "Analytic Solver Overview" to understand how this mode can impact solution time.

Using Large-Scale Solver Engines

Read the Platform Solver Engines Guide to learn more about Frontline's eight large-scale Solver Engines for optimization, including their Solver Options and special Solver Result Messages. All Large-Scale Engines are pre-installed with both Analytic Solver Desktop and Analytic Solver Cloud; even if you don't yet have a paid license for one of them, you can use them in a "Test Run" as described in the chapter "Help, Support, Licenses and Product Versions."

Getting Started with Tutorials

To quickly gain a good grasp of Analytic Solver's optimization and simulation capabilities, work through the **Examples** chapters in this Guide. For Analytic Solver's data mining capabilities, see the Data Mining User Guide.

Getting and Interpreting Results

Learn how to interpret Analytic Solver's result messages, error messages, reports and charts, and how to run multiple parameterized optimizations and simulations in the **Getting Results** chapters.

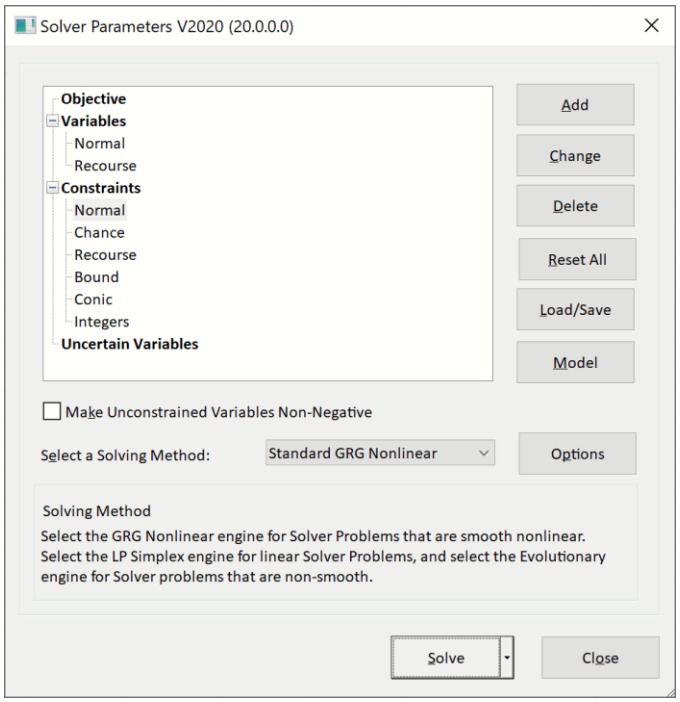
Mastering Optimization and Simulation Concepts

This guide can give you a professional education in simulation/risk analysis, conventional optimization, and stochastic optimization (with uncertainty). Go from beginner to expert and learn how to fully exploit the software by reading the **Mastering Concepts** chapters, and the Frontline Solvers Reference Guide.

Using the Traditional Solver Parameters Dialog

If you've used the **Solver in desktop Excel** (which Frontline Systems developed for Microsoft) and you're familiar with its Solver Parameters dialog, you can still use it in Analytic Solver Desktop: Click **Premium Solver** on the **Add-Ins tab** to display a slightly enhanced Solver Parameters dialog.

You can **go back and forth freely** between the Solver Parameters dialog and the new, modeless Task Pane and Ribbon. Within a few minutes, most users find the Task Pane and Ribbon faster and easier to use. If you've used the basic **Solver for Excel Online** (free in the Office Store), you're already familiar with use of the Task Pane, which is enhanced in Analytic Solver Desktop and Cloud.



Automating Your Model with VBA

VBA (Visual Basic for Applications) is available only in desktop Excel; it is not available in Office 365 in a browser. If you have Excel workbooks that use **macros** from the **Solver in desktop Excel** (such as SolverOK and SolverSolve) you can use them in Analytic Solver Desktop (**only**), provided that you use Tools -- References in the VBA Editor to set or change the reference to **Analytic Solver 2018 Type Library**. You can use the code examples in the chapters "Automating Optimization in VBA" and "Automating Simulation in VBA" – but read about **RASON** in this Guide for a modern desktop + cloud approach.

Installation and Add-Ins

What You Need

You can use Analytic Solver Cloud in Excel for the Web through a browser (such as Edge, Chrome, Firefox or Safari), without installing anything else. This is the simplest and most flexible option, but it requires a constant Internet connection.

To use Analytic Solver Cloud in Excel Desktop on a PC or Mac, you must have a current version of Windows or iOS installed, and **you will need the latest Excel version installed via your Office 365 subscription** – older non-subscription versions, even Excel 2019, do not have all the features and APIs needed for modern Office add-ins like Analytic Solver Cloud.

To use Analytic Solver Desktop (Windows PCs only), you must have first installed Microsoft Excel 2010, 2013, 2016, 2019, or the latest Office 365 version on Windows 10, Windows 8, Windows 7, or Windows Server 2019, 2016 or 2012. (Windows Vista or Windows Server 2008 may work but are no longer supported.). It's not essential to have the standard Excel Solver installed.

Installing the Software

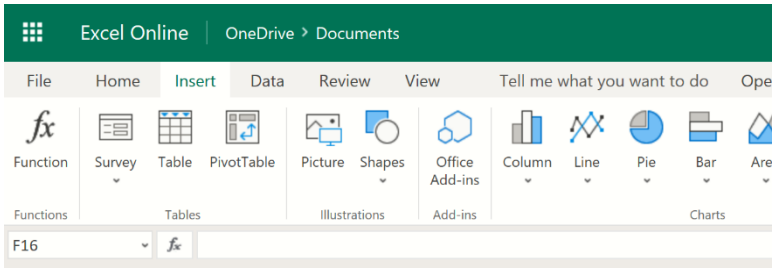
Installing Analytic Solver Cloud

Analytic Solver V2020 includes our next-generation offering, Analytic Solver Cloud – usable in the latest versions of Excel for Windows and Macintosh, and in Excel for the Web. Analytic Solver Cloud is divided into **two** add-ins that work closely together (since an Office add-in currently can have only one Ribbon tab): the **Analytic Solver** add-in builds optimization and simulation models, and the **Data Mining** add-in builds data mining or forecasting models.

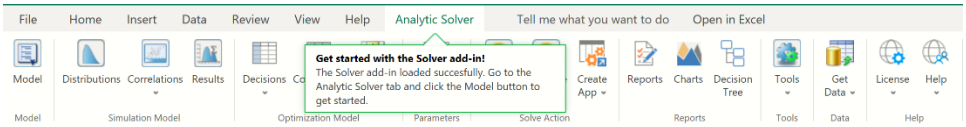
Both the Analytic Solver and Data Mining add-ins support existing models created in previous versions of Analytic Solver. Your license for Analytic Solver allows you to use Analytic Solver Desktop in desktop Excel or Analytic Solver Cloud in either desktop Excel (latest version) *or* Excel for the Web.

To use the Analytic Solver and Data Mining add-ins, **you must first "insert" them** for use in your copy of desktop Excel or Excel for the Web, while you are logged into your Office 365 account. Once you do this, the Analytic Solver and Data Mining tabs will appear on the Ribbon in each new workbook you use.

To insert the add-ins for the first time, open desktop Excel (latest version) or Excel for the Web, click the **Insert** tab on the Ribbon, then click the button **Office Add-ins** or (if you see it) the smaller button **Get Add-ins**.

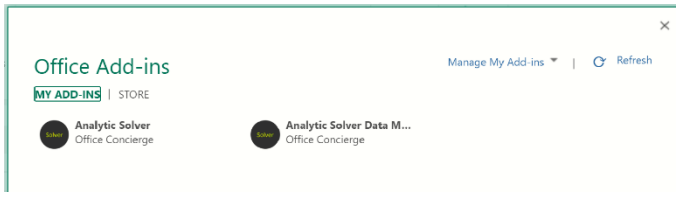


In the dialog box that appears, click the **Store** tab and type "Analytic Solver" into the Search box. Once you find the Analytic Solver add-in, click **Add**. After a moment, you should see the **Analytic Solver** tab appear on the Ribbon, with a note about how to "Get started with the Solver add-in", as shown below.



Repeat these steps to search for, locate and **Add** the Analytic Solver Data Mining add-in. After a moment, you should see the **Data Mining** tab appear on the Ribbon, with a similar "Get started" note.

After you perform these steps (one time) to insert the Analytic Solver and Analytic Solver Data Mining add-ins, they will appear under "My Add-ins". If you ever need to remove the add-ins, click the "**…**" symbol to the right of the add-in name, then click the **Remove** choice on the dropdown menu that appears.



Installing Analytic Solver Desktop

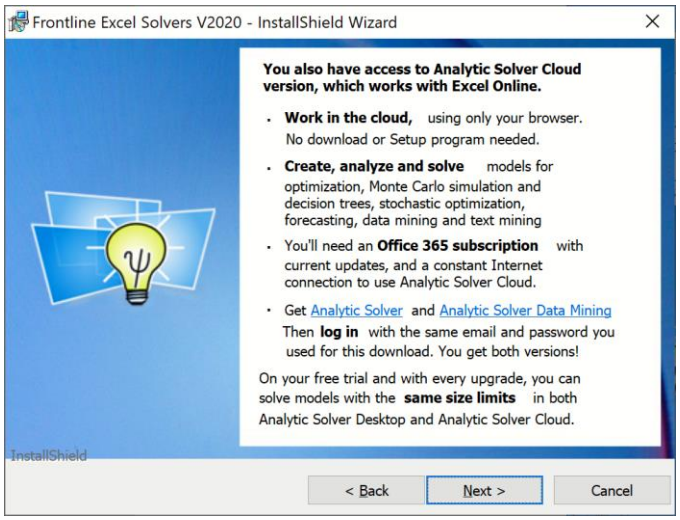
To install Analytic Solver Desktop to work with any of the supported versions of Microsoft Excel (see above), simply run the program **SolverSetup.exe**, which installs all of the Solver program, Help and example files. SolverSetup.exe checks your system, detects what version of Office you are running (32-bit or 64-bit) and then downloads and runs the appropriate Setup program version.

Note that your copy of the Setup program will usually have a filename such as SolverSetup_12345.exe; the '12345' is your user account number on Solver.com.

When you run the Setup program, depending on your antivirus program or Windows security settings, you might be prompted with a message **"[reason such as new/unknown program]. Are you sure you want to run this software?"** You may safely click **Run** in response to this message.

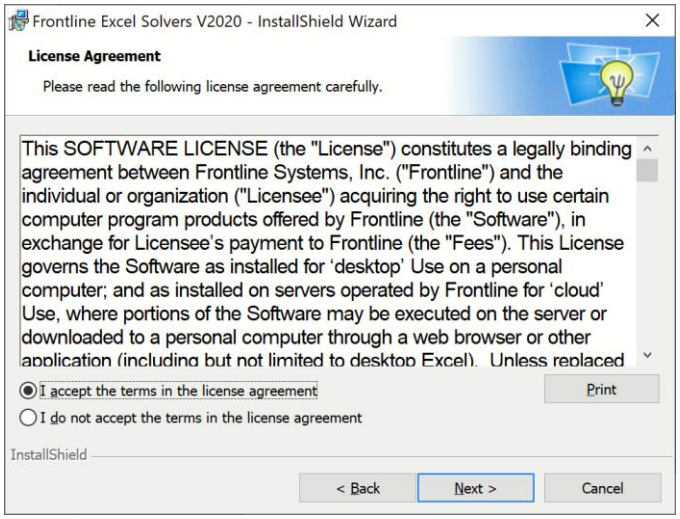
You'll briefly see the standard Windows Installer dialog. Then a dialog box like the one shown below should appear:

Read this, so you know the *difference* between Analytic Solver Basic and the upgrades to handle larger models and datasets. Then click **Next** to proceed – you'll see a dialog like the one below.

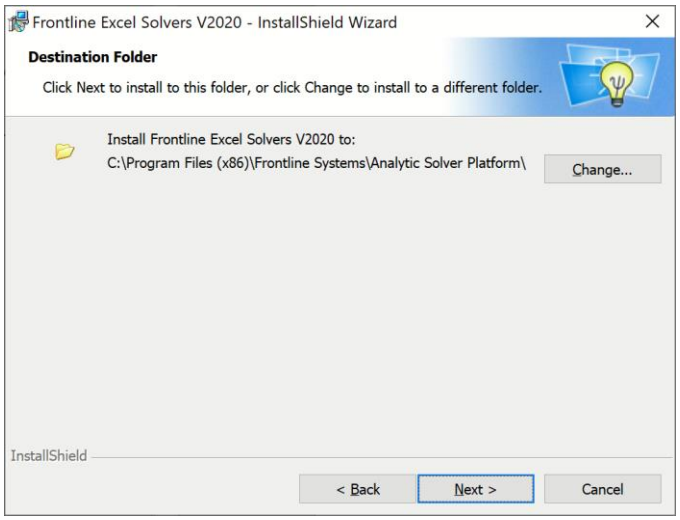


Read this to learn how you can use Analytic Solver Cloud (our new Office add-in version) – "Excel Online" is another name for "Excel for the Web".

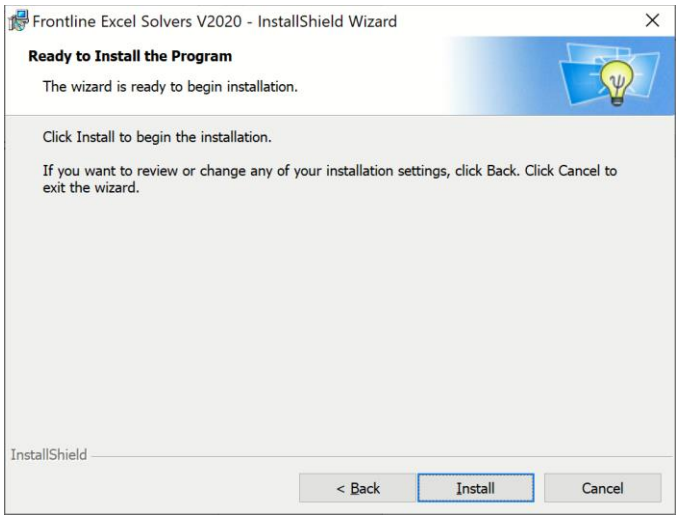
Next, the Setup program will ask if you accept Frontline's software license agreement. You must click "I accept" and **Next** in order to be able to proceed.



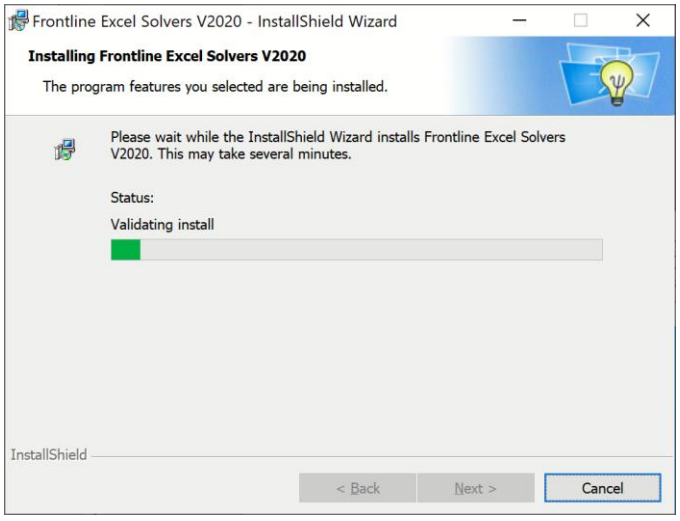
The Setup program then displays a dialog box like the one shown below, where you can select or confirm the folder to which files will be copied (normally C:\Program Files\Frontline Systems\Analytic Solver Platform, or if you're installing Analytic Solver for 32-bit Excel on 64-bit Windows, C:\Program Files (x86)\Frontline Systems\Analytic Solver Platform). Click **Next** to proceed.



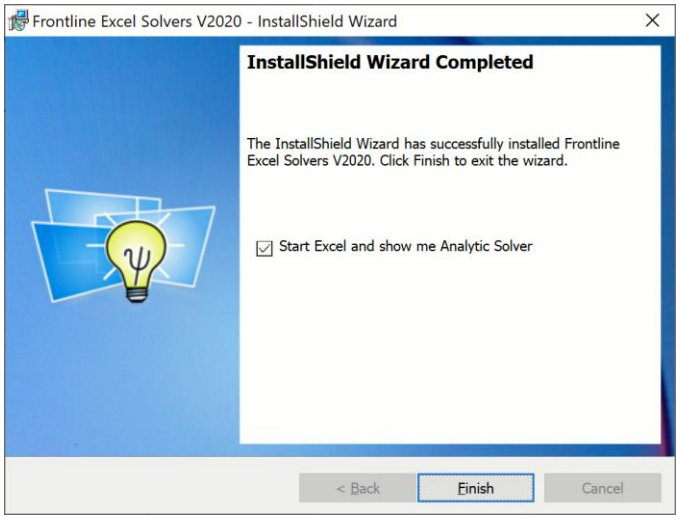
You'll see a dialog confirming that the preliminary steps are complete, and the installation is ready to begin.



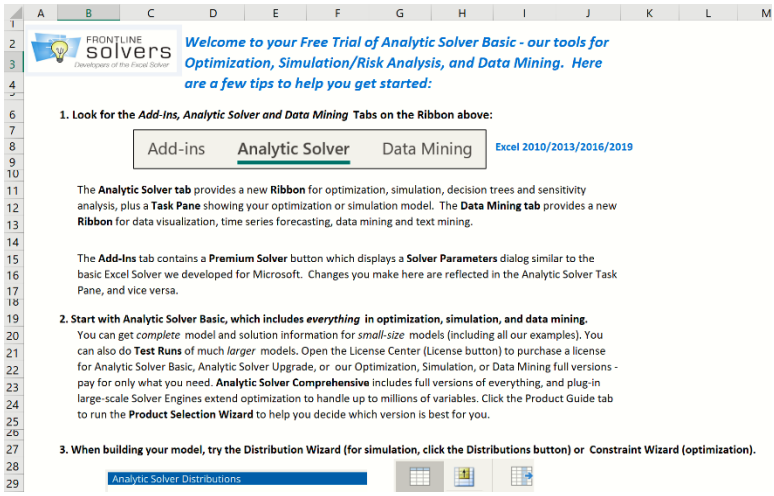
After you click **Install**, the Analytic Solver files will be installed, and the program file RSPAddin.xll will be registered as a COM add-in (which may take some time). A progress dialog may appear; be patient, since this process could take longer than it has in previous Solver Platform releases.



When the installation is complete, you'll see a dialog box like the one below. Click **Finish** to exit the installation wizard.



The full Analytic Solver product family is now installed. With your trial and paid license, you can access every feature of the software, including forecasting and data mining, simulation and risk analysis, and conventional and stochastic optimization. Simply click "Finish" and Microsoft Excel will launch with a Welcome workbook containing information to help you get started quickly.



Logging in the First Time

In Analytic Solver V2020, your license is associated with **you**, and may be used on **more than one PC**. For example, you can run SolverSetup to install the desktop software on your office PC, your company laptop, and your PC at home. But only **you** can use Analytic Solver, and only on **one** of these computers **at a time**. It is unlawful to "share" your license with another human user.

The first time you run Analytic Solver (Desktop or Cloud) after installing the software on a new computer, when you next start Excel and visit the Analytic Solver tab on the Ribbon, **you will be prompted to login**. Enter the **email address** and **password** that you used to register on Solver.com or AnalyticSolver.com. Once you've done this in Analytic Solver Desktop, your identity will be "remembered," so you won't have to login every time you start Excel and go to one of the Analytic Solver tabs. In Analytic Solver Cloud, you may be asked to login more frequently.

You can login and logout at any time, by clicking License – Login/Logout in both Analytic Solver Desktop and Analytic Solver Cloud. If you share use of a single physical computer with other Analytic Solver users, be careful to **login** with your own email and password, and **log out when you're done** – if you don't, other users could access private files in your cloud account, or use up your allotted CPU time or storage.

When you move from one computer to another, you should **log out** on one and **log in** on the other. As a convenience, if you log in to Analytic Solver on a new computer when you haven't logged out on the old computer, Analytic Solver will let you know, and offer to automatically log you out on the other computer.

Uninstalling the Software

To uninstall Analytic Solver Desktop, just run the **SolverSetup** program as outlined above. You'll be asked to confirm that you want to remove the software.

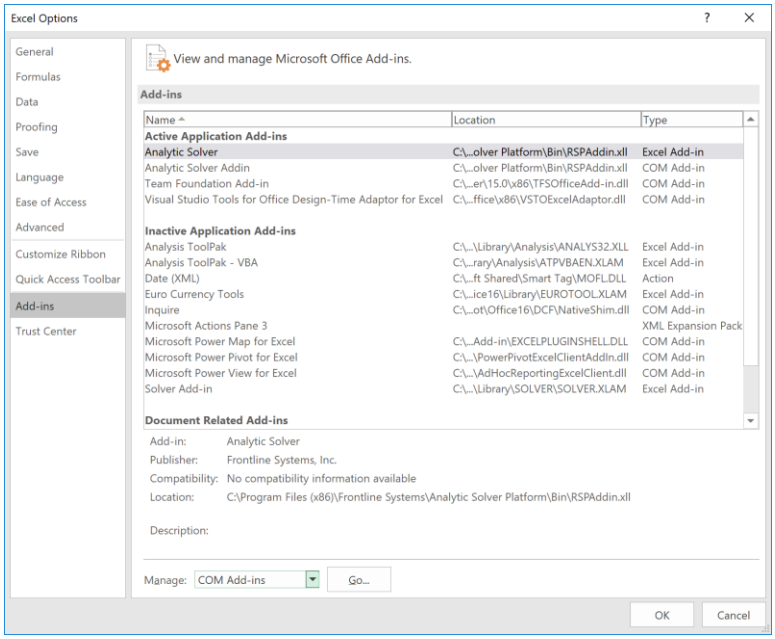
You can also uninstall by choosing **Control Panel** from the **Start** menu, and double-clicking the **Programs and Features** or **Add/Remove Programs** applet. In the list box below "Currently installed programs," scroll down if necessary until you reach the line, "Frontline Excel Solvers 2020," and click the Uninstall/Change or Add/Remove… button. Click OK in the confirming dialog box to uninstall the software.

Activating and Deactivating the Software

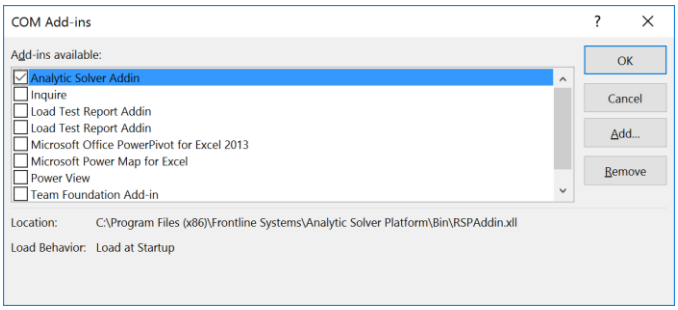
Analytic Solver Desktop's main program file RSPAddin.xll is a COM add-in, an XLL add-in, and a COM server. A reference to the add-in **Solver.xla** is needed if you wish to use the "traditional" VBA functions to control Analytic Solver, instead of its new VBA Object-Oriented API.

Excel 2019, 2016, 2013, and 2010

In Excel 2019, 2016, 2013, and 2010, you can manage all types of add-ins from one dialog, reached by clicking **File – Options -- Addins**.



You can manage add-ins by selecting the type of add-in from the dropdown list at the bottom of this dialog. For example, if you select COM Add-ins from the dropdown list and clock the Go button, the dialog shown below appears.

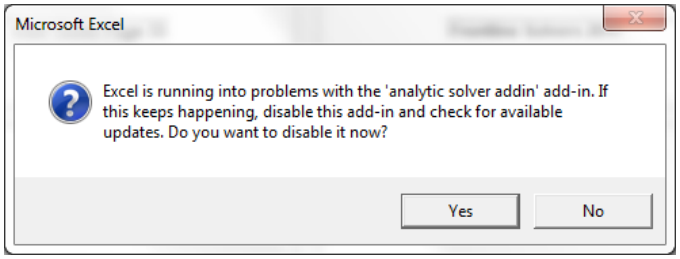


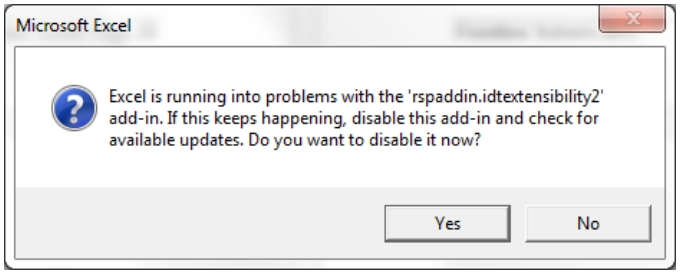
If you uncheck the box next to "Analytic Solver Addin" and click OK, you will deactivate the Analytic Solver COM add-in, which will remove the Analytic Solver tab from the Ribbon in desktop Excel, and also remove the PSI functions for optimization from the Excel Function Wizard.

If Something Goes Wrong

Under certain circumstances, desktop Microsoft Excel can "crash" or shut down, so it must be restarted. This can happen for a variety of reasons, including bugs in Excel itself, in the Analytic Solver software, or in other add-ins.

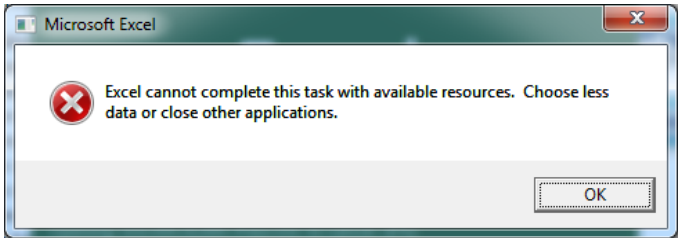
When Excel restarts, you may see one of the following messages:





If you see these messages, you should usually **click the No button**. If you've experienced a problem while using Analytic Solver software, please contact Frontline Systems Technical Support as described below. If you click the Yes button, Excel will disable the Analytic Solver add-in, and the Analytic Solver and Data Mining tabs will no longer appear on the Ribbon. To re-enable Analytic Solver and restore these Ribbon tabs, see the preceding section "Activating and Deactivating the Software:" you should select **File – Options**, then **Add-Ins**, then **Manage** COM Add-ins, **Go**. Then **check** the box next to "Analytic Solver Addin" and click OK.

In rare circumstances, Analytic Solver users have reported the following error message appearing upon opening of Excel.



This is a generic error from Microsoft Excel that can occur if you have been running Excel for a long period of time without ever deleting *Microsoft Excel's* temp files. (Note: These temp files are not generated by Analytic Solver software; they are generated through Microsoft Excel.) To resolve this error, click OK on the error message, then using Windows Explorer browse to C:\Users\<username>\AppData\Roaming\Microsoft\Excel and delete all *files* in this folder. Restart Excel. The issue should be resolved.

Frontline Systems Technical Support team may be contacted via phone (888-831-0333), email (support@solver.com) or Live Chat (Help – Support Live Chart on the Analytic Solver ribbon).

Cloud Versions

With your free trial or paid license, you can use Analytic Solver in desktop Excel, and its cloud-based counterparts: AnalyticSolver.com and, introduced in V2019, Analytic Solver Cloud.

AnalyticSolver.com is a comprehensive, SaaS (Software as a Service) toolkit for predictive and prescriptive analytics that shares technology with Analytic Solver desktop version.

Analytic Solver Cloud is a "modern Office add-in" that works in Excel for the Web, Excel for Windows and Excel for Mac (latest versions).

- All versions offer a Ribbon user interface featuring nearly-identical buttons and menus, and a Task Pane that summarizes models and provides access to Platform and Engine options.
- All versions use the same modeling languages (Excel formulas and our RASON® modeling language, handled by our PSI Interpreter), and both use the same algorithmic "engines" for mathematical optimization, Monte Carlo simulation and risk analysis, forecasting, data mining and text mining.
- All versions can create or open existing optimization, simulation and data mining models and datasets in Excel workbooks – and you can easily move such workbooks back and forth between desktop and cloud.

Security and Privacy Considerations

When you use Analytic Solver Desktop in Excel for Windows, your model is solved on the same computer, in the same memory and running process where Excel for Windows runs. You can save your workbook on your own computer, on Microsoft OneDrive "in the cloud", or elsewhere.

When you use either Analytic Solver Cloud or AnalyticSolver.com, your workbook is stored, at least temporarily, "in the cloud", and your model is **solved "in the cloud"**, using Frontline's RASON servers on Microsoft Azure. While many steps are taken to ensure your security and privacy, you should understand and be comfortable with how the technology works:

When the browser running on your computer communicates with either Excel for the Web or AnalyticSolver.com, all the information transmitted is encrypted using **Transport Layer Security (TLS) 1.2**, as is true for all "https" websites.

When you run or solve a data mining, optimization or simulation model, a copy of your Excel workbook is transmitted to Frontline's RASON servers, again using **TLS 1.2**. A copy of your workbook is stored temporarily on these Azure-based servers, but is always **encrypted** "at rest" and "in motion". After the model is run or solved, all copies of your workbook are **deleted**; only a log of filename, model size and time taken to solve remains on the RASON servers.

Analytic Solver Cloud

In AnalyticSolver.com, you are using a spreadsheet-like grid, rendered in HTML and "powered by" JavaScript code. This grid has many common spreadsheet editing features, but it is **not native Excel**, and some common editing steps work differently. Analytic Solver Cloud can be used with 'true' Excel for the Web, Excel for Windows and Excel for Mac (latest versions). Excel for the Web functions very similarly to desktop Excel so there's no learning curve; you can immediately be up to speed.

It's easy to move files between Analytic Solver Desktop and Analytic Solver Cloud products by simply saving your existing files to your Microsoft OneDrive account. Files saved on OneDrive may be opened in Microsoft Online or desktop Office. For Analytic Solver Cloud, **you will need the latest version installed via your Office 365 subscription** – older non-subscription versions, even Excel 2019, do not have all the features and APIs needed for modern Office add-ins like Analytic Solver Cloud.

AnalyticSolver.com

AnalyticSolver.com offers point-and-click, enterprise-strength optimization, simulation/risk analysis, and prescriptive analytics, *and* data mining, text mining, forecasting, and predictive analytics in your browser. Your license for Analytic Solver *includes* access in 2020 1H to AnalyticSolver.com and contains all the same features as desktop Analytic Solver. Simply login at AnalyticSolver.com to begin using this service. You *don't* need access to Excel for the Web - AnalyticSolver.com is self-contained, and will load and save Excel workbooks containing optimization, simulation, and data mining models.

Solver Home Tab Removed

The Solver Home tab was removed from Analytic Solver Desktop V2019 and V2020. You can use the License menu to Login and Logout, browse to www.solver.com, start a Live Chat, etc. See the section below for more information.

To upload a dataset in AnalyticSolver.com, click Solver Home – Upload to open the Upload File dialog. Browse to C:\Program Files\Frontline Systems\Analytic Solver Platform\Datasets to open an example dataset. (If using 32 bit Excel on a 64 bit Operating System, browse to: C:\Program Files (x86)\Frontline Systems\Analytic Solver Platform\Datasets.) Click the Open the dataset, SandlerFilms.xlsx, then click Upload.

Using Solver Server to Solve Models

With Analytic Solver Desktop (only), you also have an option to solve your optimization model, or run your simulation model on a corporate server, that may be more powerful than your desktop or laptop computer. Results appear in your spreadsheet, just as if you had solved the model on your own PCD instead of the server. To do this, you use a separate software tool called Solver Server.

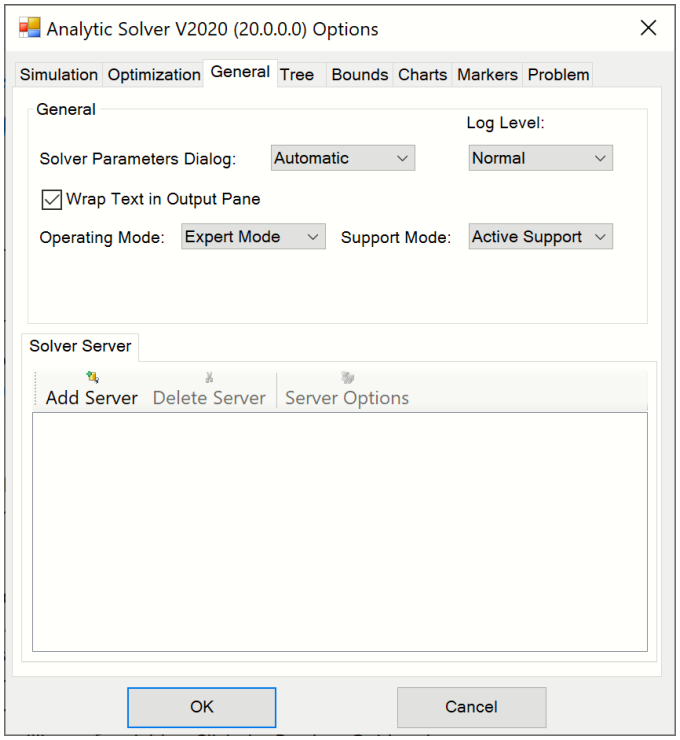
Solver Server is shipped as part of our Solver SDK Platform product; a client for Solver Server is built into each copy of Analytic Solver software, and each copy of Solver SDK Platform or Pro. You can also create your own client programs, even on mobile devices, using JavaScript and/or PHP.

If you would like more information on this service, please contact us at sales@solver.com. Note that Solver Server is a *separate* offering from our cloud versions, Analytic Solver Cloud and https://AnalyticSolver.com, and from the Analytic Solver "Create App" feature that translates your model into our RASON modeling language and may open it to be run at https://Rason.com.

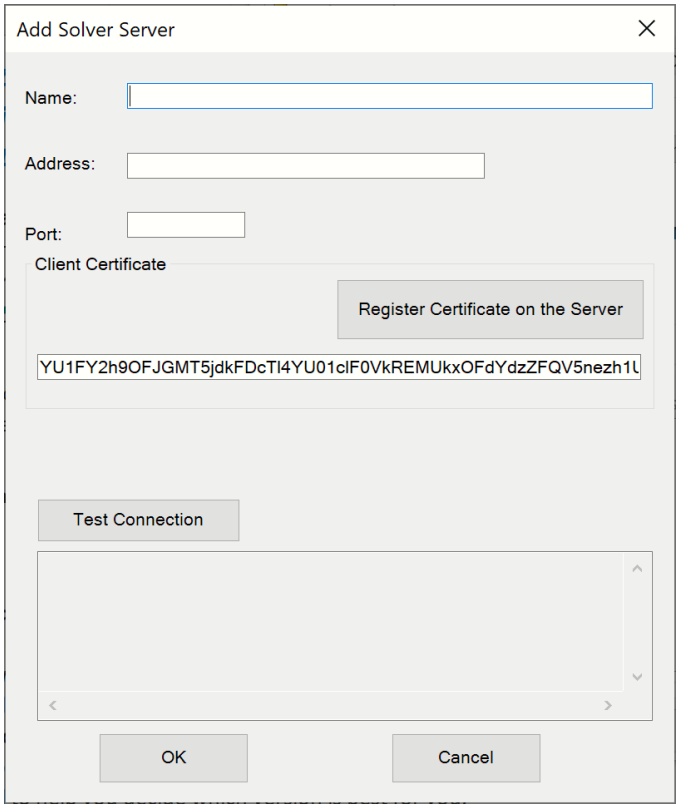
Note: SolverServer is not used with, or applicable to Analytic Solver Cloud or AnalyticSolver.com.

Adding a Server

To set up a connection to Solver Server from a client machine running Analytic Solver software, click the Options button on the Solver Ribbon, then click the General tab.



Next, click **Add Server** to display the following dialog.



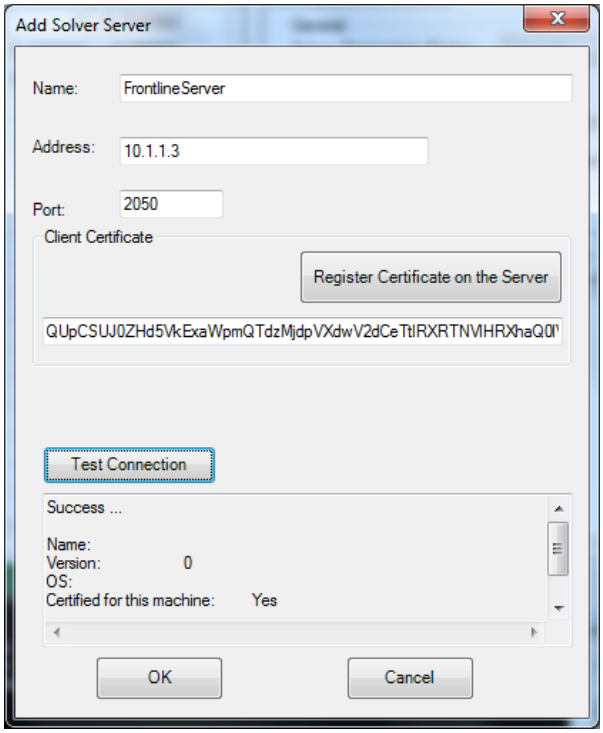
Enter information into this dialog as follows:

Name: Enter a convenient name for your server here. The name will appear as the name of this server in the Options dialog General tab display.

Address: Enter an IP address such as *10.1.1.3* or a public domain name such as *SolverServer.cloud.net* or a private domain or computer name such as *Frontline-PC\Machine1*.

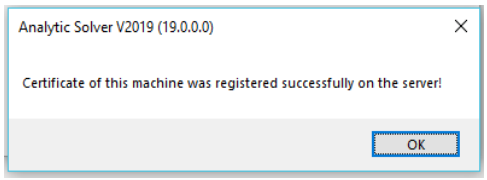
Port: The TCP/IP port entered here must match the port entered in the Solver Server application (SAdmin.exe). Solver Server is "listening" on this port. The default is 2050.

A "pre-filled"field appears under the **Register Certificate on the Server** button. This field holds the Solver Server Certificate. When connecting to Solver Server, the certificate will be inspected and if the same certificate is found on Solver Server, permission to solve the model will be granted.

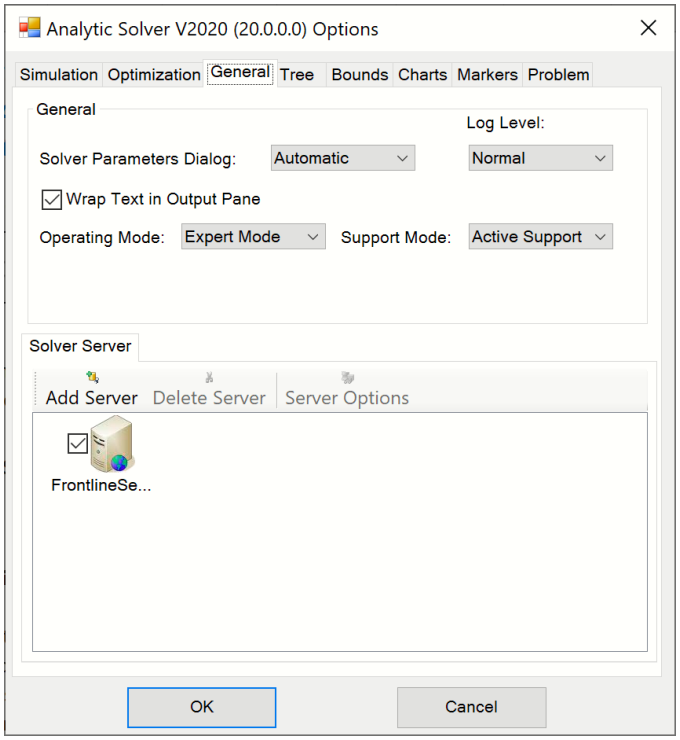


Once you've filled in the Name, Address and Port fields, click **Test Connection** to confirm a connection to the Server. If the connection is successful, click **Register Certificate on the Server** to display the following dialog. (If the test was not successful, please confirm that the Server Address and Port number are correct and that both machines (the client and server) are online.)

If registration was successful, you will see the dialog below. Click *OK* to clear this dialog and *OK* again to clear the Add Solver Server dialog.

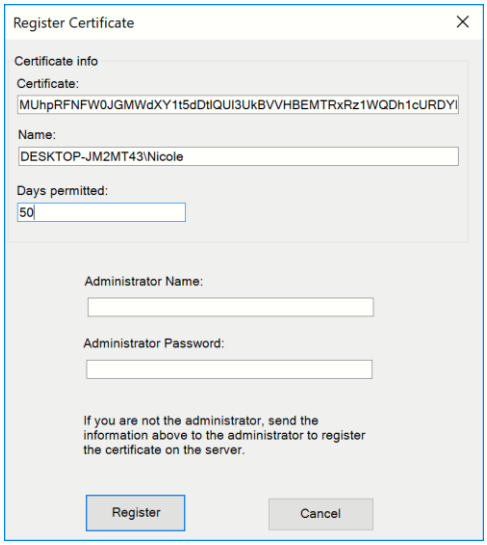


You should now see the Server listed on the General tab with a check inside the checkbox, as shown on the next page. To disable the server, simply uncheck the checkbox. Click *OK* to close the Options dialog and return to your spreadsheet.



Note that if you are not the administrator, you should send the contents of your Certificate field to the server administrator, who can manually add the certificate on the server. This must be done within *24 hours* or the certificate will expire.

Solver Server includes tools for a server administrator to manage certificates for clients. But it's also possible for the administrator to manage certificates by "logging in" to the server from your Excel-based client software, using the dialog shown below.



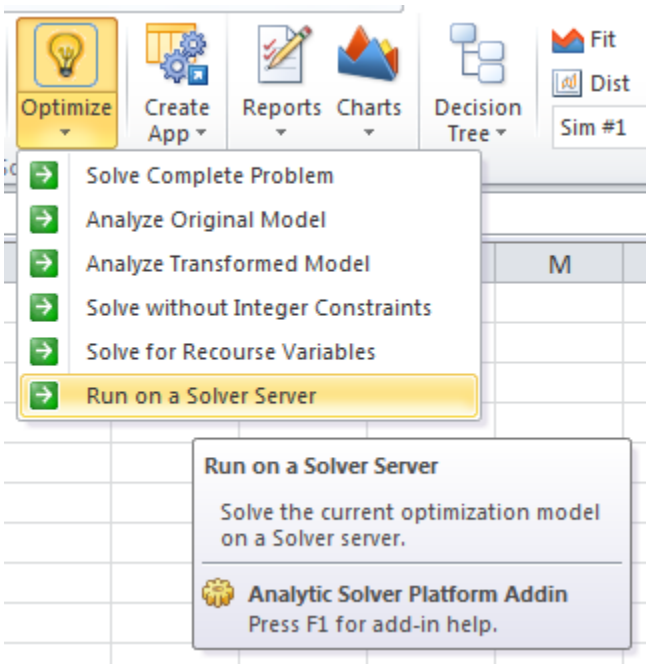
Days Permitted: An integer value, or 0 for a "permanent" certificate.

Administrator Name: Used by your server administrator.

Administrator Password: Used by your server administrator.

Solving Your Model on a Server

To solve a model on a server that you've set up previously as shown above, simply open your workbook, click the down arrow under the **Optimize** icon, and select **Run on a SolverServer** from the menu.



The Task Pane Output tab will display the Solver results, and the final variable values will be placed in your variable cells.

Sending document to the server.
The document is in the server queue.
Automatic engine selection: LP/Quadratic
Parse time: 0.00 Seconds.
Engine: LP/Quadratic
Setup time: 0.00 Seconds.
Engine Solve time: 0.00 Seconds.
Server finished solving the document.
Downloading the results.
Finished!
Solver found a solution. All constraints and optimality conditions are satisfied.

For more information on Solver Server or if you are experiencing any problems with this service, please contact us at support@solver.com.

Analytic Solver Overview

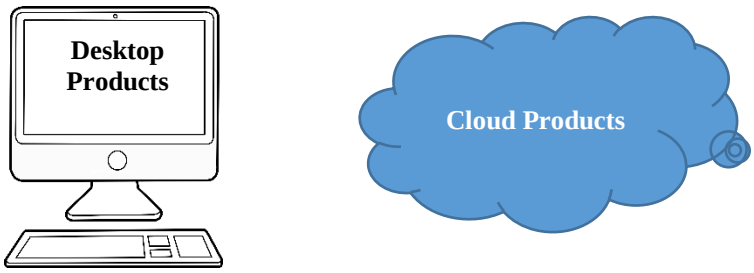
Analytic Solver Product Line

This Guide shows you how to create and solve conventional optimization, Monte Carlo simulation, and stochastic optimization models using **Analytic Solver** – Frontline Systems' "secret weapon" for business analysts. The companion Data Mining User Guide shows you how to create and evaluate forecasting and data mining models using Analytic Solver.

In Frontline Solvers V2020, every license starts with **Analytic Solver Basic**, which allows you to **use every feature** described in this User Guide, the companion Reference Guide, and the Data Mining User Guide, for learning purposes with **small models**. Upgrade versions enable you to 'scale up' and solve commercial-size models for optimization, simulation or data mining, paying for only what you need – but you ***keep*** access to all the features of Analytic Solver Basic.

Analytic Solver combines and integrates the features of Frontline's products for conventional optimization (formerly called **Premium Solver Pro** and **Premium Solver Platform**), Monte Carlo simulation and stochastic optimization (formerly **Risk Solver Pro** and **Risk Solver Platform**), and forecasting and data mining (formerly **XLMiner Pro** and **XLMiner Platform**), in a common user interface that's available both in Excel (Desktop) and in your browser (Cloud).

Analytic Solver's **optimization** features are **fully compatible upgrades for the Solver** bundled with Microsoft Excel, which was developed by Frontline Systems for Microsoft. Your Excel Solver models and macros will work without changes. In Analytic Solver Desktop, you can use either the classical **Solver Parameters dialog**, or a newer Task Pane user interface to define optimization models.



Desktop and Cloud versions

The release of Analytic Solver V2020 includes our latest offering, Analytic Solver Cloud – a "modern Office add-in" usable in both Excel for the Web and latest versions of desktop Excel, for Windows and Macintosh. Analytic Solver Cloud handles optimization and simulation models, and forecasting and data mining models, and is fully compatible with models created in previous versions of Analytic Solver. Your license for Analytic Solver will allow you to use Analytic Solver Desktop in desktop Excel or Analytic Solver Cloud in either

desktop Excel or Excel for the Web. For example, a license for Analytic Solver Optimization in desktop Excel will also grant you a license for Analytic Solver Optimization in Analytic Solver Cloud. The overwhelming majority of features in Analytic Solver Desktop are also included in Analytic Solver Cloud. However, there will be some small differences between the two versions.

Analytic Solver for desktop or cloud may be purchased in several different ways starting with the most basic version, Analytic Solver Basic, up to our most complete version, Analytic Solver Comprehensive. Continue reading to see which product will best meet your needs.

Analytic Solver Basic

As described above, **Analytic Solver Basic** allows you to **use every feature** of Frontline Solvers V2020, for learning purposes with **small models**. Its model size limits for optimization are identical to those of the Solver bundled with Microsoft Excel (200 decision variables and 100 constraints); it doesn't support plug-in large-scale Solver Engines. Its size limits for Monte Carlo simulation, data mining and text mining are sufficient to run all the examples that we install with the software.

Analytic Solver Upgrade

Analytic Solver Upgrade (formerly **Premium Solver Pro**) is Frontline's basic upgrade for the Excel Solver – enabling you to solve linear models 10 times larger (up to 2,000 variables), and nonlinear models 2.5 times larger (up to 500 variables). It includes faster versions of the LP/Quadratic, GRG Nonlinear, and Evolutionary Solvers), but it doesn't support plug-in large-scale Solver Engines. This product includes all the features of Analytic Solver Basic.

Analytic Solver Optimization

Analytic Solver Optimization (formerly **Premium Solver Platform**) is Frontline's most powerful product for *conventional* optimization. It includes the PSI Interpreter, five built-in Solvers (LP/Quadratic, SOCP Barrier, GRG Nonlinear, Interval Global, and Evolutionary), solves linear models up to 8,000 variables and nonlinear models up to 1,000 variables, and it supports plug-in large-scale Solver Engines to handle much larger models. When used with Analytic Solver Simulation, you can also solve models *with uncertainty* using simulation optimization, stochastic linear programming, and robust optimization. In addition, this product includes all the features of Analytic Solver Basic.

Analytic Solver Simulation

Analytic Solver Simulation (***expanded*** from **Risk Solver Pro**) is Frontline's full-function product for Monte Carlo simulation and simulation optimization. It includes decision tree capabilities and the PSI Interpreter – which gives you the fastest Monte Carlo simulations available in any Excel-based products, unique interactive simulation capabilities, multiple parameterized simulations, and simulation optimization using the Evolutionary Solver. When used with Analytic Solver Optimization, you can also solve models with uncertainty using stochastic linear programming and robust optimization. In addition, this product includes all the features of Analytic Solver Basic.

Together, Analytic Solver Optimization and Analytic Solver Simulation provide all the capabilities of Frontline's former product **Risk Solver Platform**.

Analytic Solver Data Mining

Analytic Solver Data Mining (formerly **XLMiner Platform**) is Frontline's most powerful product for data mining, text mining, forecasting and predictive analytics. It includes data access and sampling, data exploration and visualization, text mining, data transformation, and feature selection capabilities; time series forecasting with ARIMA and exponential smoothing; and a wide range of data mining methods for classification, prediction and affinity analysis, from multiple regression to neural networks. This product includes all the features of Analytic Solver Basic.

Analytic Solver Comprehensive

Analytic Solver Comprehensive (formerly **Analytic Solver Platform**) combines the optimization capabilities of Analytic Solver Optimization, the simulation capabilities of Analytic Solver Simulation, and the data mining capabilities of Analytic Solver Data Mining. It includes the PSI Interpreter, five built-in Solvers (LP/Quadratic, SOCP Barrier, GRG Nonlinear, Interval Global, and Evolutionary) and it accepts a full range of plug-in large- scale Solver Engines. It supports optimization, Monte Carlo simulation, simulation optimization, stochastic programming and robust optimization, and large-scale data mining and forecasting capabilities.

Enhancements in Recent Years

Frontline Solver products have been rapidly and continually enhanced for more than two decades. Below is a brief summary of enhancements in the last 6 years.

- In our V10.x (2010) releases, we included faster algorithms, 64-bit versions, and new Windows HPC Server cluster computing capabilities.
- In our V11.x (2011) releases, we introduced tabu and scatter search methods in the Evolutionary Solver, Guided Mode in Premium Solver Pro, and the Distribution Wizard and Constraint Wizard.
- In our V12.0 (2012) release, we included Excel 2013 support, GPU support in the Evolutionary Solver, new stochastic decomposition, and solving on a corporate server with Solver Server.
- In V12.5 (2013) release, we introduced Analytic Solver Platform with data mining capabilities, new data visualization features for both data mining and Monte Carlo results, improved Guided Mode, and Support Live Chat integrated into Excel.
- In our V2014 release, we introduced a fundamental new way to build Excel-based optimization and simulation models: Dimensional Modeling, with concepts such as dimensions and cubes, and tools to build and solve larger scale, better structured, more maintainable models using these concepts.
- In our V2014-R2 release, we introduced a completely re-engineered, far more powerful data mining and forecasting capability named XLMiner Platform. New data mining algorithms were up to 100 times faster, constantly exploit multiple processor cores, and offer greater accuracy and numeric stability.

- Our V2015 release introduced a wide range of new features, including powerful text mining, ensemble methods for classification and prediction, feature selection, partitioning "on-the-fly," ROC/RROC curves, and enhanced linear and logistic regression; extensive chart enhancements, distribution fitting, and new Six Sigma functions in Monte Carlo simulation; and support for "publishing" optimization and simulation models to Excel Online and Google Sheets.
- Our V2015-R2 release made it easy to share analytic model results in popular Business Intelligence software, including Microsoft Power BI and Tableau, both popular interactive data visualization tools, and it linked your Excel workbook with Big Data in compute clusters running Apache Spark.
- Our V2016 release introduced a new **Create App** feature that translates your Excel optimization or simulation model into Frontline's new **RASON** modeling language – radically simplifying the path to create an application that can run in a **web browser**, or a **mobile app** for phones or tablets. New SQP-GS and Feasibility Pump methods greatly improved the performance of the Evolutionary Solver on challenging non-smooth models.
- Our V2016-R2 release added support for **compound distributions** and **correlation using copulas** (Gaussian, Student and Archimedean forms), in Monte Carlo simulation; new "GA methods' for integer variables in the **Evolutionary Solver**, speed and memory improvements in **Dimensional Modeling**, and support for the **Web Data Connector** in Tableau 9.1.

2017: Power BI, Analytic Solver Basic, and More

In Frontline Solvers V2017, we introduced commercial users to **AnalyticSolver.com**, a new cloud-based platform for both predictive and prescriptive analytics models that you can use via a **web browser** – including all the optimization, simulation, and data mining power found in the desktop version. The AnalyticSolver.com **user interface** works just like our Excel user interface, with a Ribbon and Task Pane. And access to AnalyticSolver.com is ***included*** with your Analytic Solver license for desktop Excel.

V2017 also uses a **new licensing system** that offers you more flexible ways to use the software, both desktop and cloud. Your license is associated with **you**, and may be used on **more than one PC**. For example, you can install the software on your office PC, your company laptop, and your PC at home. But only **you** can use Analytic Solver, and only on **one** of these computers **at a time**.

V2017 introduced **Analytic Solver Basic**, as described above, to give you access to **all** Analytic Solver features, **all** the time, for learning purposes using small models. It also includes a new **License/Subscription Manager** and a **Product Selection Wizard** that makes it much easier to upgrade or change your license subscription on a self-service basis, and a new **Test Run/Summary** feature that lets you see exactly how your model will run with an Analytic Solver upgrade, even a plug-in large-scale Solver Engine, before you purchase the upgrade – and do this any time, not just during a 15-day free trial.

Feature Enhancements in V2017

V2017 introduced major enhancements to **data mining**: Automatic support for **categorical variables** in many classification and prediction algorithms that 'normally' require continuous variables; **ensembles** that combine nearly any type of algorithm as a 'weak learner', not just (for example) classification and

regression trees; general-purpose **Rescaling** as a new Data Transformation method that can also be applied 'on-the-fly' when training a model; greatly enhanced multilayer **neural networks**; ability to export models in **PMML**; and many report and chart enhancements.

The V2017 **Evolutionary Solver** includes another set of major enhancements in its handling of non-smooth models with integer variables – enough so that *most* such models will solve *significantly* faster.

And there's support for the Tableau Web Data Connector 2.0, and a new SolverSetup program that *automatically* installs the correct **32-bit or 64-bit** version of the software.

Feature Enhancements in V2017-R2

V2017-R2 introduced major enhancements to Monte Carlo simulation/risk analysis and optimization. It's now possible to **fit copula** parameters to historical data – a complement to distribution fitting that is sometimes called "correlation fitting." You can use a new family of probability distributions, called the **Metalog distributions**, even more general than the Pearson distributions – members of the family can be chosen based directly on historical data (even just a few observations), without a distribution fitting process.

The V2017-R2 PSI Interpreter includes major **speed enhancements** for large linear and nonlinear **optimization models** – users with large models are likely to see a dramatic speedup in "Setting Up Problem…" Also part of this release were new, higher performance versions of the Gurobi Solver Engine (based on Gurobi 7.5), the Xpress Solver Engine (based on Xpress 30.1), and the Knitro Solver Engine (based on Knitro 10.3).

Creating Power BI Custom Visuals

The most exciting new feature of V2017-R2 was the ability to turn your Excel-based optimization or simulation model into a **Microsoft Power BI Custom Visual**, with just a few mouse clicks! Where others must learn JavaScript (or TypeScript) programming and a whole set of Web development tools to even begin to create a Custom Visual, you'll be able to create one right away.

You simply select rows or columns of data to serve as changeable parameters, then choose **Create App – Power BI**, and save the file created by V2017-R2. You click the Load Custom Visual icon in Power BI, and select the file you just saved. What you get isn't just a chart – it's your *full optimization or simulation model*, ready to accept Power BI data**, run on demand** on the web, and display visual results in Power BI! You simply need to drag and drop appropriate Power BI datasets into the "well" of inputs to match your model parameters.

How does *that* work? The secret is that V2017-R2 translates your Excel model into **RASON**® (RESTful Analytic Solver Object Notation, embedded in JSON), then "wraps" a JavaScript-based Custom Visual around the RASON model. See the chapter "Creating Your Own Application" for full details!

2018: Tableau, Data Mining Workflows, and More

Analytic Solver V2018 extended our forecasting and data mining features with a new capability called **data mining workflows** that can save a lot of time and eliminate repetitive steps. You can combine nearly any of Analytic Solver's

data retrieval, data transformation, forecasting and data mining methods into a single, all-inclusive workflow, or pipeline.

Using the new Workflow tab in the Task Pane, you can either **"drag and drop"** icons onto a "canvas" to create a workflow diagram, or you can simply turn on a **workflow recorder**, carry out the steps as you've always done by choosing menu options and dialog selections, and the workflow diagram will be created automatically. Once the diagram or pipeline is created, you can "run" it in one step – each data mining method in the workflow will be executed in sequence.

In previous releases, you could use the trained model from a *single* data mining method (such as a Classification Tree or Neural Network) to "score" new data, by mapping features (columns) between the training set and new data set. In V2018, you can apply an *entire workflow* – including data transformations, partitioning, model training, and more – to a new dataset, by mapping features (columns) between the dataset used to create the workflow, and a new dataset.

Creating Tableau Dashboard Extensions

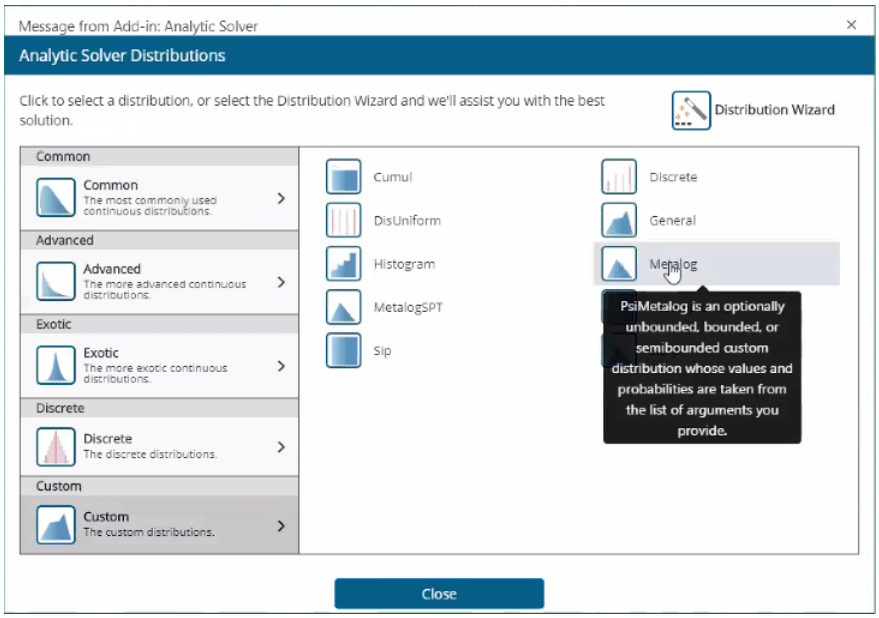
Another exciting new feature of V2018 was the ability to turn your Excel-based optimization or simulation model into a **Tableau Dashboard Extension**, with just a few mouse clicks! This is quite similar to the ability to create Power BI Custom Visuals introduced in Analytic Solver V2017-R2. It works (only) with Tableau version 2018.2 or later.

You simply select rows or columns of data to serve as changeable parameters, then choose **Create App – Tableau**, and save the file created by V2018. In Tableau, drag the **Extensions** object onto your dashboard, and choose the file you just saved. You'll be prompted to match the parameters your model needs with data in Tableau. What you get isn't just a chart – it's your *full optimization or simulation model*, ready to accept Tableau data**, run on demand** (using our **RASON** server), and display visual results in Tableau!

2019: Analytic Solver Cloud

In Frontline Solvers V2019, we introduced **Analytic Solver Cloud** – a next-generation product that's the result of **five years** of development using new cloud technologies, that we can now bring to you – since Microsoft has released a complete set of JavaScript APIs for new Excel features, such as functions like PsiNormal() and PsiMean() used in simulation and risk analysis.

In our first V2019 release, we focused on a **consistent user experience** between Analytic Solver Desktop and Analytic Solver Cloud. In a few cases, this has involved modifications to Analytic Solver Desktop. For example, older versions of Analytic Solver Desktop used "cascading submenus" to select probability distributions, and results in Monte Carlo simulations. Since an Office add-in cannot define or use cascading submenus, we have modified Analytic Solver Desktop *and* Analytic Solver Cloud so that the **Distributions** button on the Ribbon displays a dialog, rather than a cascading submenu, where you can select an appropriate probability distribution. Yet the order and layout of probability distributions remains the *same* as in previous Analytic Solver versions.



Business Rules and DMN Decision Tables

In Frontline Solvers V2019-R2, we introduced another completely new capability to Analytic Solver: Making it easy to capture rule-based decisions in the form of decision tables, with multiple columns for inputs, and multiple rows that express business rules. See the new chapter "Using Decision Tables".

While **Business Rule Management Systems** (BRMS) have been around for 15 years, with the increasing use of predictive and prescriptive analytics (like those found in Analytic Solver), these systems have begun to give way to **Decision Management Systems** that support a mix of rules and analytics. Where older BRMS systems used proprietary rules languages, the new trend embraces an open standard called **DMN** (Decision Model and Notation), with a language called **FEEL** (Friendly Enough Expression Language) for business rules.

Analytic Solver V2019-R2 and V2020 make it easy for you to create and test DMN 1.2-compatible **decision tables with business rules** expressed in FEEL. And it's equally easy to use Analytic Solver's forecasting, machine learning, simulation and optimization capabilities to create analytic **inputs** for decision tables, or use to decision table **results** in simulation and optimization models.

What's New in Analytic Solver V2020

With each new release, Analytic Solver gives you more! Our latest enhancements apply to both Analytic Solver Desktop and Analytic Solver Cloud.

Faster Solver Engines, Using Multiple Cores

In V2020, the LP/Quadratic Solver – probably the most-used Solver Engine in Analytic Solver – features significantly improved performance on linear mixed-integer models. Prior versions of this Solver would use only one processor core at a time, but V2020 will use *multiple processor cores* to speed your solution.

The plug-in large-scale Solver Engines in Analytic Solver V2020 also feature significantly improved performance (they continue to utilize multiple processor

cores). These include the **Gurobi** Solver V9.0, with a new ability to solve non-convex quadratic models; the **Xpress** Solver V35, with a new Solution Refiner, and the Artelys **Knitro** Solver V12.1, with SOCP and MIP speedups.

Monte Carlo Simulation Enhancements

Analytic Solver V2020 includes 12 new probability distribution functions, *enhanced* property functions for the PSI Distribution functions, *new* property functions for the PSI Statistics functions, and *new* "theoretical" functions that return analytic moments of distributions. Full details are in the *Frontline Solvers Reference Guide*, but here's a partial list of new/enhanced functions:

PsiBurr	PsiLevyAlt	PsiTheoMin
PsiDagum	PsiHypSecantAlt	PsiTheoMax
PsiDblTriang	PsiCumulD	PsiTheoVariance
PsiFatigue	PsiLaplace	PsiTheoStdDev
PsiFdist	PsiCauchy	PsiTheoSkewness
PsiFrechet	PsiTruncate	PsiTheoKurtosis
PsiHypSecant	PsiCensor	PsiTheoRange
PsiJohnsonSB	PsiLock	PsiTheoPercentile
PsiJohnsonUB	PsiOutput	PsiTheoPercentileD
PsiKumaraswamy	PsiTheoMean	PsiTheoTarget
PsiReciprocal	PsiTheoMedian	PsiTheoTargetD
PsiLevy	PsiTheoMode	PsiCategory

These functions make it **even easier** to adapt risk analysis models developed with other popular Excel add-ins to **work with Analytic Solver**. A simple Find and Replace of the function name prefix with 'Psi' is often all you need. And unlike those other Excel add-ins, with Analytic Solver you can easily run your model in the cloud with **Excel for the Web**, translate your model to RASON, and use it in **Power BI**, **Tableau**, or your own **web or mobile** application!

Optimization and Resource Allocation

Analytic Solver includes five bundled Solver Engines to find solutions for the full spectrum of optimization problems, up to certain size limits:

The **nonlinear GRG Solver** in Analytic Solver Comprehensive, Analytic Solver Optimization, Analytic Solver Upgrade, and Analytic Solver Basic handles large-scale smooth nonlinear (NLP) problems and includes Multistart or "clustering" methods for global optimization that can utilize multiple processor cores. In Analytic Solver Basic, this engine can solve NLP problems with up to 200 decision variables and 100 constraints, plus bounds on the variables.

In Analytic Solver Upgrade, this engine is an upgraded version of the nonlinear GRG engine included in the Microsoft Excel Solver, and can solve NLP problems with up to 500 variables and 250 constraints, plus bounds on the variables. In Analytic Solver Comprehensive and Analytic Solver Optimization, this engine can handle NLP problems with up to 1,000 decision variables and 1,000 constraints, plus bounds on the variables.

The **LP/Quadratic Solver** in Analytic Solver Comprehensive, Analytic Solver Optimization, Analytic Solver Upgrade and Analytic Solver Basic handles both linear programming (LP) and quadratic programming (QP) problems. In Analytic Solver Comprehensive and Analytic Solver Optimization, this engine can handle models with up to 8,000 decision variables and 8,000 constraints – four times the size of Analytic Solver Upgrade, and *40 times* the size of Excel Solver. In Analytic Solver Upgrade, this engine can solve LPs and QPs with up to 2,000 variables and 8,000 constraints and in Analytic Solver Basic LPs and QPs with up to 200 variables and 100 constraints. Advanced methods for LP/MIP problems yield solutions as much as hundreds of times faster than the Excel Solver, and 5 to 20 times faster than Analytic Solver Upgrade.

The **Evolutionary Solver** (in all products with optimization capabilities) uses a combination of genetic and evolutionary algorithms, tabu and scatter search methods, and classical optimization methods. In Analytic Solver Basic, it handles non-smooth (NSP) problems of up to 200 variables and 100 constraints, plus bounds on the variables. In Analytic Solver Upgrade, it handles non-smooth problems of up to 500 decision variables and 250 constraints, plus bounds on the variables. In Analytic Solver Comprehensive and Analytic Solver Optimization, an **enhanced version** of this Solver handles up to 1,000 variables and 1,000 constraints, exploits multiple processor cores in many of its algorithms, and exploits GPU processors in its local search.

The **Interval Global Solver** in (in all products with optimization capabilities) uses state-of-the-art interval methods to find the globally optimal solution to a nonlinear optimization problem, all real solutions to a system of nonlinear equations, or an "inner solution" to a system of nonlinear inequalities. In Analytic Solver Basic and Analytic Solver Upgrade, this engine handles smooth nonlinear (NLP) problems of up to 200 decision variables and 100 constraints, plus bounds on the variables. In Analytic Solver Comprehensive and Analytic Solver Optimization, it handles smooth nonlinear problems of up to 500 decision variables and 250 constraints, plus bounds on the variables.

The **SOCP Barrier Solver** in (in all products with optimization capabilities) uses an interior point method to solve linear (LP), quadratic (QP), quadratically constrained (QCP), and second order cone programming (SOCP) problems – the *natural generalization* of linear and quadratic programming – with up to 2,000 variables and 8,000 constraints in Analytic Solver Comprehensive and Analytic Solver Optimization. In Analytic Solver Upgrade and Analytic Solver Basic this engine has limits fo 200 variables and 100 constraints. In Analytic Solver Comprehensive and Analytic Solver Optimization with Analytic Solver Simulation, the SOCP Barrier Solver can be used to solve linear programming models *with uncertainty* via robust optimization with the L2 norm.

Simulation and Risk Analysis

Analytic Solver includes a full-featured Monte Carlo simulation capability. Unlike other Excel-based simulation products, this feature enables you to play 'what if' with uncertain values as easily as you do with ordinary numbers. Each time you run a simulation, thousands of trials are executed, and a full range of simulation results and statistics will be displayed *on the spreadsheet*. It uses Frontline's *Polymorphic Spreadsheet Interpreter* technology to achieve breakthrough simulation speeds – up to **100 times faster** than normal Excel-based Monte Carlo simulation.

Analytic Solver supports over 50 analytic and custom distributions (continuous and discrete), over 30 statistics and risk measures, rank order correlation,

distribution fitting, multiple random number generators and sampling methods with variance reduction, and powerful capabilities for multiple parameterized simulations.

In addition, Analytic Solver's **graphics** help you assess uncertainty, including charts of probability distributions, output frequency charts, sensitivity ("Tornado") charts, scatter plots, and Overlay, Trend, and Box-Whisker charts, in two or three dimensions. You can customize chart colors, titles, legends, grid lines, and markers, resize and rotate charts, and print charts or use them in PowerPoint presentations.

Optimal Solutions for Models with Uncertainty

Analytic Solver Comprehensive, Analytic Solver Upgrade, Analytic Solver Basic and Analytic Solver Optimization with Analytic Solver Simulation support several powerful methods for finding robust solutions to optimization problems with uncertainty:

- High-speed **simulation optimization** methods for more general (non-linear, non-smooth or non-convex) problems, where uncertainties may depend on the first-stage decisions. Normal and chance constraints may be used, and a wide range of statistical aggregates can be used to summarize uncertainty in the objective and constraints. A simulation is performed on each major iteration of the optimization. This method is very general, but computationally very expensive, and usually *not scalable* to large size problems.
- **Robust optimization** (RO) methods for linear programming problems with uncertainties affecting the objective and constraints. Chance constraints specify a probability of satisfaction, which is converted to a 'budget of uncertainty.' Monte Carlo simulation is used to obtain bound and shape information for the uncertainties. This information is used to *automatically* create a robust counterpart problem, which is then solved. This method is *scalable* to large size models.
- **Robust optimization** methods and **stochastic programming** (SP) methods for *two-stage* stochastic linear programming problems with recourse ("wait and see") decisions. Scenarios are automatically created via built-in Monte Carlo simulation, or they may be drawn from user-defined cell ranges of sample values on the spreadsheet. With the benefit of second stage or *recourse* decisions, solutions are typically 'well-hedged' but not overly conservative. The RO and SP methods are relatively *scalable* to large size. A state-of-the-art implementation of **stochastic decomposition**, the most powerful and scalable method known for solving two-stage stochastic linear programming problems, is also included. Note: Stochastic decomposition is supported only in Analytic Solver Desktop.

Automatic Model Transformation to RASON

All Analytic Solver products include facilities for automatic transformation of an existing model into the RASON modeling language.

RASON (which stands for Restful Analytic Solver Object Notation) is Frontline Systems modeling language embedded in JSON and a REST API that makes it

easy to create, test and deploy analytic models using optimization, simulation, and data mining, in web and mobile applications.

Users of Frontline's Excel Solvers will find that converting an existing Solver model in Excel to RASON is as easy as clicking a button. But we didn't stop there, in V2016, we created the ability to create an entire custom web application *in seconds*! Months of development work have been reduced to a single click of your mouse.

Web Application Developers who are familiar with AJAX and the use of REST API's, can immediately see first-hand how exceptionally easy it is to embed RASON models as JSON by viewing the automatically generated code. In just a few seconds, you can see how to solve the models using Frontline's RASON server, which exposes a simple REST API that's scalable to handle very large, compute-intensive analytic models.

Sensitivity Analysis and Model Parameters

All Analytic Solver products include facilities for sensitivity analysis of your Excel model, that can be used before even starting an optimization or simulation model. It is especially easy to identify the model parameters with the most impact on your computed results – you can simply select *any formula cell* and choose **Parameters – Identify** from the Ribbon to quickly find the input cells with the greatest impact on this formula, ranked and shown in a Tornado chart.

You can choose some of these input cells to serve as Sensitivity Parameters, and then produce reports and charts that show the impact on computed results of varying these parameters over a range you specify. You can also turn these parameters into (or define other cells as) Simulation Parameters or Optimization Parameters and produce reports and charts of simulation and optimization results as your parameters are automatically varied.

Multiple Optimizations and Simulations

All Analytic Solver Products (except Analytic Solver Data Mining or Data Mining Cloud) have powerful capabilities to perform multiple optimizations or simulations, automatically varying the values of parameters you specify, and collecting both optimization and simulation results, which may be displayed on the spreadsheet, or summarized in a variety of built-in reports and charts. Many operations that would require a programming language in other systems, or VBA in the Excel Solver, can be easily performed without programming.

The **Dimensional Modeling** capability available in the Analytic Solver Desktop products greatly enriches the scope of multiple parameterized optimizations and simulations. You can define multiple dimensions and multiple parameters indexed over each dimension, run an optimization or simulation for various combinations of these parameter values, and create tabular reports, Pivot Tables, and charts of the results. This functionality is not supported in Analytic Solver Cloud products.

Decision Trees on the Spreadsheet

All Analytic Solver Products (except Analytic Solver Data Mining and the Data Mining Cloud app) also include a facility to create decision trees on your Excel spreadsheet. Using the Ribbon, you can easily create decision nodes and

branches, event nodes and branches, and terminal nodes. The tree is drawn in graphic form on the spreadsheet; standard Excel worksheet formulas compute 'rollback' values at each node, and the best-choice value at the root node, based on either expected value or utility function (certainty equivalent) criteria. With a Ribbon choice, you can graphically highlight the optimal path through the tree.

Since all computations for decision trees are performed via standard Excel worksheet formulas, you can use decision trees in your simulation and optimization models. You must make discrete choices for decisions, and define discrete alternatives for events, but you can, for example, define distributions for event outcomes and/or costs incurred for decisions, and view the composite distribution of outcomes at the root node.

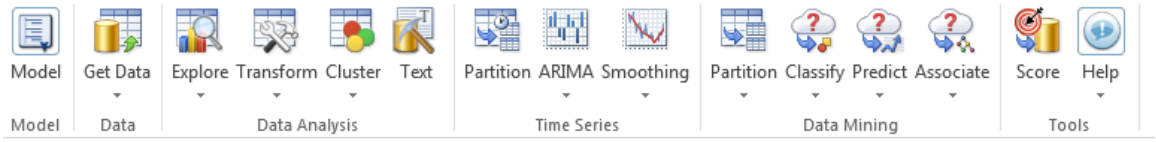
Bringing Big Data into Excel using Apache Spark

All Analytic Solver products include the ability to compute summary measures (sum, average, standard deviation, minimum or maximum) for variables in a dataset with up to billions of rows, stored across many hard disks in an external compute cluster running Apache Spark (https://spark.apache.org/), by clicking the **Get Data** icon. The results, which can be obtained immediately upon completion or at a later time, will include the number of variables included in the dataset and their names along with data counts for categorical variables. This kind of summary data is often what you need as input parameters to an optimization or simulation model. See the Analytic Solver Data Mining User Guide for more help on this new feature.

Forecasting and Data Mining

Analytic Solver Comprehensive, Analytic Solver Data Mining and the Data Mining Cloud app include powerful features for data visualization, forecasting and data mining. You can explore these features using Analytic Solver Basic – just click the Data Mining tab on the Excel Ribbon, and consult the Analytic Solver Data Mining User Guide:

Desktop Analytic Solver Data Mining



Data Mining Cloud

- Click the Model button to display the Solver Task Pane. This new feature (added in V2016) allows you to quickly navigate through datasets and worksheets containing Analytic Solver Data Mining results.
- Click the **Get Data** button to draw a random sample of data, or summarize data from a (i) an Excel worksheet, (ii) the PowerPivot "spreadsheet data

model" which can hold 10 to 100 million rows of data in Excel, (iii) an external SQL database such as Oracle, DB2 or SQL Server, or (iv) a dataset with up to billions of rows, stored across many hard disks in an external **Big Data** compute cluster running Apache Spark (https://spark.apache.org/).

- You can use the **Data Analysis** group of buttons to explore your data, both visually and through methods like cluster analysis, transform your data with methods like Principal Components, Missing Value imputation, Binning continuous data, and Transforming categorical data, or use the Text Mining feature to extract information from text documents.
- Use the **Time Series** group of buttons for time series forecasting, using both Exponential Smoothing (including Holt-Winters) and ARIMA (Auto-Regressive Integrated Moving Average) models, the two most popular time series forecasting methods from classical statistics. These methods forecast a single data series forward in time.
- The **Data Mining** group of buttons give you access to a broad range of methods for prediction, classification and affinity analysis, from both classical statistics and data mining. These methods use multiple input variables to predict an outcome variable or classify the outcome into one of several categories. Introduced in V2015, Analytic Solver Data Mining and now the Data Mining Cloud app, offer Ensemble Methods for use with Classification Trees, Regression Trees, and Neural Networks.
- Use the **Predict** button to build prediction models using Multiple Linear Regression (with variable subset selection and diagnostics), k-Nearest Neighbors, Regression Trees, and Neural Networks. Use Ensemble Methods with Regression Trees and Neural Networks to create more accurate prediction models.
- Use the **Classify** button to build classification models with Discriminant Analysis, Logistic Regression, k-Nearest Neighbors, Classification Trees, Naïve Bayes, and Neural Networks. Use Ensemble Methods with Classification Trees and Neural Networks to create more accurate classification models.
- Use the **Associate** button to perform affinity analysis ("what goes with what" or market basket analysis) using Association Rules.

If forecasting and data mining are new for you, don't worry – you can learn a lot about them by consulting our extensive in-product Help. Click **Help – Help Text** on the Data Mining tab, or click **Help – Help Text – Forecasting/Data Mining** on the Analytic Solver tab (these open the same Help file).

If you'd like to learn more and get started as a 'data scientist,' consult the excellent book *Data Mining for Business Intelligence*, which was written by the original Data Mining (formally known as XLMiner) designers and early academic users. You'll be able to run all the Data Mining examples and exercises in Analytic Solver.

Analytic Solver Data Mining, along with the Data Mining Cloud app, can be purchased as a stand-alone product. A stand-alone license for Analytic Solver Data Mining includes all of the data analysis, time series data capabilities, classification and prediction features available in Analytic Solver Comprehensive but does not support optimization or simulation. See the Analytic Solver Data Mining User Guide Data Specifications for each product.

Large-Scale Solver Engines

Frontline's Analytic Solver Comprehensive and Analytic Solver Optimization (in both Desktop and Cloud apps) support multiple optional, plug-in Solver

engines, in addition to their "bundled" Solver engines. Such Solver engines are licensed as separate products; they provide additional power and capacity to solve problems much larger and/or more difficult than the problems handled by the bundled Solver engines. Unlike most other optimization software, a license for one of Frontline's Solver engines enables you to use that Solver in desktop Excel or Excel Online. In addition, if using Solver SDK Platform, you may call the engine through C/C++, C#, Visual Basic, VB.NET, as MATLAB, Java, PHP, JavaScript and other languages.

These Solver engines are seamlessly integrated – to use one, you simply select the Solver engine by name in the dropdown list that appears in the Task Pane Engine tab. They produce reports as Excel worksheets, like the bundled Solver engines; their options can be set in the Task Pane, or, if using Analytic Solver Desktop, in Solver Options dialogs; and they can be controlled by VBA code in your custom applications. The Solver engines are also seamlessly integrated into the Solver Platform SDK. Trial licenses for these Solver engines are available, allowing you to evaluate how well they perform on a challenging Solver model that you've developed.

The large-scale Solver Engines are more valuable than ever in our Analytic Solver products, where you can create large, structured models more easily with **Dimensional Modeling**, and transform linear programming models *with uncertainty* into larger, *conventional* linear programming or second order cone programming models, using stochastic programming and robust optimization. Note: Dimensional Modeling is not supported in Analytic Solver Cloud.

Automatic Mode and Solution Time

Analytic Solver has many performance enhancements, ranging from faster startup and faster switching among workbooks to faster Solver engines, and a deeply parallelized design that exploits multi-core processors. But its Automatic mode can sometimes *increase* solution time.

If using Analytic Solver Desktop, **Automatic mode** refers to the Automatic choice available for several Platform options, which formerly required some thought and manual setting by the user. (Since Analytic Solver Cloud always uses Automatic mode, this option is not applicable in Analytic Solver Cloud.)

In the desktop products, Automatic is the *default* choice for these options in newly created models. The options (found on the Task Pane Platform tab) include:

Optimization Model Interpreter	Simulation Model Interpreter
Solve Uncertain Models	Supply Engine With
Nonsmooth Model Transformation	Automatically Select Engine (on the Task Pane Engine tab)
Stochastic Transformation	

Each Automatic choice means that Analytic Solver can analyze your model and automatically choose the best setting for these options. This normally results in better solutions and faster times; however, the process of *analyzing* your model and *trying* certain alternatives can take *extra* time, especially for large models.

To improve solution time when you re-run your model, you can inspect the solution log in the Task Pane Output tab to see what choices were made automatically, **manually set the Platform options** to these same choices, and save your workbook. This will save time when you next run the model.

The desktop version of Analytic Solver Upgrade includes Automatic Mode for analyzing the model and selecting the best available engine. However, this product does not include the ability to automatically *transform* models.

Help, Guided Mode and Proactive Support

Frontline's Solvers include User Guides, Reference Guides and over a hundred example models – but we've gone much further to provide help. If using a desktop product, the in-product help will open whenever you click any hyperlinked element in the Task Pane or Help icon in the Ribbon

Our **Wizards** can help you with the hardest parts of defining a simulation model (probability distributions) or an optimization model (constraints). **Guided Mode** helps you step-by-step with optimization solutions, when you're first getting started. **Auto-Help Mode**, the default setting, is something you can use all the time, since it displays explanatory dialogs only when you encounter a problem!

Support Live Chat enables you to connect instantly to Frontline's technical support personnel from inside Excel, send your last error message, model diagnosis and other information , and get help from a live person, and **Proactive Support**, which automatically creates a support ticket in our Help Desk when you're struggling with repeated error messages or modeling problems.

Help, Support, Licenses and Product Versions

Introduction

This chapter summarizes the Frontline Solvers V2020 product line, explains the licensing system in V2020 and how it benefits you, and describes how to use the newly introduced Cloud apps and the new License and Help Centers.

Working with Licenses in V2020

A **license** is a grant of rights, from Frontline Systems to you, to use our software in specified ways. As we learned in the last chapter, when you run the SolverSetup program to install Analytic Solver Desktop, software for the full Analytic Solver product family is installed. However, the product features you see in Analytic Solver Desktop, Analytic Solver Cloud and AnalyticSolver.com, and the size of models you can solve, depends on the license you have. Frontline Solvers V2020 uses a **licensing system**, developed in V2017-R2, that offers you more flexible ways to use the software, both desktop and cloud.

Licenses Tied to You, Not Your Computer

Information about a license, including the features and size limits it enables and its expiration date, is maintained on Frontline's cloud servers, associated with your **user account ID**, **email address** and **password** on Solver.com and AnalyticSolver.com. When you're using Analytic Solver on your desktop, license information is periodically downloaded or 'refreshed' from the cloud servers, but is stored on your PC for short periods, to enable you to run even when not connected to the Internet.

In Analytic Solver V2020, your license is associated with **you**, and may be used on **more than one PC**. For example, you can run SolverSetup to install the software on your office PC, your company laptop, and your PC at home. But only **you** can use Analytic Solver, and only on **one** of these computers **at a time**.

Using Your License: Login and Logout

When you first use Analytic Solver either in the cloud or on a new computer, **you will be prompted to login**. Enter the **email address** and **password** that you used to register on Solver.com or AnalyticSolver.com. Once you've done this in Analytic Solver Desktop, your identity will be "remembered," so you won't have to login every time you start Excel, and go to one of the Analytic Solver tabs. If you are using Analytic Solver Cloud or AnalyticSolver.com, you will need to login at the beginning of each session.

You can login and logout at any time, using **Login/Logout** on the License menu. If you share use of a single physical computer with other Analytic Solver users, be careful to **login** with your own email and password, and **log out when**

you're done – if you don't, other users could access private files in your cloud account, or use up your allotted CPU time or storage.

When you move from one computer to another, you should **log out** on one and **log in** on the other. As a convenience, if you log in to Analytic Solver on a new computer when you haven't logged out on the old computer, Analytic Solver will let you know, and offer to automatically log you out on the other computer.

Upgrading from Earlier Desktop Versions

A new license will not be required for V2020 if you're upgrading from Frontline Solvers V2017/V2018. Old license codes for V2016 and earlier have no negative effect in 2018. If they exist in the obsolete Solver.lic file (located at C:\ProgramData\Frontline Systems), they will be ignored. A new license will be issued at the time of purchase.

Analytic Solver Basic

In previous Frontline Solvers releases, SolverSetup installed a family of integrated products, where Analytic Solver Platform was the 'superset' product that included all features of 'subset' products' such as Premium Solver Platform or Premium Solver Pro. After a free trial, most licenses would allow you to use only a subset of features, for example features related to optimization.

In Frontline Solvers V2018, we changed this, to give you more: A free trial gives you a license for a product called **Analytic Solver Basic**. This product is closely related to Analytic Solver Platform for Education, the leading software used in MBA education – but it's available to everyone, not just to students.

With a trial or paid license for Analytic Solver Basic, you can access *every feature* of the software either on the Cloud or in desktop Excel, including forecasting and data mining, simulation and risk analysis, and conventional and stochastic optimization – but only for small models and datasets. A license for Analytic Solver Upgrade, Analytic Solver Optimization, Analytic Solver Simulation, or Analytic Solver Data Mining (*see below*) enables you to solve much larger models, and also enables speed and memory use features to efficiently handle these larger models.

Renamed Products Offering More

In Frontline Solvers V2017-R2, we simplified the names of products that are subsets of full Analytic Solver Platform, which is now called **Analytic Solver Comprehensive**:

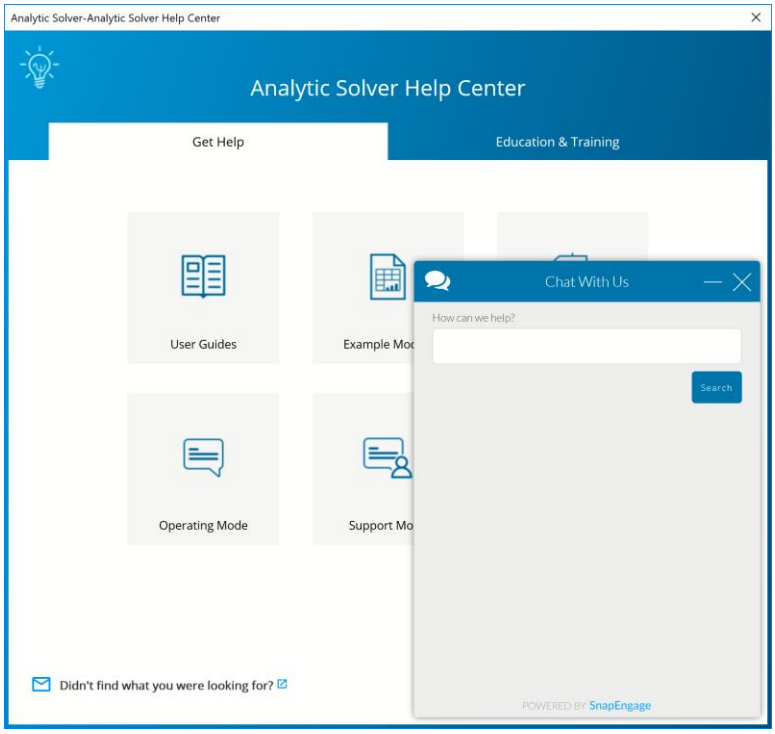
- **Analytic Solver Upgrade** – Formerly Premium Solver Pro, our basic 'Excel Solver Upgrade'
- **Analytic Solver Optimization** – Formerly Premium Solver Platform, full-size conventional optimization
- **Analytic Solver Simulation** – Full size Monte Carlo simulation, risk analysis and decision trees, plus simulation optimization (only)
- **Analytic Solver Data Mining** – Formerly XLMiner Platform, with major enhancements in this release
- **Analytic Solver Comprehensive** – Formerly Analytic Solver Platform
- **Analytic Solver Large-Scale** – A special bundle of Analytic Solver Comprehensive, Large-Scale LP/QP Solver, and Large-Scale GRG Solver

Every product above also includes all the features of Analytic Solver Basic. This means, for example, that when you upgrade to Analytic Solver Upgrade or Analytic Solver Optimization, you still have access to all of Analytic Solver's simulation and data mining features, for small models and datasets.

Getting Help

Should you run into any problems downloading or installing any of our products, we're happy to help. Call us at 775-831-0300 or email us at support@solver.com.

Click *Support Live Chat*, in the bottom right hand corner, to open a Live Chat window. If you run into any issues when using the software, the best way to get help is to start a Live Chat with our support specialists This will start a Live Chat during our business hours (or send us a message at other hours), just as if you were to start a Live Chat on www.solver.com – but it saves you *and* our tech support rep a lot of time – because the software reports your latest error message, model diagnosis, license issue or other problem, without you having to type anything or explain verbally what's happened. You'll see a dialog like this:

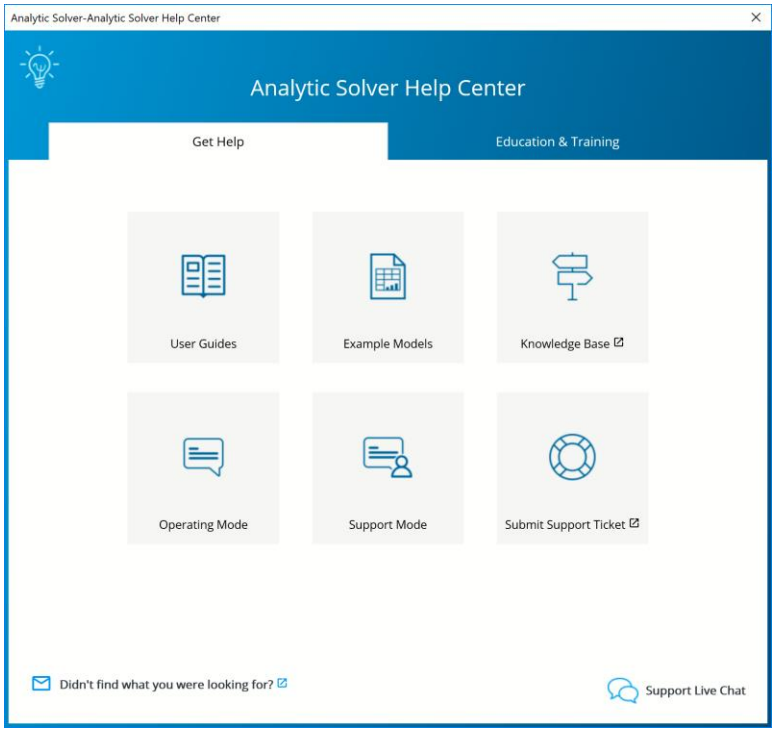


Since the software automatically sends diagnostic information to Tech Support, we can usually identify and resolve the problem faster. (Note: No contents from your actual spreadsheet model is sent, only information such as the number of variables and constraints, last error message, and Excel and Windows version.)

Note: If Support Live Chat is disabled, click the down arrow beneath Help and select *Support Mode – Active Support.*

Accessing Resources

To open Analytic Solver Help, simply click the Help icon on the Analytic Solver ribbon in either App to gain access to video demos, User Guides, online Help, example models, and Website support pages to learn how to use our software tools, and how to build an effective model.



User Guides

Click the User Guides menu choice to open PDF files of the Analytic Solver Optimization and Simulation User and Reference Guides, Analytic Solver Data Mining User or Reference Guides, or our Quick Start Guides.

Example Models

Clicking this menu item will open a browser pointing to the workbook, Frontline Example Models Overview.xlsx, located at C:\Program Files\Frontline Systems\ Analytic Solver Platform\Examples. See the table below for a description of each example dataset.

By going to **Help – Welcome Screen** you can easily access a range of support and training resources.

Knowledge Base

Click Knowledge Base to peruse a multitude of online articles related to support and installation issues or to locate articles that will help you to quickly build accurate, efficient optimization, simulation, and data mining models.

Operating Mode

Click Operating Mode to switch between three different levels of help. The Excel formulas and functions you use in your model have a huge impact on how fast it runs and how well it solves. If you learn more about this, you can get better results, but if you don't, your results will be limited. Guided Mode can help you learn.

- Guided Mode prompts you step-by-step when solving, with dialogs.
- Auto-Help Mode shows dialogs or Help only when there's a problem or error condition.
- Expert Mode provides only messages in the Task Pane Output tab. (This mode not supported when using a trial license.)

Support Mode

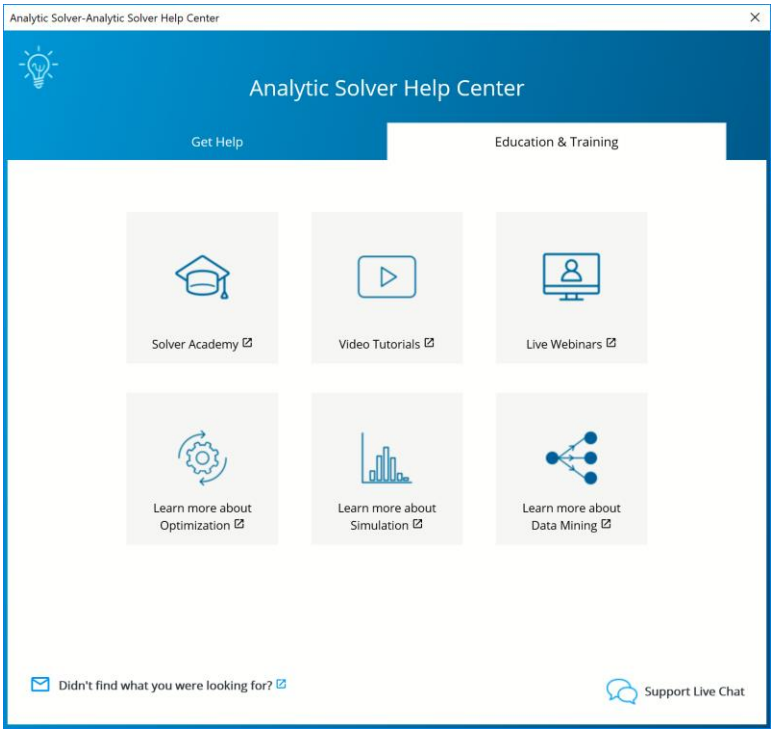
Click Support Mode to switch between three different levels of support. No information (cell contents etc.) from your Excel model is ever reported automatically to Frontline Systems, in any of these Support Modes. Only events in Frontline's software, such as menu selections, Solver Result messages, or error messages are reported.

- **Active Support** automatically reports events, errors and problems to Frontline Support, receives and displays messages to you from Support, and allows you to start a Live Chat with Support while working in Excel (**Recommended**).Auto-Help Mode shows dialogs or Help only when there's a problem or error condition.
- **Standard Support** automatically reports events, errors and problems anonymously (not associated with you) to Frontline Support, but does not provide a means to receive messages or start a Live Chat with Support.
- **Basic Support** provides no automatic connection to Frontline Support. You will have to contact Frontline Support manually via email, website or phone if you need help.

Submit a Support Ticket

If you're having installation, technical, or modeling issues, submit a Support Ticket to open an online support request form. Submit your email address and a short, concise description of the issue that you are experiencing. You'll receive a reply from one of Frontline's highly trained Support Specialists within 24 hours, and generally much sooner.

Our technical support service is designed to supplement your own efforts: Getting you over stumbling blocks, pointing out relevant sections of our User Guides or example models, helping you fix a modeling error, or -- in rare cases -- working around an issue with our software (always at our expense).



Solver Academy

Solver Academy is Frontline Systems' own learning platform. It's the place where business analysts can gain expertise in advanced analytics: forecasting, data mining, text mining, mathematical optimization, simulation and risk analysis, and stochastic optimization.

Video Tutorials/Live Webinars

Click Video Tutorials to be directed to Frontline's You Tube Channel. Browse videos on how to create an optimization or simulation model or construct a data mining or prediction model using Analytic Solver.

Click Live Webinars to be redirected to www.solver.com to join a live or pre-recorded webinar. Topics include *Using Analytic Solver Data Mining to Gain Insights from your Excel Data*, *Overview of Monte Carlo Simulation Applications*, *Applications of Optimization in Excel*, etc.

Learn more!

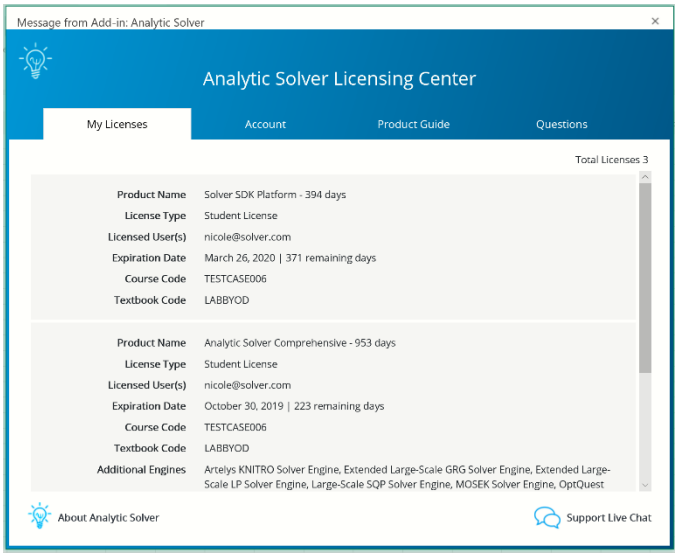
Click any of the three Learn More buttons to learn more about how you can solve large-scale optimization, simulation, and data mining models, reduce costs, quantify and mitigate risk, and create forecasting, data mining and text mining models using Analytic Solver.

License Button

Click the License button to open the License Manager where you can manage your current licenses and accounts, open our Product Selection Wizard, connect to Live Chat or peruse through a list of FAQs.

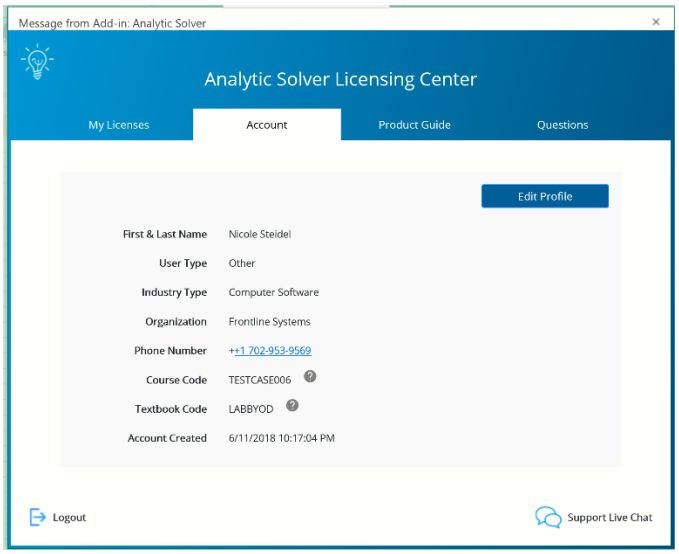
Click License – Manage License/Manage Account to open the Licensing Center.

The "MyLicenses" tab displays your current license and license type, along with the expiration date.

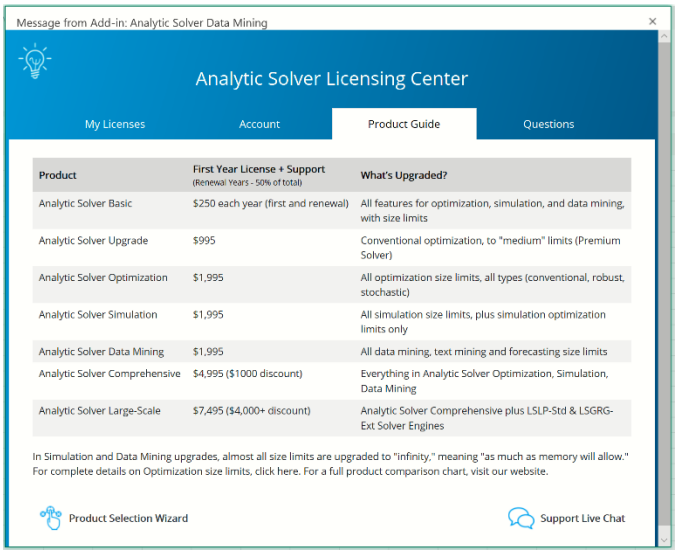


Click *About Analytic Solver* to open the following dialog containing information on this release.

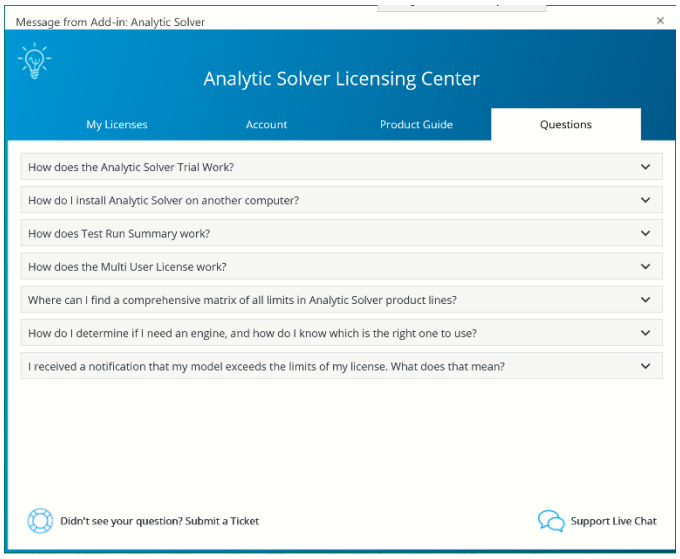
Click the Account tab to view your account on www.solver.com. Click Edit Profile to edit the information. Click Live Chat to open a Live Chat window or Log Out to log out of the product.



Click the Product Guide tab to view a list of products and pricing information. Click Product Selection Wizard to open the Product Selection Wizard. See the next section for information on this feature.

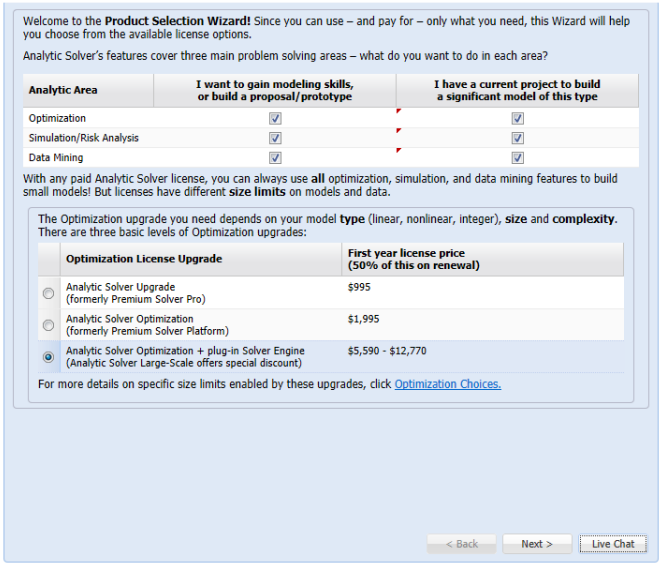


Click the Questions tab to review a list of FAQs, submit a support ticket or start a live chat.

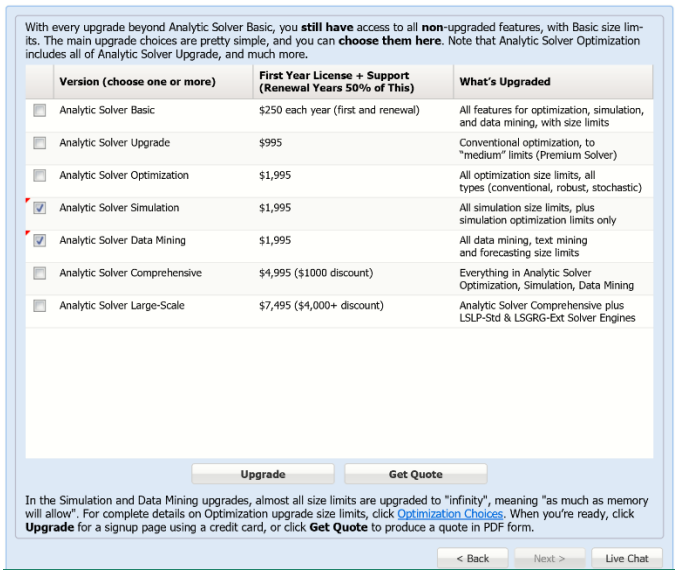


Product Selection Wizard

Select **Product Selection Wizard** from the Product Guide tab in the Licensing Center to open a series of dialogs that will help you determine which product will best meet your needs based on your recent pattern of use.

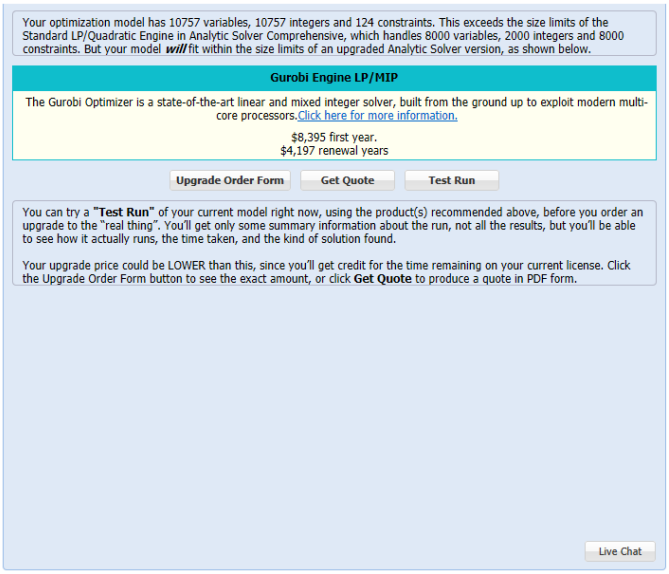


Select the Product that you'd like to purchase and then click **Next**. Click the *Optimization Choices* link to learn more about Analytic Solver products that can solve optimization models and to find more information on speed, memory, and the use of plug-in Solver Engines.



On this screen, the Product Selection Wizard will recommend a product or products based on your answers on the previous screens. Click Upgrade to purchase the recommended product. Click the *Optimization Choices* link to learn more about Analytic Solver products that can solve optimization models. If at any time you'd like to chat with a member of our Technical Support staff, click **Live Chat**. Or if you'd like to amend your answers on a previous dialog, click **Back**.

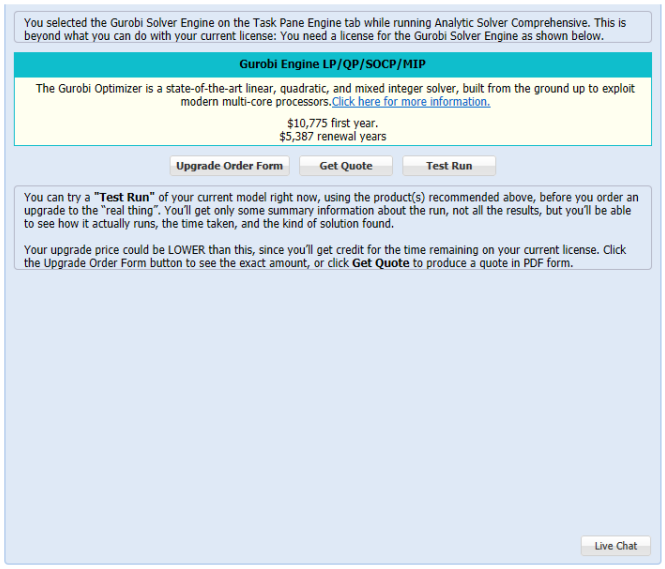
When you run a simulation or optimization model that contains too many decision variables/uncertain variables or constraints/uncertain functions for the selected engine, the Product Wizard will automatically appear and recommend a product that *can* solve your model.



When you click "Test Run", the Product Wizard will immediately run the optimization or simulation model using the recommended product. (Only summary information will be available.) At this point, you can purchase the recommended product(s), or close the dialog.

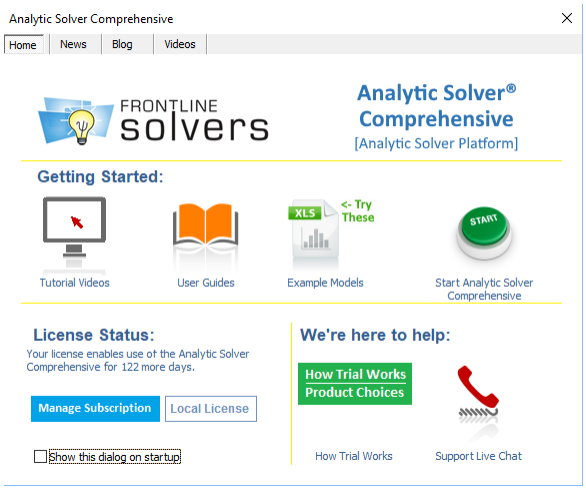
This same behavior will also occur when solving smaller models, if you select a specific external engine, from the Engine drop down menu on the Engine tab of

the Solver Task Pane, for which you do not have a license. The Product Wizard will recommend the selected engine, and allow you to solve your model using this engine. Once Solver has finished solving, you will have the option to purchase the product.



Using the Welcome Screen in Analytic Solver Desktop

When using Analytic Solver Desktop, the first time you click the Analytic Solver tab on the Ribbon, you'll see the Welcome Screen, pictured on the next page. You can display the Welcome Screen manually by choosing **Help – Welcome Screen** from the Ribbon. And if you *don't* want to see it, you can control whether the screen appears automatically by selecting or clearing the check box in the lower left corner, "Show this dialog on startup."



The Welcome Screen was considerably enhanced in V2017-R2. As in earlier releases, it reports the status of your license, and provides links to Tutorial Videos, User Guides, Example Models, and Live Chat with tech support (also available from the Help drop-down menu on the Ribbon). The **blue** button below License Status takes you directly to the License / Subscription Manager

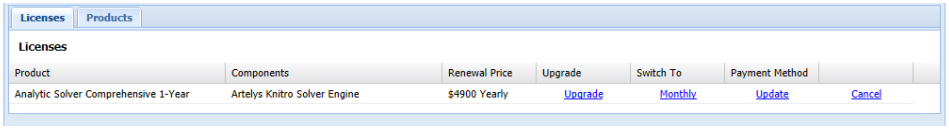
(also available from the Options drop-down menu). The Local License button to the right opens Frontline Solvers License Manager. And the **green** button displays an explanation of Analytic Solver Basic, your free trial, and upgrade options – much like this section.

There's more: Click the **News**, **Blog** and **Videos** tabs at the top of the dialog to see the latest application news and case studies, Frontline Systems blog posts, and videos from Solver.com. And from time to time, you'll see a **Messages** tab at the top of this dialog, with *individual* messages for you from Frontline's Tech Support and Customer Success teams.

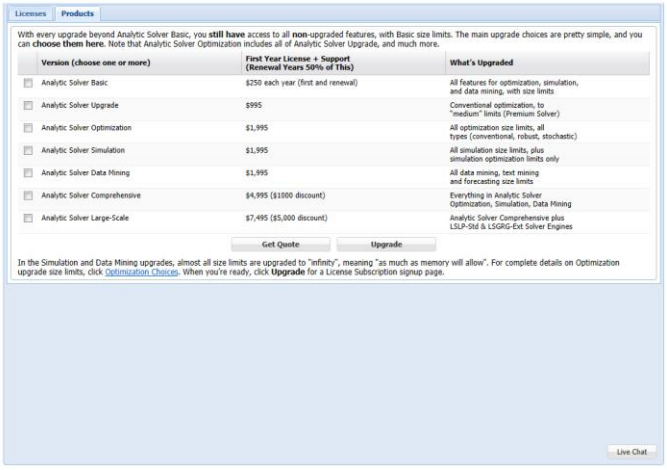
License/Subscription in Analytic Solver Desktop

Since Frontline Solvers V2015, our products have been offered on an annual subscription basis, including the software license and Annual Support (technical support and software upgrades). But in order to renew your subscription, or upgrade or change the product you were using, you had to talk to someone in Frontline Systems sales or customer service, who would make the change, and email you a new license code that you'd copy and paste into a dialog box.

With Frontline Solvers V2018, all those steps have been *automated*: You can review your subscription status, renew, upgrade or downgrade your subscription, or add plug-in Solver Engines, all 'self-service' using the License / Subscription Manager – accessible via the blue button in the Welcome Screen, **or Options - License / Subscription** on the Analytic Solver Ribbon. The next page shows a example of the License / Subscription Manager dialog.



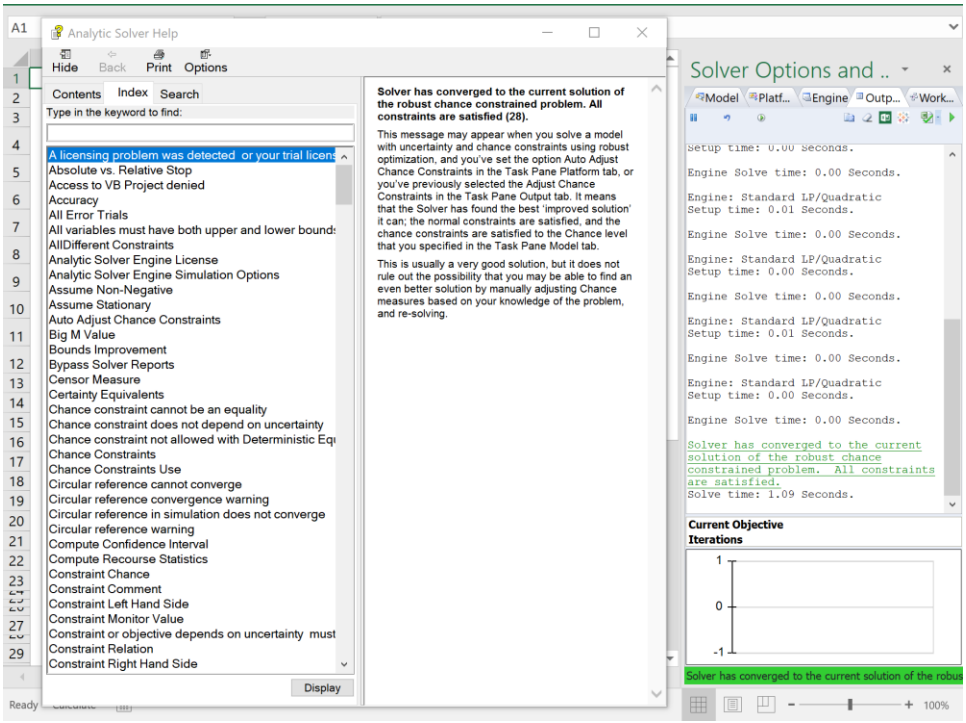
The **Products** tab in the License / Subscription Manager dialog shows you a list of the products that are 'upgrade options' for your current subscription. You can click the hyperlinks for more information about the products on Solver.com, or click the buttons to go step-by-step through the upgrade process.



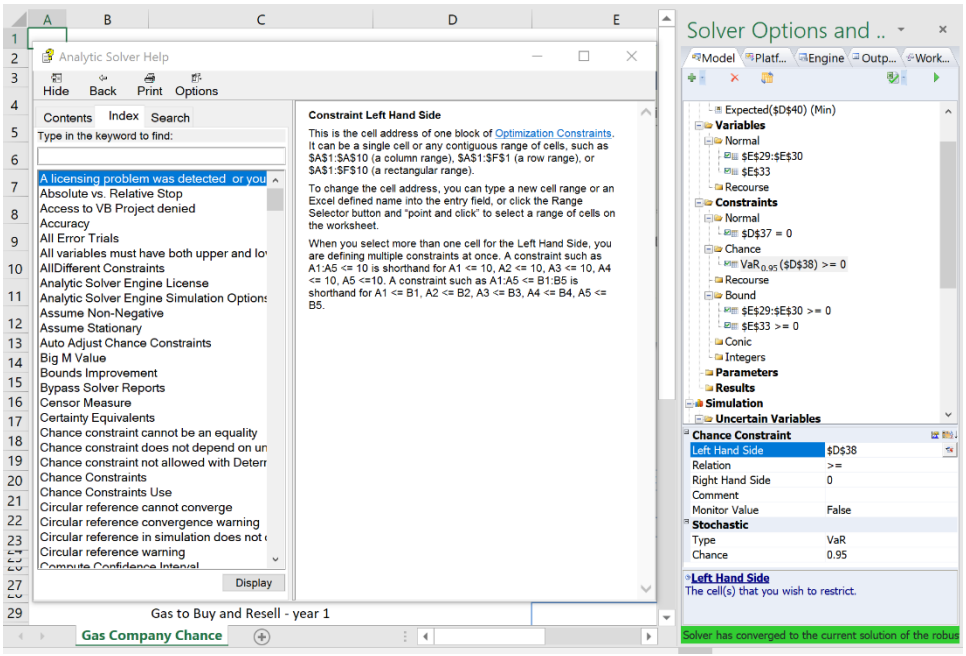
Context-Sensitive Help in Analytic Solver Desktop

Analytic Solver Desktop 2020 has a significant amount of context-sensitive Help. You can quickly access Help on any Solver Result message that appears in the Task Pane Output tab, any option that appears on the Engine tab or Platform tab, or any element of your model that appears on the Model tab.

Solver Result messages appear as underlined links – you can simply click them. For example, here's the Help that appears when you click the Solver Results message for the Gas Company Chance example in StochasticExamples.xls:



To access Help on any Platform option, Engine option, or Model element, click the underlined link in the brief explanation that appears at the bottom of the Task Pane. For example, here's the Help that appears when you click the Type field link for a chance constraint in your model:



To access help in Analytic Solver Cloud, click Help – Help Center or Help – Analytic Solver Help in AnalyticSolver.com.

Examples: Conventional Optimization

Introduction

This chapter introduces conventional optimization (with no uncertainty) in both the Desktop and Cloud apps using Analytic Solver Comprehensive, Analytic Solver Optimization, Analytic Solver Upgrade, and Analytic Solver Basic with a series of examples. Except as noted in specific sections, all of these examples can be used in any of the above product subsets.

- "A First Optimization Model" takes you step-by-step through the process of creating an optimization model from scratch. It illustrates use of the Ribbon and Task Pane, and its relationship to the Excel Solver Parameters dialog.
- "Introducing the Standard Examples," "Linear Programming Examples" and "Nonlinear Optimization Examples" takes you through the workbook **StandardExamples.xls**, with seven examples that illustrate a number of Analytic Solver features.

A First Optimization Model

This section is meant for you if you're familiar with optimization, but you've never used Excel Solver or Analytic Solver Basic. It shows how you can translate from the algebraic statement of an optimization problem to a spreadsheet Solver model. If *optimization* is new to you, consult the chapter "Mastering Conventional Optimization Concepts."

Note: This first step-by-step example is a 'quick and dirty' approach that can be used to solve the example problem, but is not well documented or easy to maintain. If using Analytic Solver Desktop or Cloud you'll have access to Microsoft Excel's many features that can help you organize and display the structure of your model, through tools such as defined names, formatting and outlining. The models in the **StandardExamples.xls** workbook illustrate some of these features. This workbook is normally installed into C:\Program Files\Frontline Systems\Analytic Solver Platform\Examples. As models become larger, the problems of managing data for constraints, coefficients, and so on become more significant, and a properly organized spreadsheet model can help manage this complexity.

Setting Up a Model

To set up an optimization model in a spreadsheet either in Microsoft Excel, Excel Online or in AnalyticSolver.com, you will follow these essential steps:

1. Reserve a cell to hold the value of each decision variable. We'll use A1:A3 in the example below.
2. Pick a cell to represent the objective function, and enter a formula that calculates the objective function value in this cell. We'll use A4 in the example below.

3. Pick other cells and use them to enter the formulas that calculate the left hand sides of the constraints. We'll use B1:B5 in the example below.

4. The constraint right hand sides can be entered as numbers in other cells, or entered directly in the Solver's Add Constraint dialog. We'll use C1:C5 for this purpose in the example below.

Within this overall framework, you have a great deal of flexibility in choosing cells to use, and calculating the objective and constraints. For example, the objective function will ultimately depend on the decision variable cells, but you don't have to calculate the entire function in one formula cell. You can use any number of formula cells to compute intermediate results, and use these to calculate the objective function or the constraints.

In desktop Excel and Excel Online, you can write a linear expression easily with Excel's SUMPRODUCT function, or you can use + and * operators, as shown below. You can use Excel's *array* formulas, and Excel functions that return vector and matrix results. And you can use Excel's rich facilities to access data in external text files, Web pages, and relational and multidimensional databases to 'populate' your model.

AnalyticSolver.com offers a spreadsheet-like grid that works much like Excel but does not include the rich array of features that Excel offers.

The Model in Algebraic and Spreadsheet Form

Consider the following problem. Our factory is building three products: TV sets, stereos and speakers. Each product is assembled from parts in inventory, and there are five types of parts: chassis, picture tubes, speaker cones, power supplies and electronics units. Our goal is to produce the mix of products that will maximize profits, given the inventory of parts on hand. This is a simple linear programming problem, also used to illustrate other ideas later in "Linear Programming Examples."

The Algebraic Form

The problem can be described in algebraic form as follows. The decision variables are the number of products of each type to build: x_1 for TV sets, x_2 for stereos and x_3 for speakers. There is a fixed profit per unit for each product, so the objective function (the quantity we want to maximize) is:

Maximize $75\ x_1 + 50\ x_2 + 35\ x_3$ (Profit)

Building each product requires a certain number of parts of each type. For example, TV sets and stereos each require one chassis, but speakers don't use one. The number of parts used depends on the mix of products built (the left hand side of each constraint), and we have a limited number of parts of each type on hand (the corresponding constraint right hand side):

Subject to
$1\ x_1 + 1\ x_2 + 0\ x_3 <= 400$ (Chassis)
$1\ x_1 + 0\ x_2 + 0\ x_3 <= 200$ (Picture tubes)
$2\ x_1 + 2\ x_2 + 1\ x_3 <= 800$ (Speaker cones)
$1\ x_1 + 1\ x_2 + 0\ x_3 <= 400$ (Power supplies)
$2\ x_1 + 1\ x_2 + 1\ x_3 <= 600$ (Electronics)

Since the number of products built must be nonnegative, we also have the constraints $x_1, x_2, x_3 >= 0$. Note that terms like $0\ x_3$ are included purely to show the structure of the model – they can be either omitted or included when entering formulas in Excel.

The Spreadsheet Formulas

The fastest (though not necessarily the best) way to lay out this problem on the spreadsheet is to pick (for example) cell A1 for x_1, cell A2 for x_2 and cell A3 for x_3. Then the objective can be entered in cell A4, much like the algebraic form above:

A4: =75*A1+50*A2+35*A3

We can go on to enter a formula in (say) cell B1 for the first constraint left hand side (Chassis) as =1*A1+1*A2+0*A3, or the simpler form:

B1: =A1+A2

Similarly, we can use cell B2 for the formula =A1 (Picture tubes), B3 for the formula =2*A1+2*A2+A3 (Speaker cones), B4 for the formula =A1+A2 (Power supplies), and B5 for the formula =2*A1+A2+A3 (Electronics):

B2: =A1
B3: =2*A1+2*A2+A3
B4: =A1+A2
B5: =2*A1+A2+A3

Finally, we'll enter the constraint right hand side values in cells C1:C5:

C1: 400
C2: 200
C3: 800
C4: 400
C5: 600

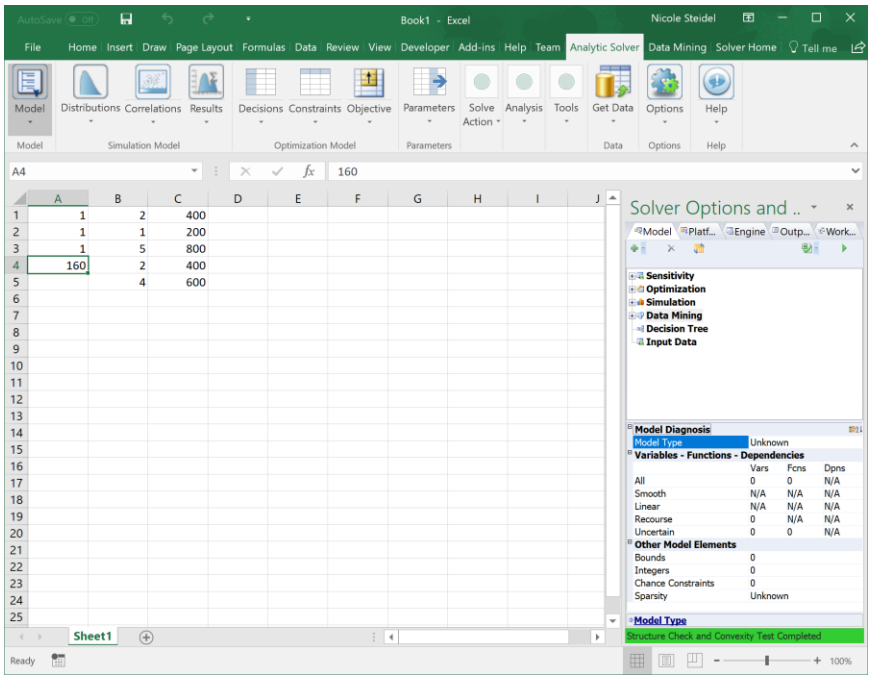
We now have a simple spreadsheet model that we can use to play 'what if.' For any values we enter for the decision variables in cells A1, A2 and A3, the objective (Total Profit) and the corresponding values of the constraint left hand sides (the numbers of parts used) will be calculated.

We want to turn this 'what if' spreadsheet model into an optimization model, where the Solver will automatically find *optimal* values for the cells A1:A3, so that the objective function at A4 is maximized, and the constraints are satisfied.

Defining and Solving the Optimization Model

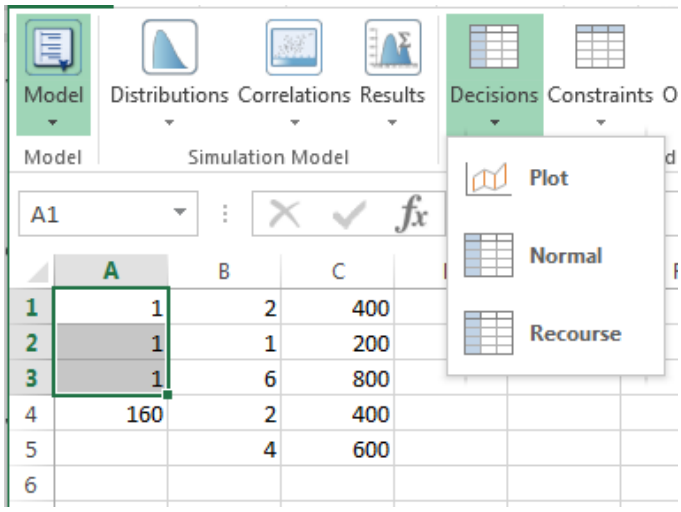
To begin, click the Analytic Solver tab on the Ribbon. Your worksheet with an empty **Task Pane** ("Solver Options and Model Specifications") **Model tab** should appear, as shown on the next page.

To define the optimization problem, we'll use the Ribbon to point out to the Solver (i) the cells that we've reserved for the decision variables, (ii) the cell that calculates the value of the objective function, and (iii) the cells that calculate the constraint left hand sides. We'll also enter values for the constraint right hand sides, and non-negativity constraints on the variables. We can perform these steps in any order.



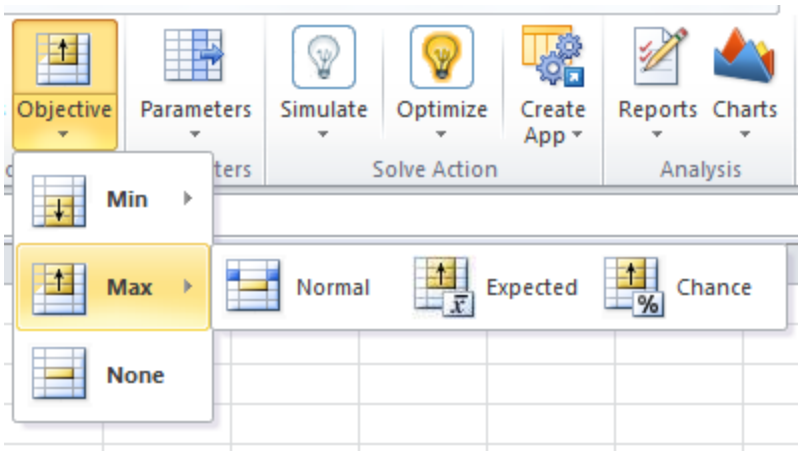
Defining Decision Variables

To define the **decision variables**, use your mouse to select the range A1:A3 on the worksheet. Then click the **Decisions** button to open the dropdown gallery (shown below), and click **Normal** to define A1:A3 as normal decision variables or, if using Analytic Solver Desktop or AnalyticSolver.com, simply click the Decisions button to define A1:A3 as normal decision variables.

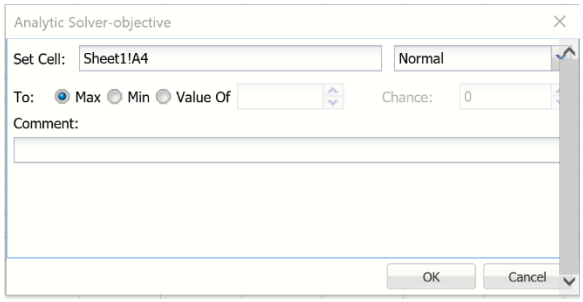


Defining the Objective

To define the **objective**, use your mouse to select cell A4 on the worksheet. In Analytic Solver Desktop and AnalyticSolver.com, click the down arrow under **Objective**, then select **Max** and **Normal** from the menu to define A4 as a normal objective to be maximized – as shown on the next page. Alternatively, you can click the **Objective** button to open the Add Objective dialog. Click OK to accept the defaults and to define A4 as a normal objective to be maximized.



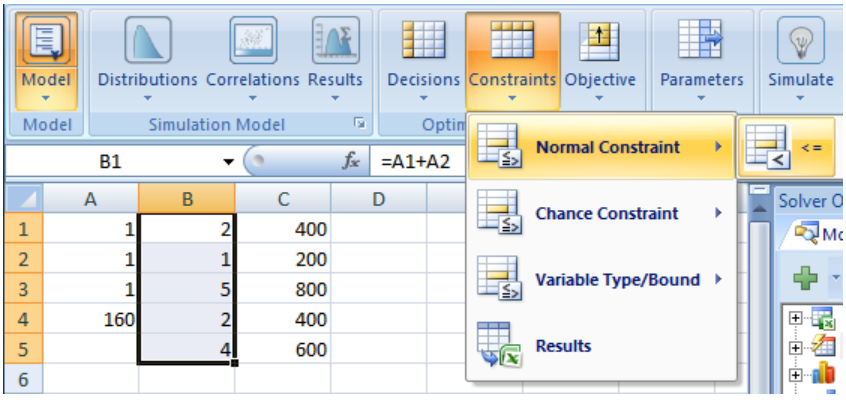
In Analytic Solver Cloud, click the down arrow under Objective and select Add/Change Objective. Click OK to accept the defaults and to define A4 as a normal objective to be maximized.



Defining Constraints

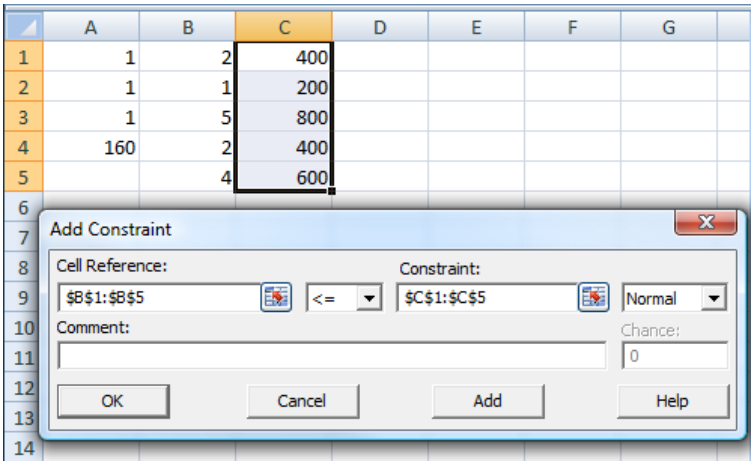
To define the **constraints**, use your mouse to select the range B1:B5 on the worksheet. Then, if using Analytic Solver Desktop or AnalyticSolver.com, click the **Constraints** button to open the Add Constraint dialog.

Alternatively, you could also click the down arrow under Constraints, then click **Normal Constraint** and <= to define B1:B5 as the left hand sides of five <= constraints.



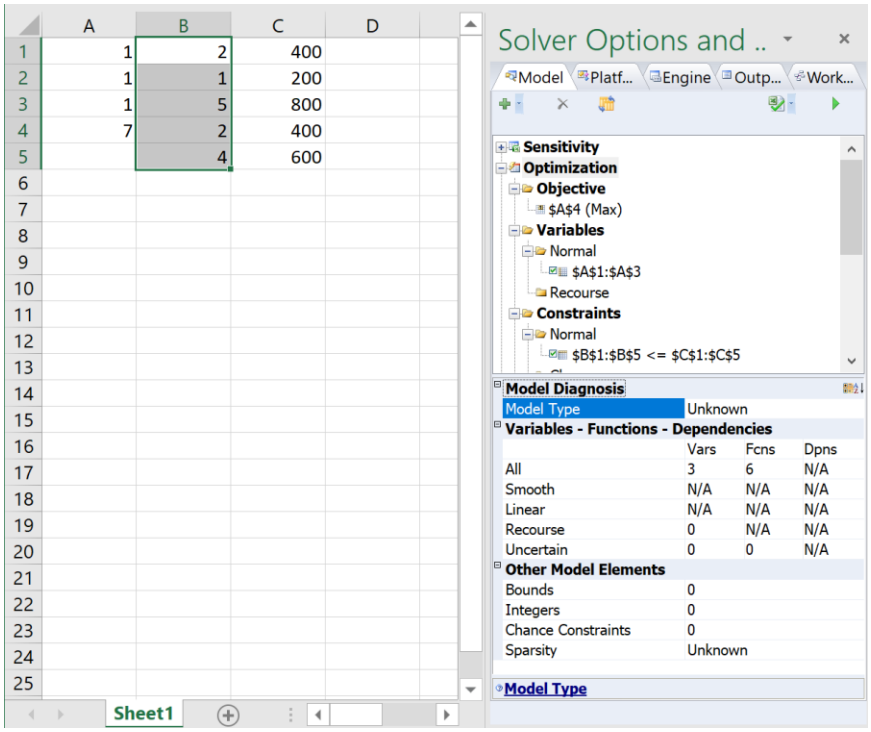
If using Analytic Solver Cloud, click the down arrow under Constraints, then click Add Constraint to open the Add Constraint dialog.

Within this dialog, you can enter the right hand side(s) as a constant number, a cell range, or a defined name. Click in the **Constraint** edit box, or click the **range selector icon** to its right, and use your mouse to select the cell range C1:C5 for the right hand sides:

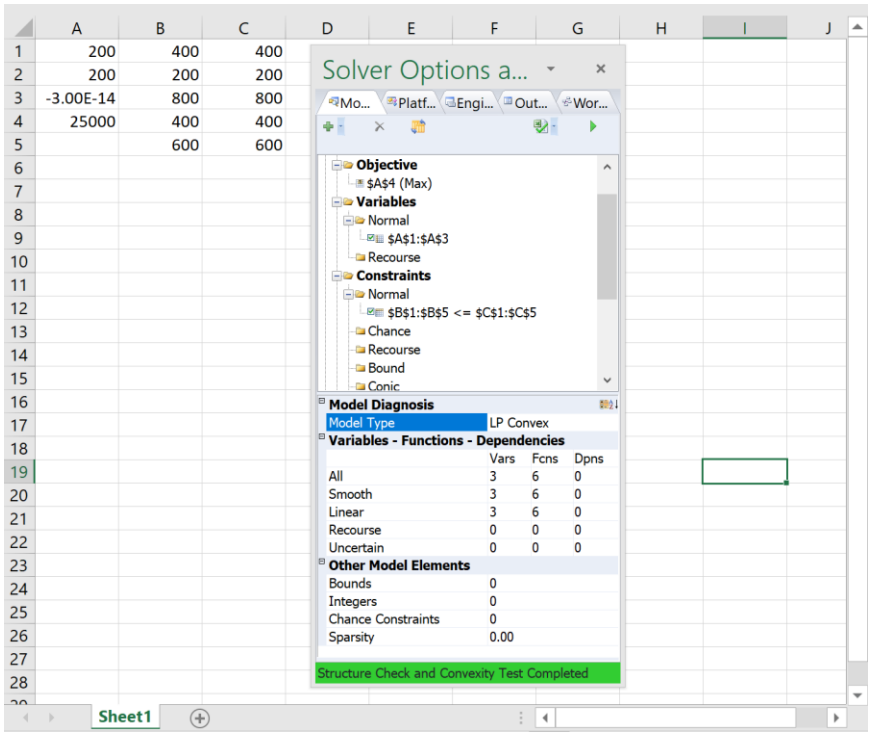


Then click OK. This will define five constraints: B1 <= C1, B2 <= C2, B3 <= C3, B4 <= C4, and B5 <= C5.

The Task Pane Model tab now shows all the elements of the optimization model you've just defined in outline form.



You can solve the model immediately by clicking the **Optimize** button on the Ribbon, or by clicking the **green arrow** at the top right of the Task Pane.

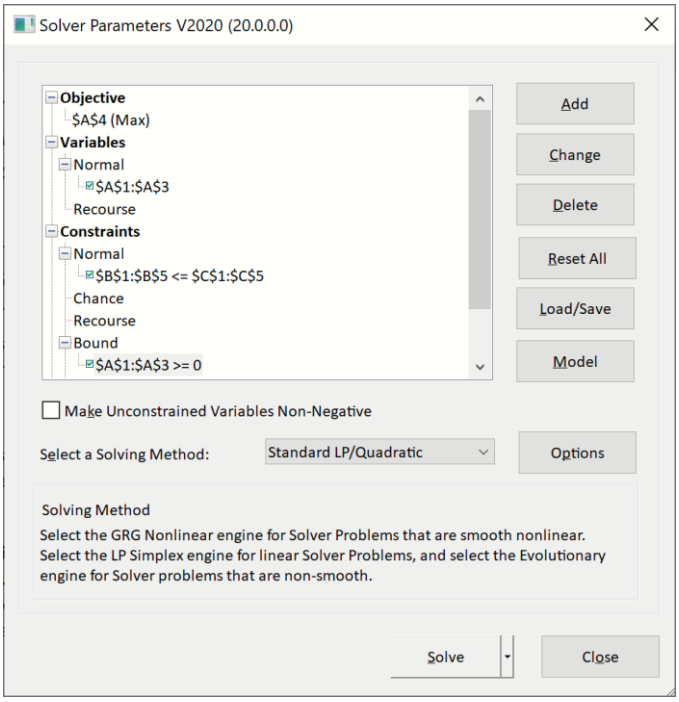


The optimal values of the decision variables at A1:A3, the objective at A4, and the constraints at B1:B5 appear on the worksheet, and a **Solver Result message** ("Solver found a solution. All constraints and optimality conditions are satisfied") appears in green at the bottom of the Task Pane.

You can view a log of solution messages on the Task Pane Output tab in Analytic Solver Desktop, and you can produce optimization reports by selecting **Reports – Optimization** from the Ribbon. For more information about these features, keep reading!

Using the Classical Solver Parameters Dialog

When using Analytic Solver Desktop, you can also view – and create or edit – this model through the classical Solver Parameters dialog (as used in the standard Excel Solver). To do so simply click **Premium Solver** on the **Add-Ins** tab on the Ribbon to display the Solver Parameters dialog. Note: This dialog is not supported in Analytic Solver Cloud or AnalyticSolver.com.



Comparing the Task Pane and Solver Parameters Dialog

As you can see, the Task Pane Model tab and the Solver Parameters dialog contain the same information. But where the Solver Parameters dialog is *modal* (moving the mouse outside the dialog displays a wait cursor – you must close the dialog to do anything else), the Task Pane is *modeless*: You can move the mouse outside the pane, edit formulas on the worksheet, or use other commands.

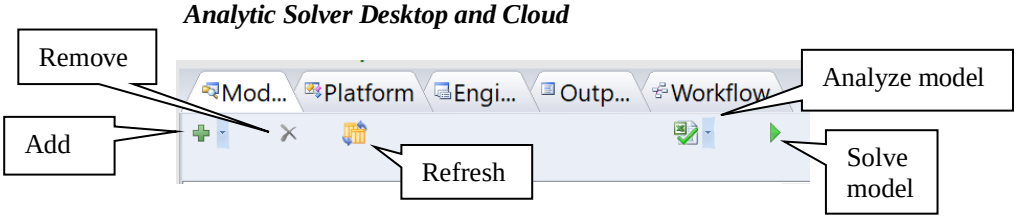
The Task Pane is initially docked to the right side of the Excel window, but you can select its title bar with your mouse, **drag** it to another position, and **resize** it, as shown on the next page. To "re-dock" the Task Pane, select its title bar with the mouse, drag to a position just beyond the right edge of the Excel window, then release the mouse.

Use the **Model tab** to view your model in outline form, and optionally edit model elements in-place. Use the **Platform tab** to view or change Platform options, such as the number of optimizations or simulations to run, or default bounds on decision variables or uncertain variables. Use the **Engine tab** to select a Solver Engine and view or change its options. Use the **Output tab** to view a log of solution messages, or a chart of the objective values.

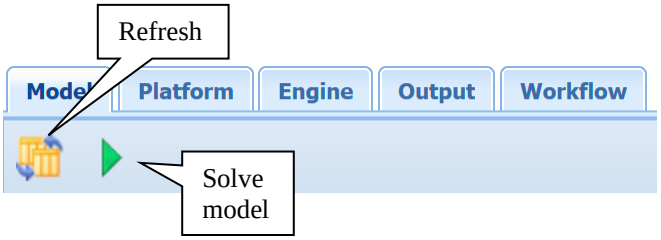
Using Buttons on the Task Pane

Use the **buttons** at the top of the **Model tab** to add or remove model elements (you can also use the Ribbon options to do this, as shown earlier), refresh the model outline when you've made unusual changes to the worksheet, analyze the structure of your model, or solve (run) the optimization or simulation model:

Analytic Solver Desktop and Cloud

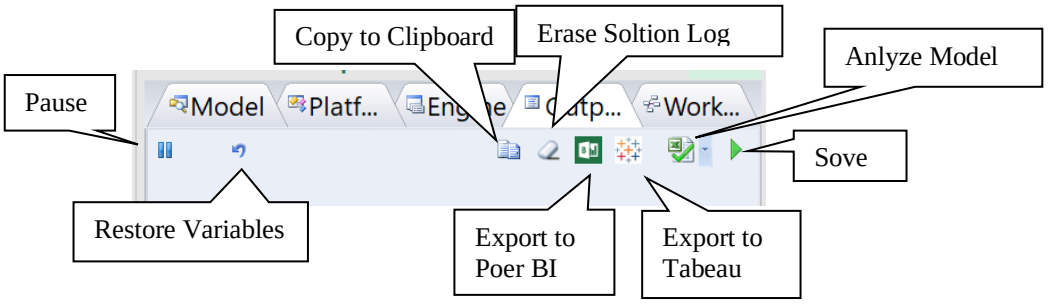


AnalyticSolver.com

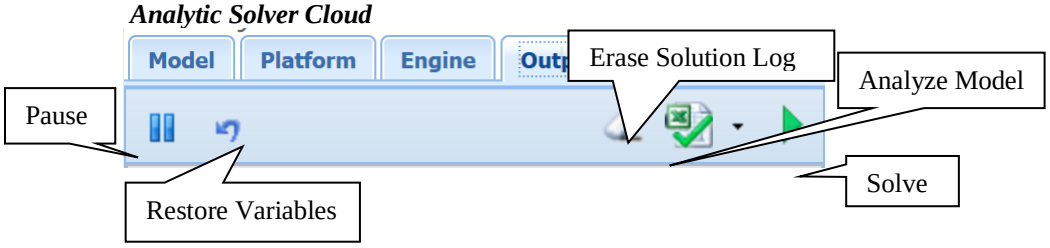


Use the **buttons** at the top of the **Output tab** to pause or stop the Solver, restore the original values of the decision variables, copy the solution message log to the Windows Clipboard (so you can paste the text into another application – Analytic Solver Desktop only), erase the solution log, analyze/solve the model and upload your results to Microsoft's Power BI or Tableau (see step by step instructions below – Analytic Solver Desktop only).

Analytic Solver Desktop

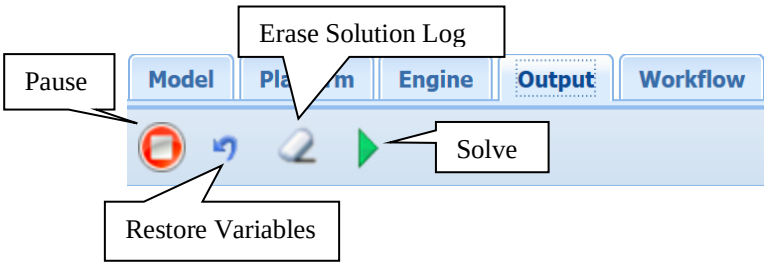


Analytic Solver Cloud



d

AnalyticSolver.com

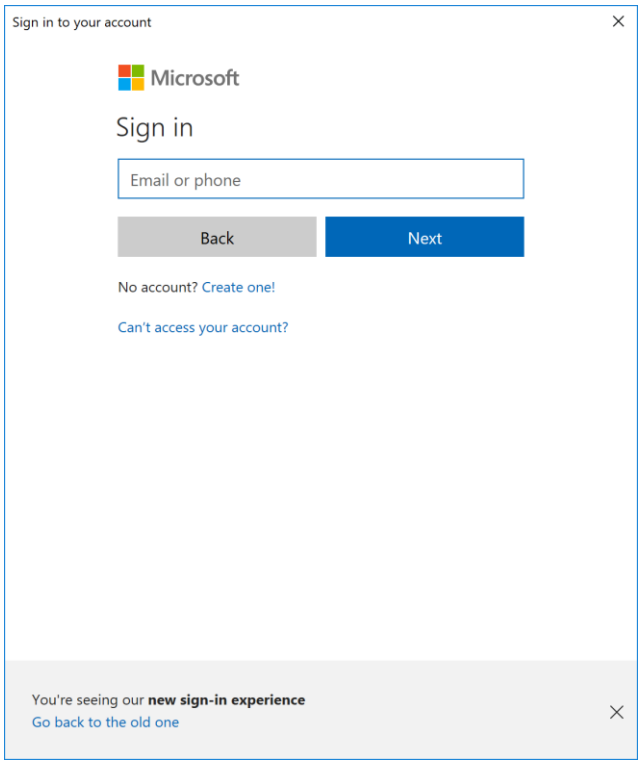


Exporting Data to Microsoft's Power BI

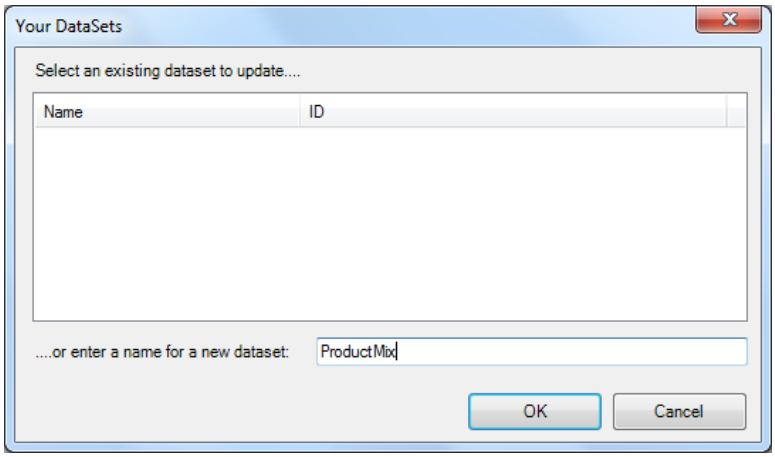
Microsoft's POWER BI, for use with Office 365, is a cloud-based service that works with Excel to help you visualize your data using various charts and reports. Analytic Solver Desktop includes the ability to export a fixed set of data from your optimization model, including final variable values, final constraint values, final objective function values, variable shadow prices or constraint reduced costs, etc., directly into a dataset in Power BI.

Note: Exporting your model to Power BI via the Output Pane on the Solver Task Pane is not supported in Analytic Solver Cloud or AnalyticSolver.com. However, it is possible to upload your model to Power BI using the Create App menu. See the chapter, Creating Power BI Custom Visuals, that appears later on in this guide for more information.

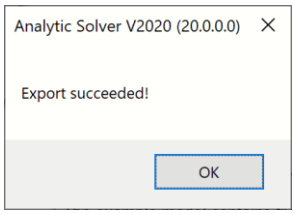
Once Solver has stopped with a final result message (even if a solution was not found), click the icon on the Output tab to upload the model to the Power BI dashboard. If this is the first time that the icon has been clicked within the current Excel instance, you will be asked to log in to Power BI.



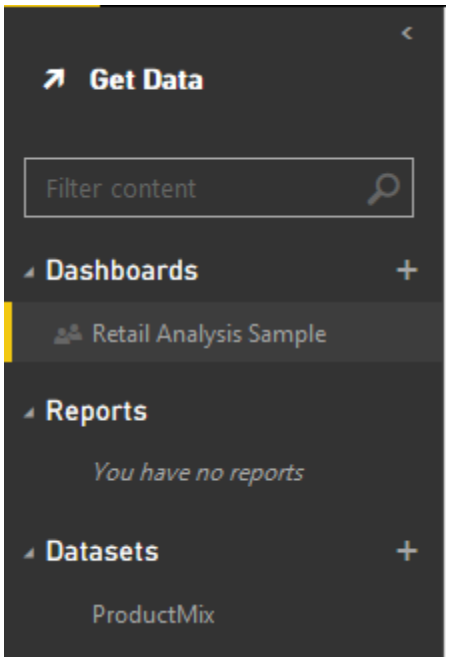
Once logged in, you will be asked to either update an existing dataset or create a new dataset.



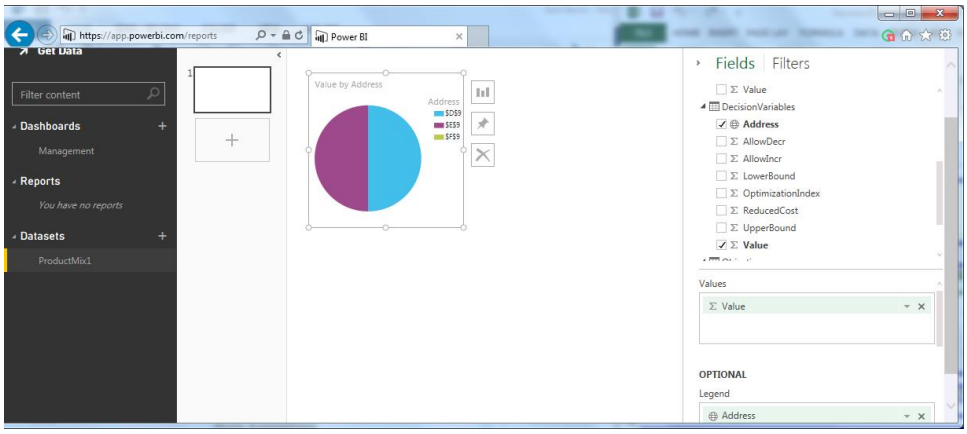
In the screenshot above, we have created a new dataset, ProductMix, which will contain the objective, variable and constraint final values, shadow prices, dual values, etc from our optimization model. Once the upload is complete, the following message will appear.



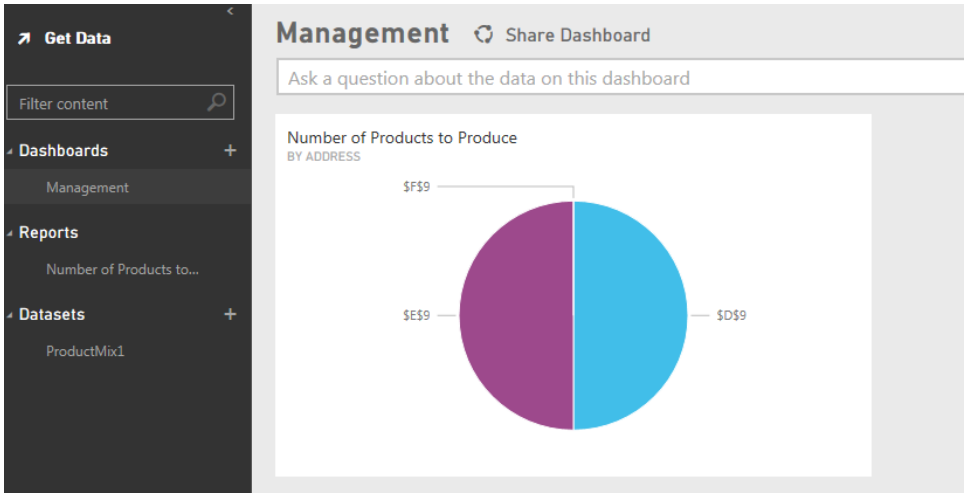
Logon to Power BI (http://powerbi.microsoft.com/). The newly created dataset will be listed under Datasets.



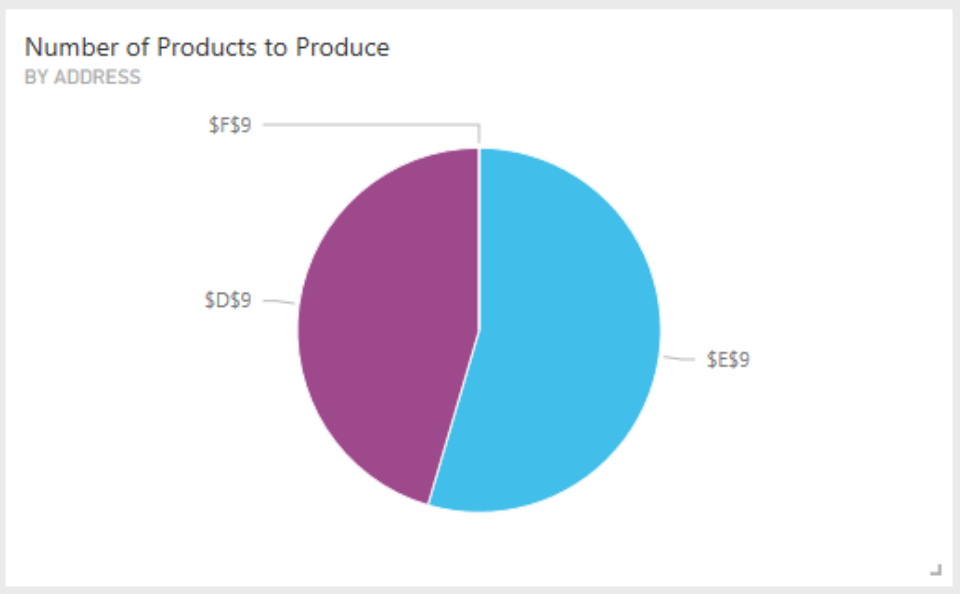
Select ProductMix, then determine the components to be included in the graph. In the screenshot below we have created a pie chart displaying the final variable values by clicking the icon to the right of the graph.



Use the icon to pin this graph to the Dashboard.



Now, each time the model is solved, the results may be uploaded to your Power BI dashboard. Click back to Excel and change the number of Speaker Cones in inventory from 800 to 825, then resolve either by clicking the green arrow on the Model tab in the Solver Task Pane or by clicking the Optimize icon on the Analytic Solver ribbon. Once Solver stops with the final result message, "Solver found a solution. All constraints and optimality conditions are satisfied.", click the icon on the Output tab to upload the most recent results. (Note: We are not asked to log in to the Power BI site a second time since we are using the same instance of Excel.) Click back to Power BI in your browser and refresh, the chart will update automatically with the new final variable values, as shown below.



Exporting Data to Tableau

Tableau is a popular interactive software package that allows you to visually explore and analyze your data. Tableau can import data from a wide range of sources, including Excel workbooks, and it is often used in conjunction with Excel. Because Tableau is designed to import data in table form, it hasn't been easy to import the *results* of an optimization model (such as final values of the decision variables, constraints and objective) into Tableau, unless those model elements occur in table form by themselves in your spreadsheet (which usually isn't the case).

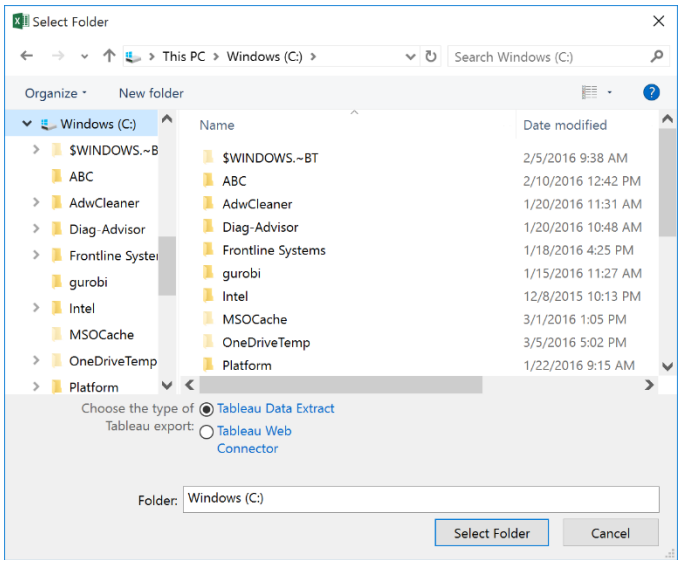
Analytic Solver simplifies this process considerably. With a single click, you can convert the results of your optimization model into a set of Tableau Data Extract (.tde) files or HTML files using the Tableau Web Connector, open them directly in Tableau, and visualize them with a few clicks.

Note: Exporting your model to Tableau via the Output Pane on the Solver Task Pane is not supported in Analytic Solver Cloud or AnalyticSolver.com. However, it is possible to upload your model to Tableau using the Create App menu. See the chapter, Creating Custom Extensions in Tableau, that appears later on in this guide for more information.

Click the green arrow on the Output Tab to solve your optimization model.

Once Solver has stopped with a final result message, click the icon on the Task Pane Output tab to save the values for the objective function, constraints and variables to *.tde files or HTML files. You will be prompted to select a folder where the Tableau files will be saved along with the type of Tableau export desired: Tableau Data Extract or Tableau Web Connector.

Note: If exporting to an existing .tde file, data will be appended rather than overwritten. As a result, when exporting to an existing .tde file, all data must be of the same structure as when the .tde file was first created.



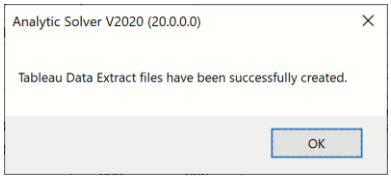
Tablea Data Extract

If Tableau Data Extract is selected, static data is exported to three files: Constraints.tde, Objective.tde and Variables.tde. (Although .tde files are designed to hold multiple tables, currently Tableau's software allows only one table per file.) When you import this data into Tableau, Variables.tde will have one row for each decision variable, Constraints.tde will have one row for each constraint and Objective.tde will have just one row for the objective.

- Each row of Variables.tde will contain the Excel cell address, the values of the variables at the time of extraction, the lower and upper bound of each variable, the optimization index and sensitivity information such as the reduced cost and allowable increase/decrease.
- Each row of Constraints.tde will contain the Excel cell address where the constraint is located, the value of each constraint at time of extraction, the constraint lower and upper bounds, and information that would appear on a sensitivity report such as the shadow price, slack value, a 1 or 0 to indicate if the constraint was binding (1) or not (0), and the allowable increase/decrease.
- Objective.tde will contain the Excel cell address where the objective is located, the value of the objective function at the time of extraction, and the optimization index.

Note: If exporting to an existing .tde file, data will be appended rather than overwritten. As a result, when exporting to an existing .tde file, all data must be of the same structure as when the .tde file was first created.

Once you select a folder, the *.tde files will be created, and the following message will appear.



To open the files in Tableau, either double click each file (if using Desktop Tableau) or click **Other Files** under *Connect* and open the desired file(s).

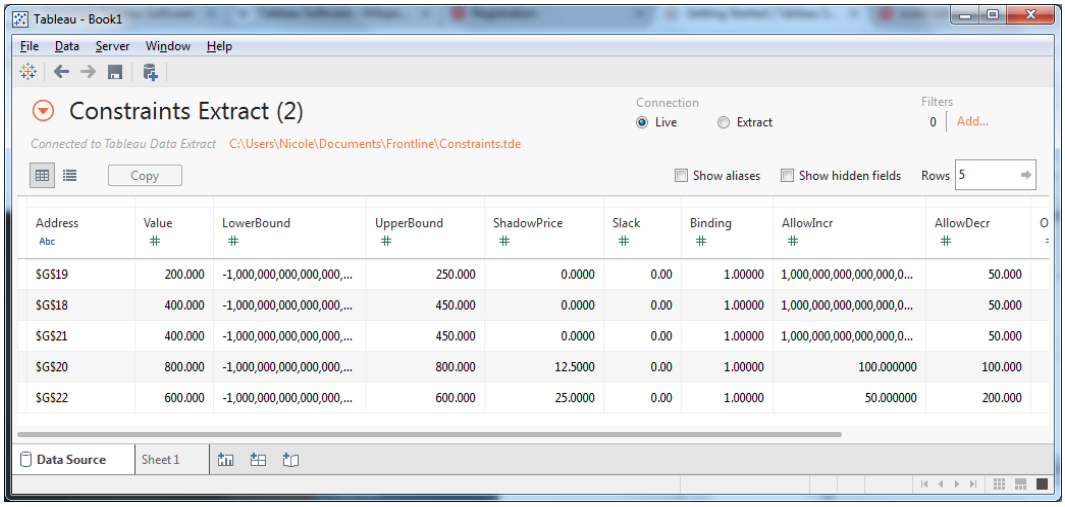
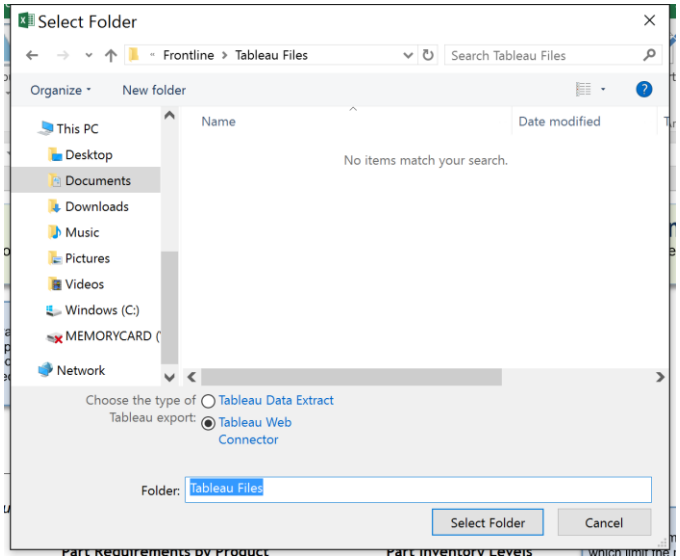


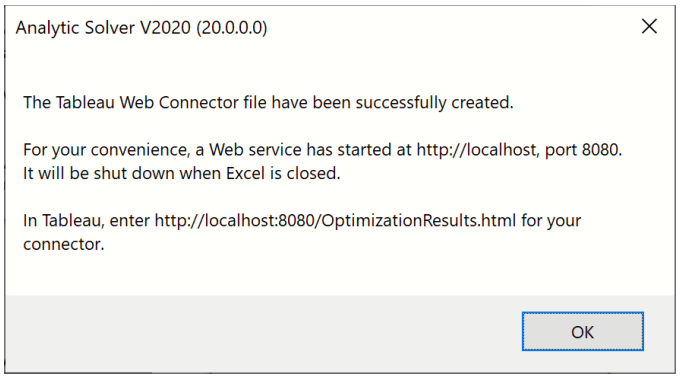
Tableau Web Connector

The Tableau Web Connector offers much more flexibility over Tableau Data Extract by allowing you to refresh your data dynamically inside of Tableau.

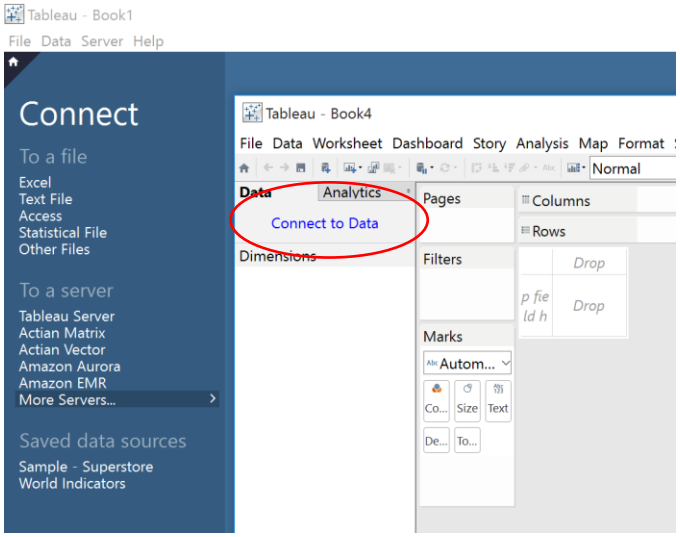


If Tableau Web Connector is selected, you will be prompted to select a folder in which to save OptimizationResults.html. This file will hold all contents described above for Constraints.tde, Objective.tde and Variables.tde. The following message will appear.

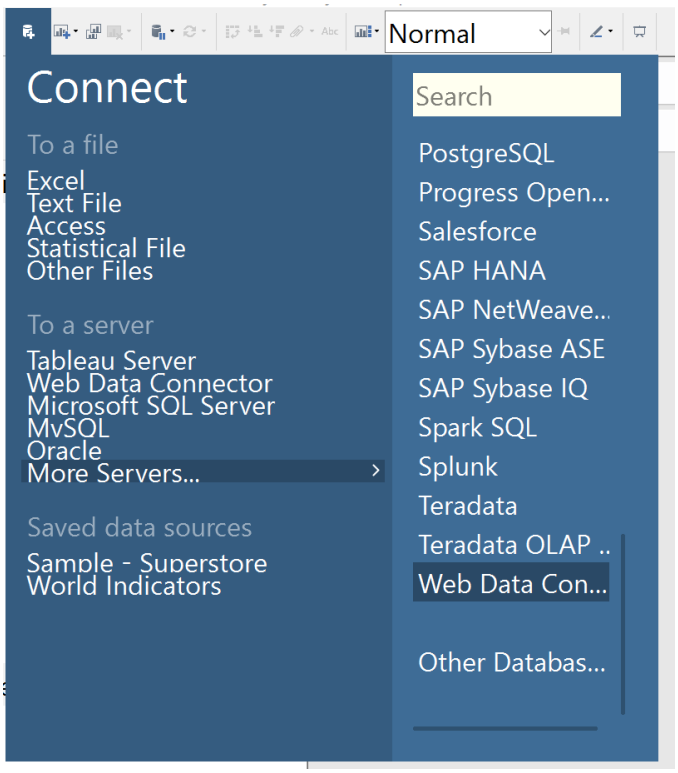
Note: If exporting to an existing .tde file, data will be appended rather than overwritten. As a result, when exporting to an existing .tde file, all data must be of the same structure as when the .tde file was first created.



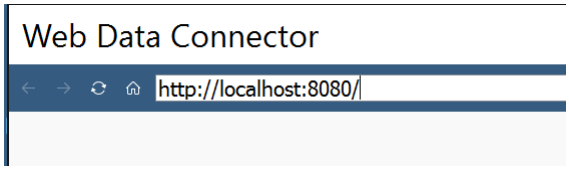
To open the files in Tableau, open a new workbook in Tableau and click **Connect to Data**.



On the connect menu, select **More Servers – Web Data Connector** on the Connect menu.

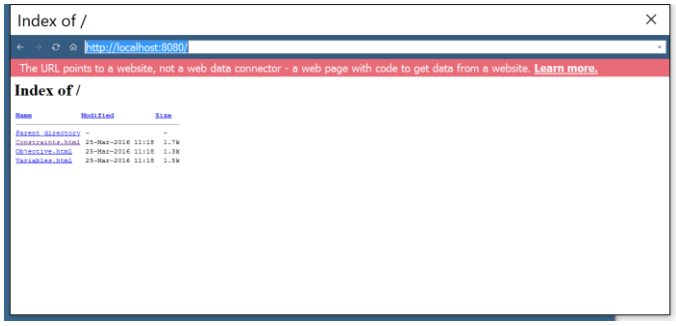


On the Web Data Connector dialog, enter the location displayed on the dialog shown above (i.e., http://localhost:8080/) and press **Enter**.

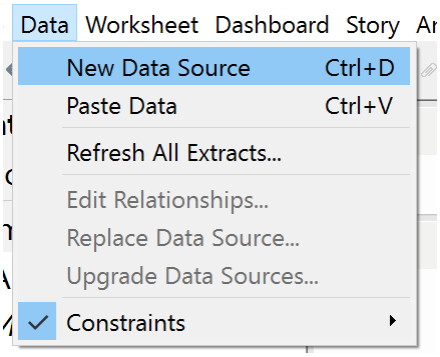


When the following dialog appears, click Constraints.html.

Note: The error highlighted in red is a simple warning that the URL is not pointing to a Tableau Web Data Connector file. If we had entered a file name, such as http://localhost:8080/Constraints.html, the results would have immediately been uploaded to Tableau.



To add more data, click **Data – New Data Source** on the Tableau ribbon, then repeat the actions described above.



If your Solver results have changed, you'll need to refresh the results within the Tableau Web Connector HTML files. To do so:

1. In ASP, re-run your model
2. Click the Tableau icon on the Output tab in the Solver Task Pane.
3. Select **Tableau Web Connector** and the folder where the files should be saved.
4. Click **OK**.
5. In Tableau, click **Data – Refresh All Extracts** to update your data.

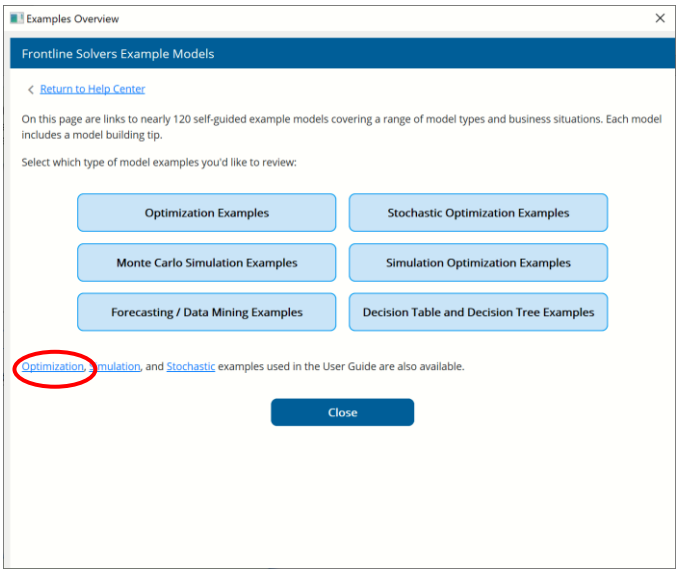
For more information on using Tableau, please refer to the Tableau documentation found at http://www.tableau.com/.

Introducing the Standard Example Models

The approach outlined above in "From Algebra to Spreadsheets" is a 'quick and dirty' way to translate from a model in algebraic form to an equivalent spreadsheet model, ready for optimization. However, that approach will soon prove to be short-sighted when you wish to change the data (for example unit profits or parts on hand), expand the model to include more products or parts, or show the model to someone unfamiliar with the problem or uncomfortable with algebraic notation.

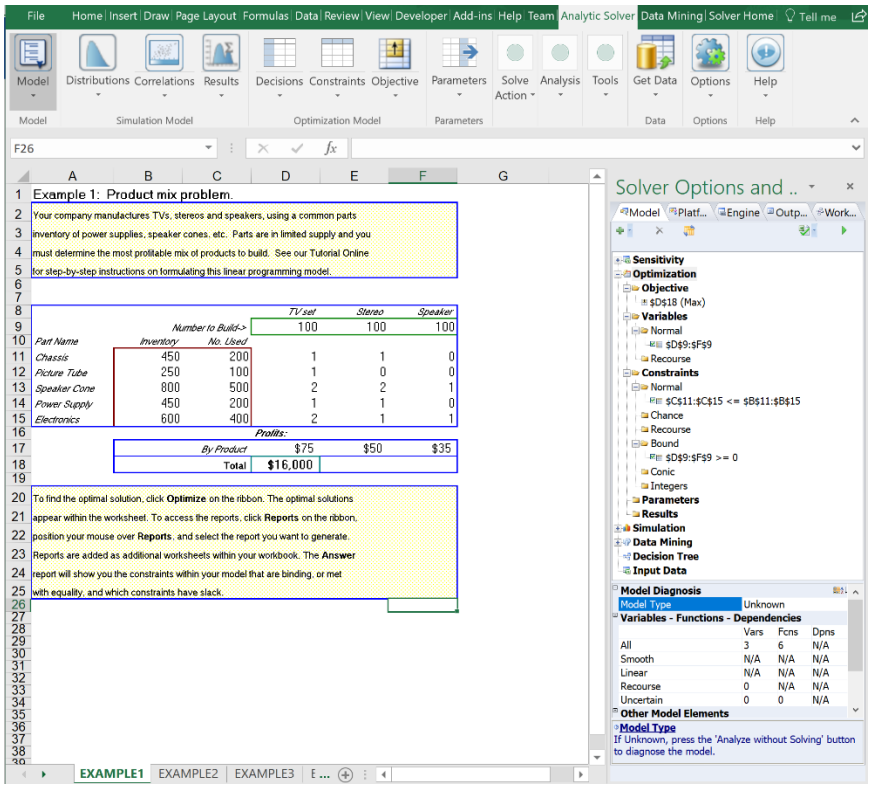
Opening the Examples

To see a better approach to defining this model, click **Help – Examples** on the Ribbon, which opens the workbook, Frontline Example Models Overview.xls. Click Optimization on the Overview tab.



Then click the link **StandardExamples.xls** to open the workbook, showing the first worksheet EXAMPLE1. In AnalyticSolver.com click *Help – Examples – Optimization Examples* and scroll down to *StandardExamples.xlsx*.

An optimization model – like the one we created 'from scratch' in the previous section – is already defined on this worksheet, and appears in the Task Pane Model tab, as shown below. We could *immediately* solve this model by clicking the green arrow on the Model tab of the Solver Task pane.



How did this optimization model appear pre-defined in the workbook, you ask? We simply used the Ribbon (or the Solver Parameters dialog) to select the

decision variables, objective and constraints, and the Solver engine (and any options or settings it requires). Then we saved the workbook, in the usual way, with Excel's Save command. Models created in the standard Excel Solver, or an earlier version of Analytic Solver, Premium Solver, or Risk Solver can also be saved this way, and opened and immediately solved in Analytic Solver.

More Readable and Expandable Models

Worksheet EXAMPLE1 models the same problem we described in the previous section "From Algebra to Spreadsheets," but the model is organized and laid out for easier readability and expandability.

The decision variables (A1:A3 in the previous section) are in cells D9:F9, and nearby labels show their meaning. The left hand sides of the constraints (B1:B5 in the previous section) are in cells C11:C15, and the right hand sides are in cells B11:B15 – since these constant values can be in any position on the worksheet.

Instead of using constants such as 75, 50 and 35 directly in the formula for the objective – as we did in the previous section – we've put these numbers in cells D17:F17. The formula for the objective is =SUMPRODUCT(D17:F17,D9:F9) in cell D18. This makes it easier to change product selling prices, or to obtain this data from an external data source, such as a database or accounting data file.

Similarly, we've placed the *coefficients* of the constraints in cells D11:F15. These are exactly the constant values we saw in the algebraic statement of the problem in the previous section:

Subject to $1\ x_1 + 1\ x_2 + 0\ x_3 <= 450$ (Chassis)
$1\ x_1 + 0\ x_2 + 0\ x_3 <= 250$ (Picture tubes)
$2\ x_1 + 2\ x_2 + 1\ x_3 <= 800$ (Speaker cones)
$1\ x_1 + 1\ x_2 + 0\ x_3 <= 450$ (Power supplies)
$2\ x_1 + 1\ x_2 + 1\ x_3 <= 600$ (Electronics)

In EXAMPLE1, the formula at cell C11 – the left hand side of the first constraint – is =SUMPRODUCT(D11:F11,$D$9:$F$9). The formulas at C12:C15 were created by copying C11 downward.

To enhance readability, borders and labels have been used to draw attention to the decision variables, the constraints, and the objective function. If you haven't used these Excel features before, select one or more cells, then choose the Home tab in Excel to see how to do this.

EXAMPLE1 is also much easier to maintain and expand than a model constructed with 'hardwired' formulas, as in the previous section. You can add products by inserting new columns, and add more parts by inserting rows, and copying any one of the existing left hand side formulas to the new rows; Excel will automatically adjust the formula cell references.

In the next section, we'll solve EXAMPLE1, and create and examine the Answer Report and Sensitivity Report for this model.

Models, Worksheets and Workbooks

There are several worksheets (EXAMPLE1, EXAMPLE2, etc.) in the StandardExamples.xls workbook. As we proceed through this chapter, you'll see that we can simply click a worksheet tab to display a new and different model in the Task Pane on that worksheet. Each of these models was created in the same way, and all of them are saved when you save the Excel workbook.

In StandardExamples.xls, each model is entirely contained on one worksheet. But this is not required – one model can include cells from *many* different worksheets in the same workbook, and it can refer to constant information in other workbooks. By default, models have the same names as the worksheets on which they are created, but you can give *your own names* to models, and create as many of them as you like. This is described in the Frontline Solvers Reference Guide.

Linear Programming Examples

This section takes you on a quick tour of Analytic Solver features for linear programming (LP) problems. We highly recommend that you 'follow along' by opening and actually solving the examples in this section.

The first three examples are variants of the Product Mix model introduced earlier in this chapter. Our factory is building three products: TV sets, stereos and speakers. Each product is assembled from parts in inventory, and there are five types of parts: chassis, picture tubes, speaker cones, power supplies and electronics units. Our goal is to produce the mix of products that will maximize profits, given the inventory of parts on hand. Be sure to read "Introducing the Standard Example Models" above.

Using the Output Tab and Creating Reports

Click the tab to display the EXAMPLE1 worksheet. To solve this linear programming problem;

- In Analytic Solver Desktop, click the **Optimize** button on the Ribbon or click the **green arrow** at the top right of the Task Pane.
- In Analytic Solver Cloud, click the **Model** button to open the task pane, then click the **green arrow** at the top right of the Task Pane or click the **down arrow** beneath Optimize on the Ribbon and select **Solve Complete Problem**.
- In AnalyticSolver.com, click the **Optimize** button on the Ribbon or click the **green arrow** at the top right of the Task Pane.

Almost immediately, the solution values appear in the decision variable cells:

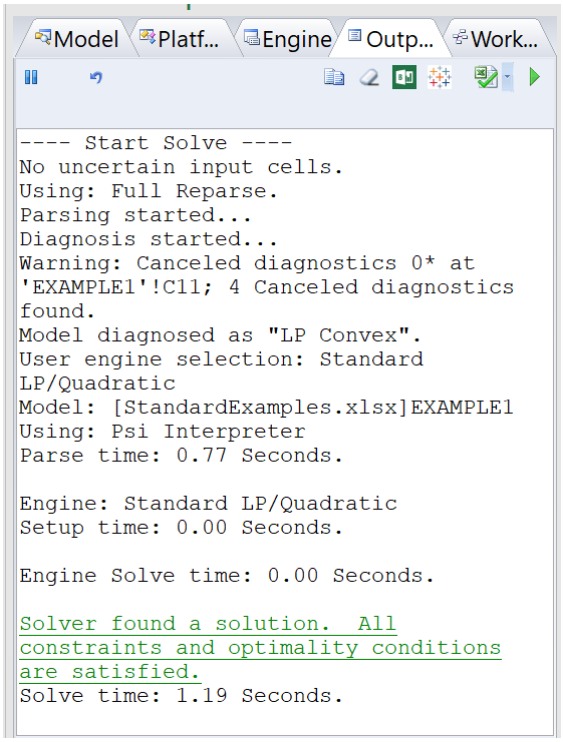
			TV set	Stereo	Speaker
		Number to Build->	200	200	0
Part Name	Inventory	No. Used			
Chassis	450	400	1	1	0
Picture Tube	250	200	1	0	0
Speaker Cone	800	800	2	2	1
Power Supply	450	400	1	1	0
Electronics	600	600	2	1	1
		Profits:			
		By Product	$75	$50	$35
		Total	$25,000		

To maximize profit, we should make 200 TV sets, 200 stereos, and 0 speakers.

The Solver Results message "Solver found a solution. All constraints and optimality conditions are satisfied" appears in green at the bottom of the Task Pane. **Don't ignore this message**, because it provides critical information about

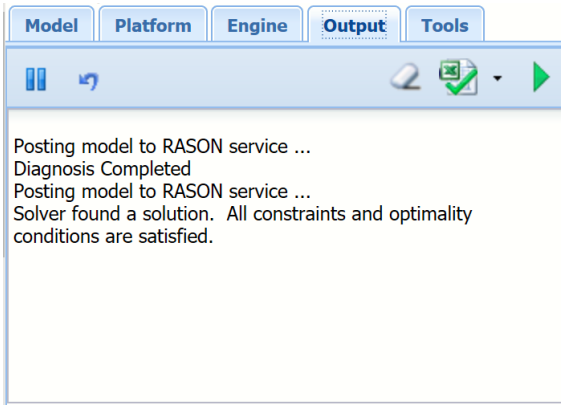
what happened during the solution process, and what you *can* and *cannot* assume about the solution on the worksheet!

If using Analytic Solver Desktop, click the **Output** tab at the top of the Task Pane to learn more about the solution process. The solution log in the upper part of this pane reports what happened during the solution process. If you are puzzled by the Solver Result message, simply **click the underlined message** in the log to open online Help to a full explanation of that message.



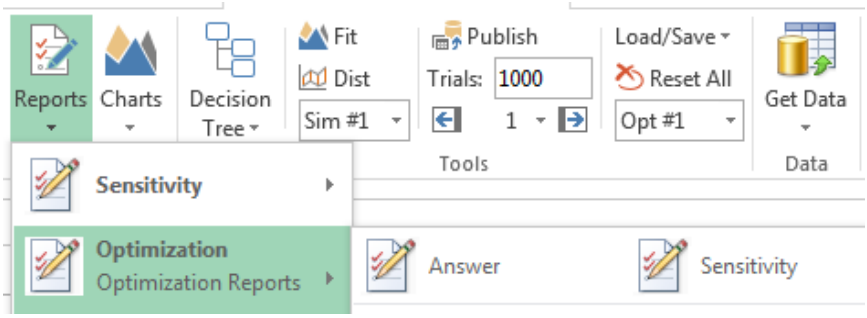
If solving takes more than a few seconds, the Output tab automatically appears, and current **best objective** and other information, plus a **running chart** of the objective value, appears in the bottom part of the Task Pane.

If using Analytic Solver Cloud or AnalyticSolver.com, the output pane will display the status of the model on the Solver Server as shown below.



After solving, you can produce reports (such as the Answer Report and Sensitivity Report) by selecting **Reports – Optimization** from the Ribbon.

Unlike the standard Solver, you don't have to choose reports *immediately* in the Solver Results dialog – you can select them later (until you perform another operation that creates new reports).



The Answer and Sensitivity Reports appear as new worksheets, inserted into the workbook just to the left of the EXAMPLE worksheet, as shown on the next page. The Sensitivity Report, which provides *dual values* (shadow prices and reduced costs) and associated *ranges*, is described in the Frontline Solvers Reference Guide.

The Answer Report shows the message from the Task Pane Output tab, the Solver engine used, and statistics about the solution process. It shows the beginning and ending values of the objective function and the decision variables. For the constraints, it shows the final cell value and formula, a status (whether the constraint was "binding" – satisfied with equality – at the solution, and a "slack value" for non-binding constraints.

If using Analytic Solver Desktop, you can ask for **outlined** reports by clicking the "Reports are not outlined" choice on the Ribbon to change it to "Reports are outlined," as shown above. In this case, each block of decision variables and constraints appears in its own outline group. Click the + symbol at the left edge of the report worksheet to show or hide each group in the outline. Any comments that you enter when defining decision variables or constraints appear for each group in the report. These features help you quickly find the information you want in a report created for a large model.

Analytic Solver Desktop

Microsoft Excel 14.0 Answer Report
Worksheet: [StandardExamples.xls]EXAMPLE1
Report Created: 4/29/2014 12:58:45 PM
Result: Solver found a solution. All constraints and optimality conditions are satisfied.
Engine: Standard LP/Quadratic
Solution Time: 00 Seconds
Iterations: 0
Subproblems: 0
Incumbent Solutions: 0

Objective Cell (Max)

Cell	Name	Original Value	Final Value
$D$18	Total Profits:	16000	25000

Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
$D$9	Number to Build-> TV set	100	200	Normal
$E$9	Number to Build-> Stereo	100	200	Normal
$F$9	Number to Build-> Speaker	100	0	Normal

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$C$11	Chassis No. Used	400	$C$11<=$B$11	Not Binding	50
$C$12	Picture Tube No. Used	200	$C$12<=$B$12	Not Binding	50
$C$13	Speaker Cone No. Used	800	$C$13<=$B$13	Binding	0
$C$14	Power Supply No. Used	400	$C$14<=$B$14	Not Binding	50
$C$15	Electronics No. Used	600	$C$15<=$B$15	Binding	0
$D$9	Number to Build-> TV set	200	$D$9>=0	Not Binding	200
$E$9	Number to Build-> Stereo	200	$E$9>=0	Not Binding	200
$F$9	Number to Build-> Speaker	0	$F$9>=0	Binding	0

Analytic Solver Cloud

Answer Report

Info	
Worksheet	EXAMPLE1
Report Created	Wed Mar 27 2019 17:56:46 GMT-0700 (Pacific Daylight Time)
Result	Solver found a solution. All constraints and optimality conditions are satisfied.
Engine	Standard LP/Quadratic
Solution Time	249 milliseconds
Iterations	3
Subproblems	0
Incumbent Solutions	0

Objective

Cell	Original Value	Final Value
$D$18	25000	25000

Decision Variable Cells

Cell	Original Value	Final Value
$D$9	200	200
$E$9	200	200
$F$9	0	0

Constraints

Cell	Original Value	Final Value	Lower Bound	Upper Bound	Slack
$C$11	400	400	-1E+30	450	50
$C$12	200	200	-1E+30	250	50
$C$13	800	800	-1E+30	800	0
$C$14	400	400	-1E+30	450	50
$C$15	600	600	-1E+30	600	0

A Model with No Feasible Solution

What does it mean when the Solver can find no feasible solution – no combination of values for the decision variables that satisfies all the constraints? It may be that the underlying business problem has no feasible solution – if so,

you'd like to focus on the 'hardest-to-satisfy' constraints, to see if you can do anything about them. Or you might have just made a mistake setting up the model – for example choosing <= when you meant to choose >=.

But in a large model, with thousands of constraints, how do you find your mistake, or focus on the 'hardest-to-satisfy' constraints? Analytic Solver can help, by producing a Feasibility Report.

Click the tab to display the EXAMPLE2 worksheet. This is the same Product Mix model as in EXAMPLE1, but the supply of Chassis parts at B11 has been changed from 450 to -1. Click the **Optimize** button in Analytic Solver Desktop or AnalyticSolver.com or **Optimize** then **Solve Complete Problem** in Analytic Solver Cloud. The message "Solver could not find a feasible solution" appears in red at the bottom of the Task Pane.

Still TBD Click **Reports – Optimization – Feasibility** on the Ribbon. A Feasibility Report worksheet is inserted into the workbook, immediately to the left of EXAMPLE2 – with the contents shown on the next page.

	A	B	C	D	E	F	G
1	**Microsoft Excel 14.0 Feasibility Report**						
2	**Worksheet: [StandardExamples.xls]EXAMPLE2**						
3	**Report Created: 4/29/2014 1:02:06 PM**						
4	**Engine: Standard LP/Quadratic**						
5							
6	Constraints that Make the Problem Infeasible						
7		**Cell**	**Name**	**Cell Value**	**Formula**	**Status**	**Slack**
8		$C$11	Chassis No. Used	-1	$C$11<=$B$11	Binding	0
9		$D$9	Number to Build-> TV set	0	$D$9>=0	Binding	0
10		$E$9	Number to Build-> Stereo	-1	$E$9>=0	Violated	-1

Notice that the report highlights the constraint on Chassis parts used, and the non-negativity constraints on products that are built from Chassis parts. To satisfy the constraint C11 <= B11 where B11 is -1, we'd have to build a negative number of stereos (or TV sets). In a large model with thousands of constraints with no feasible solution, this report can focus your attention on the "trouble spots" – the constraints that make the problem infeasible. The set of constraints shown is called an IIS or *Irreducibly Infeasible Subset* of all the constraints. For more information, please see the Frontline Solvers Reference Guide.

An 'Accidentally' Nonlinear Model

What if you intended to build a linear programming model, but you made a mistake and introduced a nonlinear function into the model? Even if you understand the requirements of linear functions (explained in the chapter "Mastering Conventional Optimization Concepts"), in a large model with thousands of variables and constraints, where each constraint is computed by a chain of formulas, an accidentally introduced nonlinearity may be difficult to find. Sometimes, a first-generation LP model is modified to make a previously fixed parameter into a decision variable – and this leads to an accidental multiplication of two variables.

Click the tab to display the EXAMPLE3 worksheet. This is the same Product Mix model as in EXAMPLE1, but the constraint left hand side formula for Chassis parts at C11 has been changed to read =SUMPRODUCT(D11:F11,D9:F9)^0.9. (The power function clearly makes the constraint nonlinear.) Click the **Optimize** button, or the down arrow beneath **Optimize** then **Solve Complete Problem**. The message "The linearity conditions required by this Solver Engine are not satisfied" appears in red at the

bottom of the Task Pane. (Note that we're solving this model with the LP/Quadratic Solver.)

If you are using Analytic Solver Desktop, click **Reports – Optimization – Linearity** on the Ribbon. A Linearity Report worksheet is inserted into the workbook, immediately to the left of EXAMPLE3 – with the contents shown on the next page. Note: The Linearity Report is not supported in Analytic Solver Cloud or AnalyticSolver.com.

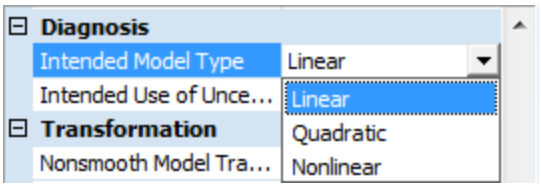
The report highlights the constraint at C11 as a nonlinear function, and variables D9 and E9 that participate in calculation of this function. (F9 does not appear, because its coefficient at F11 is zero.) In a large model, this report can help you quickly find the source of an unintended nonlinearity.

	A	B	C	D	E	F
1	**Microsoft Excel 14.0 Linearity Report**					
2	**Worksheet: [StandardExamples.xls]EXAMPLE3**					
3	**Report Created: 4/29/2014 1:05:41 PM**					
4	**Engine: Standard LP/Quadratic**					
5						
6	Objective Cell (Max)					
7		**Cell**	**Name**	**Original Value**	**Final Value**	**Linear Function**
8		$D$18	Total Profits:	$16,000	$16,000	Yes
9						
10						
11	Decision Variable Cells					
12		**Cell**	**Name**	**Original Value**	**Final Value**	**Occurs Linearly**
13		$D$9	Number to Build-> TV set	100	100	**No**
14		$E$9	Number to Build-> Stereo	100	100	**No**
15		$F$9	Number to Build-> Speaker	100	100	Yes
16						
17	Constraints					
18		**Cell**	**Name**	**Cell Value**	**Formula**	**Linear Function**
19		$C$11	Chassis No. Used	118	$C$11<=$B$11	**No**
20		$C$12	Picture Tube No. Used	100	$C$12<=$B$12	Yes
21		$C$13	Speaker Cone No. Used	500	$C$13<=$B$13	Yes
22		$C$14	Power Supply No. Used	200	$C$14<=$B$14	Yes
23		$C$15	Electronics No. Used	400	$C$15<=$B$15	Yes

The Linearity Report, which is available in all of the Analytic Solver Desktop subsets that perform optimization, is very useful, but it does have two drawbacks: (i) It highlights only a *constraint* that behaves nonlinearly – but if this constraint is calculated through a chain of formulas, it may not highlight the exact *cell formula* where the nonlinearity first occurs. (ii) It is based on a *numerical* test for linear or nonlinear behavior – a test that can be 'fooled' by a poorly scaled model. (A 'poorly scaled model' is one that computes values of the objective, constraints, or intermediate results that differ by many orders of magnitude, which can lead to inaccuracy in computer arithmetic.)

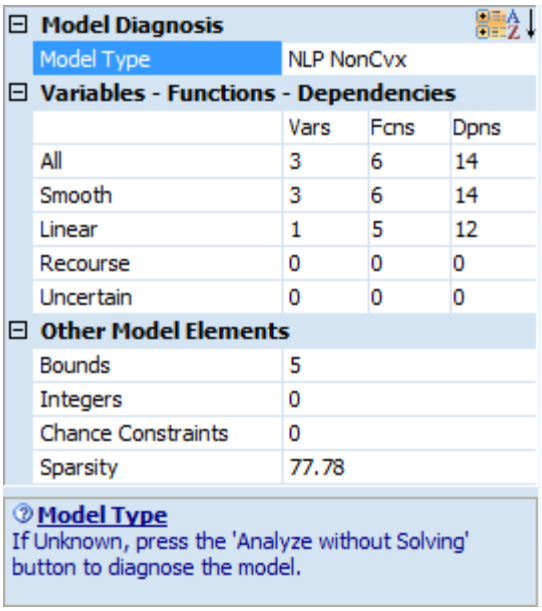
Using the PSI Interpreter to Check for Linearity

If you have Analytic Solver Comprehensive, Analytic Solver Optimization, Analytic Solver Upgrade or Analytic Solver Basic in Analytic Solver Desktop or Cloud, you can use the Polymorphic Spreadsheet Interpreter to perform a *symbolic* test for linearity that cannot be 'fooled' by scaling problems. (This functionality is not supported in AnalyticSolver.com.) Click the tab to display the EXAMPLE3 worksheet. On the Task Pane Platform tab, in the Diagnosis group of options, and ensure that the **Intended Model Type** is set to **Linear**:

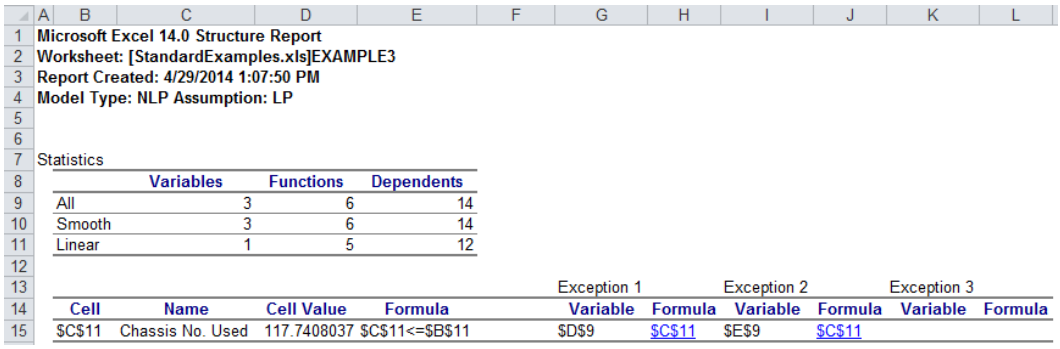


Now click the **Analyze** button in the Task Pane, or select the dropdown choice **Analyze Original Problem** below the **Optimize** button on the Ribbon. The Model Diagnosis portion of the Task Pane will pop up, showing the Model Type and related statistics, as shown on the next page.

Notice that the Model Type is "NLP NonCvx". If you're not sure about the meaning of any of the elements shown here, and you are using Analytic Solver Desktop, **click the underlined link** at the bottom of the Task Pane to display Help on that model element.



Now click **Reports – Optimization – Structure** on the Ribbon. A Structure Report is inserted into the workbook, just to the left of EXAMPLE3. This report highlights the formula cells in your worksheet that violate the requirements of your **Intended Model Type** (in this case Linear). In other words, this report shows the formulas that make your model nonlinear.



Microsoft Excel 14.0 Structure Report
Worksheet: [StandardExamples.xls]EXAMPLE3
Report Created: 4/29/2014 1:07:50 PM
Model Type: NLP Assumption: LP

Statistics

	Variables	Functions	Dependents
All	3	6	14
Smooth	3	6	14
Linear	1	5	12

				Exception 1		Exception 2		Exception 3	
Cell	Name	Cell Value	Formula	Variable	Formula	Variable	Formula	Variable	Formula
$C$11	Chassis No. Used	117.7408037	$C$11<=$B$11	$D$9	$C$11	$E$9	$C$11		

For EXAMPLE3, this report again highlights the constraint at C11 and the two variables D9 and E9 (E9 in columns I and J, not shown to save space). But

when a constraint or objective is calculated through a chain of formulas, this report normally finds the formula cell that first introduces a nonlinear relationship (such as a power operator, a function such as LOG, or multiplication of two cells that both depend on decision variables). EXAMPLE3!$C$11 in this report can be clicked to jump directly to that cell, so you can quickly inspect its formula.

Note: The Structure Report in Analytic Solver does not include the Name or Cell Value columns.

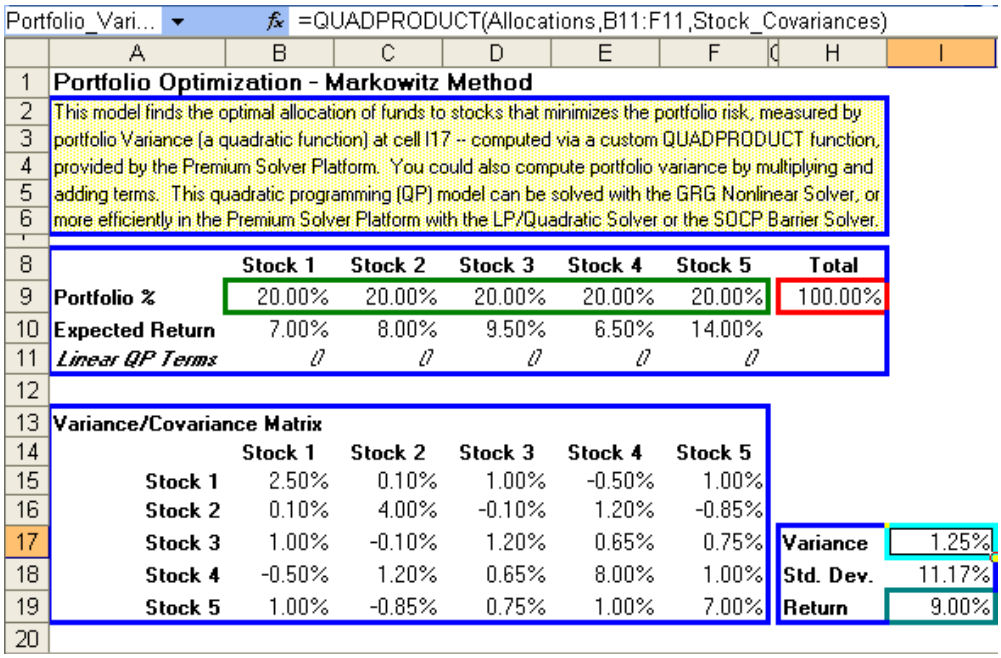
Nonlinear Optimization Examples

This section takes you on a quick tour of Analytic Solver features for nonlinear programming (NLP) and non-smooth optimization (NSP) problems, using the SOCP Barrier Solver, GRG Nonlinear Solver, and Evolutionary Solver. We highly recommend that you 'follow along' by opening and actually solving the examples in this section.

Portfolio Optimization: Quadratic Programming

The simplest kind of nonlinear optimization model is a quadratic programming (QP) model, with a quadratic objective and all linear constraints. Such a problem can be solved with a quadratic extension to the linear programming Simplex method – as in the LP/Quadratic Solver in Analytic Solver Comprehensive or Analytic Solver Optimization – or with the GRG Nonlinear Solver included in Analytic Solver Upgrade and Analytic Solver Basic.

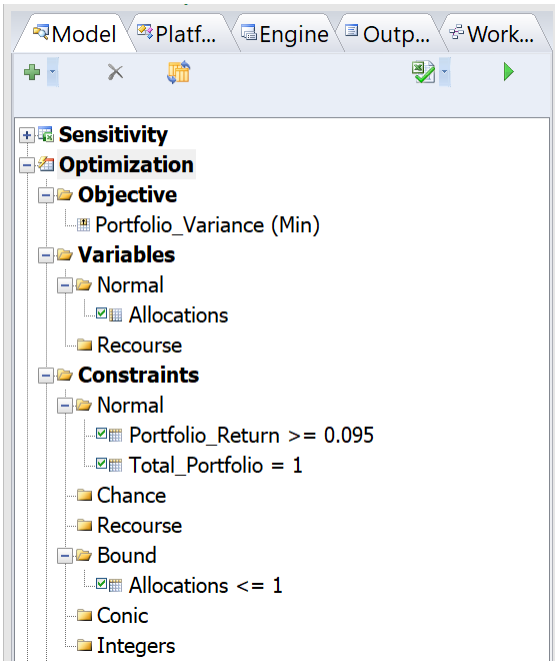
A classic example of this kind of model, shown in EXAMPLE4 in **StandardExamples.xls**, is a Markowitz-style portfolio optimization problem. In this model, we want to choose the mix of stocks to form an 'efficient portfolio' with the lowest possible risk (measured by portfolio variance) for a specified target rate of return. Click the EXAMPLE4 tab to display the model.



Portfolio_Vari... =QUADPRODUCT(Allocations,B11:F11,Stock_Covariances)

	A	B	C	D	E	F	H	I
1	**Portfolio Optimization - Markowitz Method**							
2	This model finds the optimal allocation of funds to stocks that minimizes the portfolio risk, measured by							
3	portfolio Variance (a quadratic function) at cell I17 -- computed via a custom QUADPRODUCT function,							
4	provided by the Premium Solver Platform. You could also compute portfolio variance by multiplying and							
5	adding terms. This quadratic programming (QP) model can be solved with the GRG Nonlinear Solver, or							
6	more efficiently in the Premium Solver Platform with the LP/Quadratic Solver or the SOCP Barrier Solver.							
8		**Stock 1**	**Stock 2**	**Stock 3**	**Stock 4**	**Stock 5**	**Total**	
9	**Portfolio %**	20.00%	20.00%	20.00%	20.00%	20.00%	100.00%	
10	**Expected Return**	7.00%	8.00%	9.50%	6.50%	14.00%		
11	***Linear QP Terms***	*0*	*0*	*0*	*0*	*0*		
12								
13	**Variance/Covariance Matrix**							
14		**Stock 1**	**Stock 2**	**Stock 3**	**Stock 4**	**Stock 5**		
15	**Stock 1**	2.50%	0.10%	1.00%	-0.50%	1.00%		
16	**Stock 2**	0.10%	4.00%	-0.10%	1.20%	-0.85%		
17	**Stock 3**	1.00%	-0.10%	1.20%	0.65%	0.75%	**Variance**	1.25%
18	**Stock 4**	-0.50%	1.20%	0.65%	8.00%	1.00%	**Std. Dev.**	11.17%
19	**Stock 5**	1.00%	-0.85%	0.75%	1.00%	7.00%	**Return**	9.00%
20								

This model uses Excel **defined names** for certain cell ranges: The objective cell I17 has the name Portfolio_Variance, which appears to the left of the formula bar when I17 is selected. Cell I19 has the name Portfolio_Return. The decision variables – the percentage of funds to invest in each of five stocks – are cells B9:F9, and this cell range has the name Allocations. Cell H9 has the name Total_Portfolio. These defined names appear in the Task Pane Model tab, as shown on the next page.



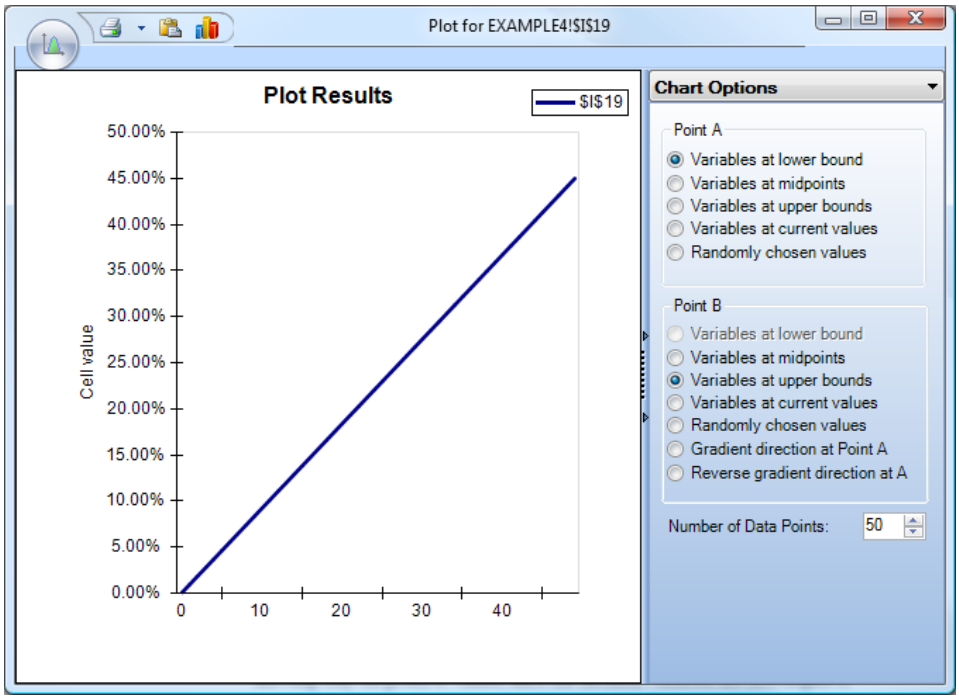
We can see immediately that this model will find values for the stock allocations that minimize portfolio variance, subject to constraints that (i) all funds are used (the sum of the stock allocations is 100% or 1.0) and (ii) the portfolio return is at least 9.5%.

Cell I17 computes the portfolio variance using a special function QUADPRODUCT, which is defined by Analytic Solver. This function can be used to compute any 'quadratic form' such as $x^TQx + cx$. In EXAMPLE4, the elements of the matrix Q are the covariances of returns of pairs of stocks, and the elements of the vector c (at B11:F11) are all zero. You could instead compute portfolio variance using a series of Excel formulas using multiplication and addition, but it's more convenient to use QUADPRODUCT.

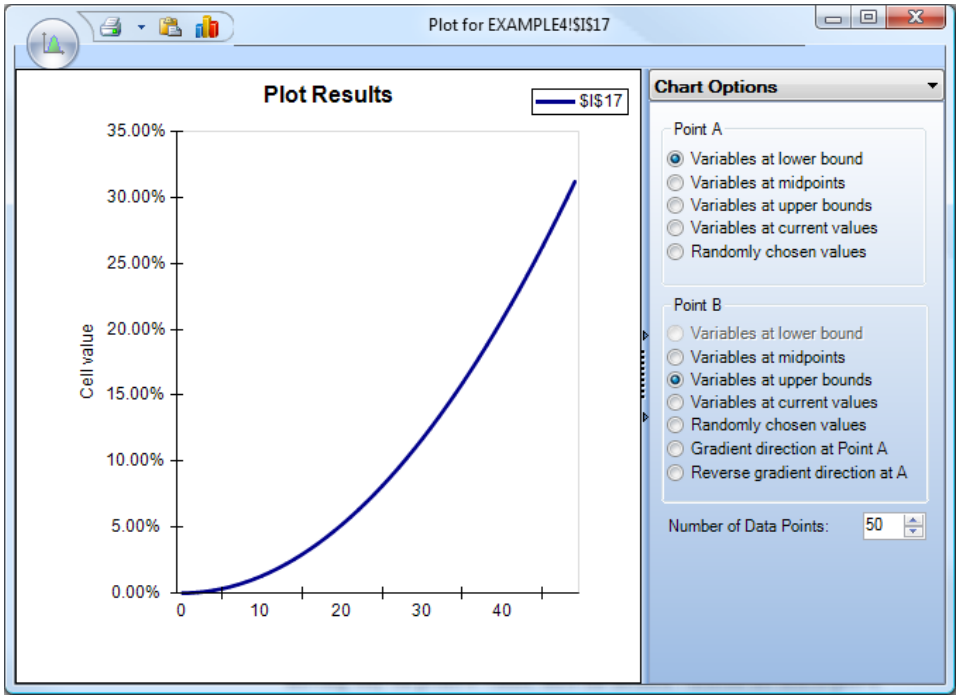
Charts of the Objective and Constraints

Analytic Solver can help you visualize the shape of your problem functions (the objective and constraints). If you haven't been sure of the difference between a linear, quadratic, smooth nonlinear, and non-smooth function, you can use Analytic Solver to plot it.

As an example, select cell I19 (the Portfolio Return) on the worksheet, and choose **Decisions – Plot** from the Ribbon. This will plot I19 (whose formula is =SUMPRODUCT(Allocations,Stock_Returns)) as a function of the decision variables for Stock 1 through Stock 5, as shown on the next page.



The SUMPRODUCT function is a linear function, so unsurprisingly, Portfolio Return plots as a straight. In contrast, select cell I17 (Portfolio Variance, the QUADPRODUCT function), and choose **Decisions – Plot** from the Ribbon. This function plots as a parabola – as expected for a quadratic function – showing only the positive values, since the decision variables are non-negative.



Both of these plots are actually projections of a function in five dimensions (Stock 1 through Stock 5) onto two dimensions, along a vector from Point A to Point B, shown in the side panel. You have many choices for Points A and B.

To find an optimal allocation of funds to stocks, just click the **Optimize** button. In an instant, the message "Solver found a solution. All constraints and optimality conditions are satisfied" appears in green at the bottom of the Task Pane, the Portfolio Variance is 0.85% and the Portfolio return is 9.5%, and the decision variables contain:

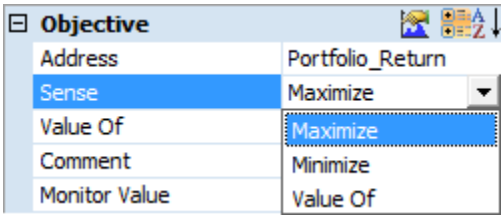
	Stock 1	Stock 2	Stock 3	Stock 4	Stock 5
Portfolio %	1.41%	24.01%	65.80%	0.00%	8.79%
Expected Return	7.00%	8.00%	9.50%	6.50%	14.00%

Solving with the GRG Nonlinear Solver yields the same values (to two decimal places) for the decision variables. If you have Analytic Solver Comprehensive, Analytic Solver Optimization, Analytic Solver Upgrade or Analytic Solver Basic, you can also use the Standard SOCP Barrier Solver – just select it from the dropdown list at the top of the Task Pane Engine tab and click the **Optimize** button again. This yields nearly the same values for the decision variables, Portfolio Return at I19, and Portfolio Variance at I17.

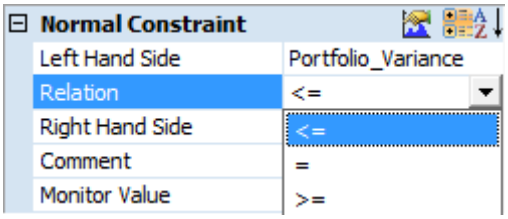
	Stock 1	Stock 2	Stock 3	Stock 4	Stock 5
Portfolio %	1.39%	23.98%	65.77%	0.06%	8.81%
Expected Return	7.00%	8.00%	9.50%	6.50%	14.00%

We can also "turn this problem around" and seek to maximize Portfolio Return, subject to a constraint that Portfolio Variance is (say) no more than 1%. To do this in Analytic Solver Desktop, we can edit the optimization model directly in the Task Pane:

1. Select "Portfolio_Variance (Min)" under Objective in the outline.
2. In the Objective Properties area below the outline, click the **Address** property and type or select cell I19 (or type "Portfolio_Return"). Change the **Sense** dropdown choice from Minimize to Maximize.

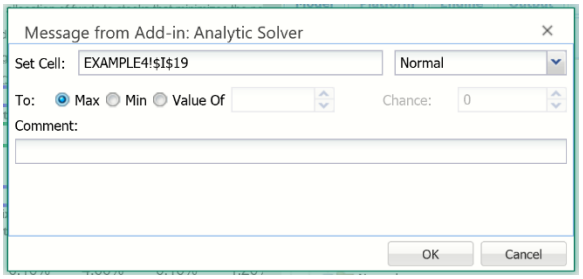


3. Select "Portfolio_Return >= 0.095" under Constraints in the outline.
4. In the Normal Constraint Properties area below the outline, click the **Address** property and type or select cell I17 (or type "Portfolio_Variance"), change the Relation dropdown choice to <=, and type 0.01 as the Right Hand Side) value.

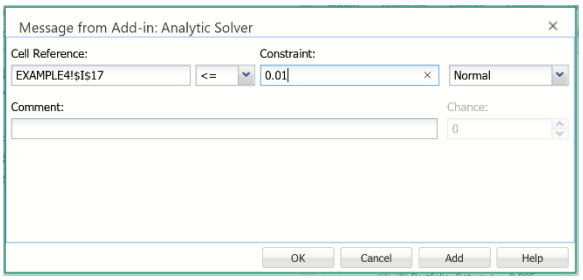


Since the Task Pane is not editable in neither Analytic Solver Cloud nor AnalyticSolver.com, we must perform a few different steps to edit the model when using either of these products.

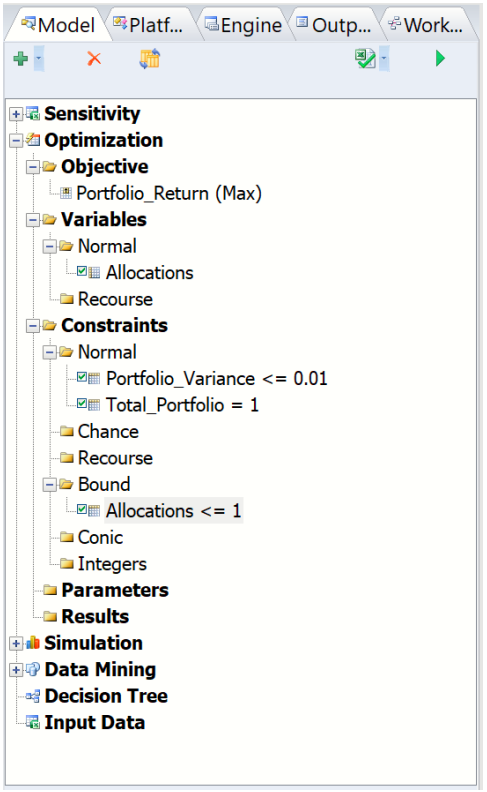
1. Double click Portfolio_Variance (Min) under Objective, change Set Cell to I19 and set the "sense" of the objective to Max, then click OK.



2. Double click Portfolio_Return >= 0.095 under Constraints, change Cell Reference to I17, change the constraint sense to <= and type 0.01 as the Right Hand Side Constraint value. Then click OK.



The Task Pane Model tab should now appear similar to the one shown below.



This problem now has a *linear* objective and a *quadratic* constraint; it is called a *quadratically constrained* or QCP problem. It can no longer be solved by the methods used in the LP/Quadratic Solver (a quadratic extension of the Simplex method), but it can be solved by the GRG Nonlinear Solver, or (more efficiently) by the SOCP Barrier Solver.

Solving with the SOCP Barrier Solver yields a Portfolio Return of 10.2%, a Portfolio Variance of 1% as expected, and the following values for the decision variables:

	Stock 1	Stock 2	Stock 3	Stock 4	Stock 5
Portfolio %	0.00%	19.33%	58.67%	0.00%	22.00%
Expected Return	7.00%	8.00%	9.50%	6.50%	14.00%

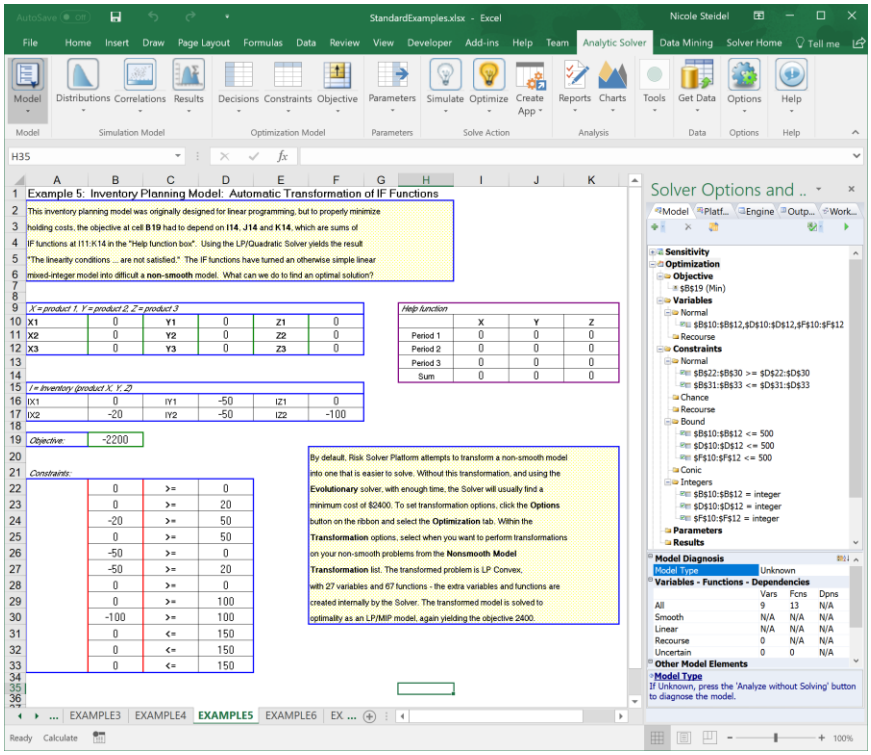
In "Multiple Parameterized Optimizations" in the chapter "Getting Results: Optimization," we return to EXAMPLE4 and show how to automatically vary the Portfolio Return threshold, solve multiple instances of this portfolio optimization model, and create a chart of the efficient frontier.

The original EXAMPLE4 QP model can be 'scaled up' to portfolios of many thousands of stocks, and solved quickly to optimality by the Large-Scale LP/QP Solver, the XPRESS Solver and the MOSEK Solver. The modified QCP model can also be scaled up to portfolios of thousands of stocks, and solved quickly to optimality by the MOSEK Solver.

A Model with IF Functions

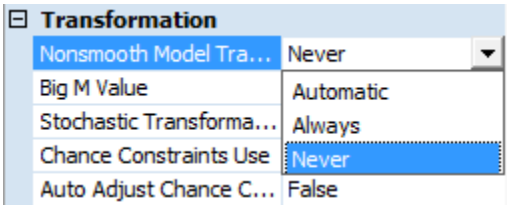
EXAMPLE5 in the **StandardExamples.xls** workbook was adapted from an actual user model, and illustrates a common situation seen by Frontline Systems in technical support. This model was *meant* to be a linear mixed-integer (LP/MIP) model, but the user calculated the objective function based on several IF functions. IF functions are certainly not linear functions – in fact they aren't even smooth nonlinear functions!

One of the remarkable things about Analytic Solver is that, in Automatic mode, it will transform this model to a linear mixed-integer model, and solve it to optimality in seconds, without any user intervention. But in this Guide, we'll first see how Analytic Solver behaves *without* Automatic mode. Click the EXAMPLE5 tab to display the model.



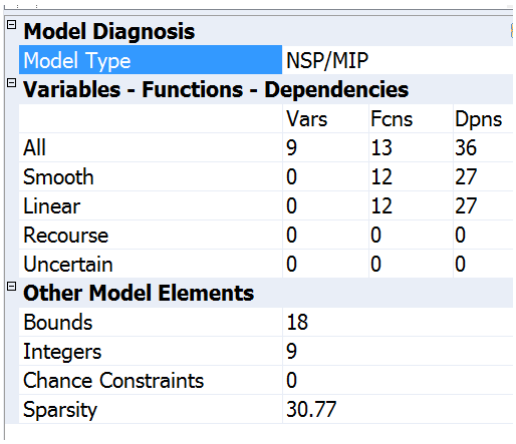
The model has 9 decision variables, all constrained to be integer. The general constraints are linear functions of the decision variables. But the objective depends on I14, J14 and K14, each of which is a sum of three IF functions.

To turn off Automatic mode, in the Task Pane Platform tab **Transformation** group of options, set the **Nonsmooth Model Transformation** option to **Never**.



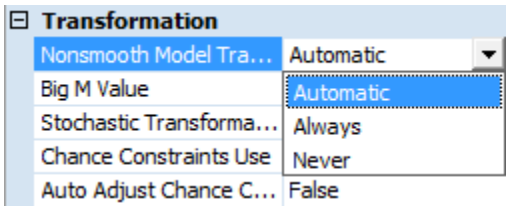
If we now click the **Optimize** button with the LP/Quadratic Solver selected, the message "The linearity conditions required by this Solver engine are not satisfied" appears in red at the bottom of the Task Pane.

If we click the **Analyze** button in the Task Pane, or select the dropdown choice **Analyze Original Problem** below the **Optimize** button on the Ribbon, Analytic Solver reports that the model is nonsmooth with integers (NSP/MIP), as shown on the next page.

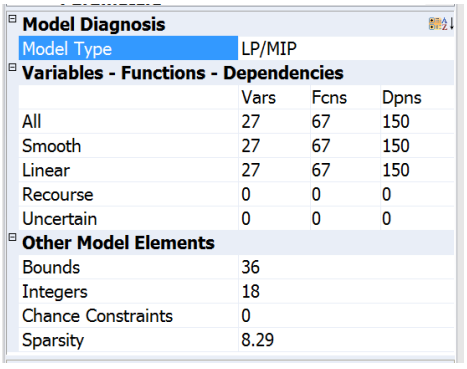


Model Diagnosis			
Model Type	NSP/MIP		
Variables - Functions - Dependencies			
	Vars	Fcns	Dpns
All	9	13	36
Smooth	0	12	27
Linear	0	12	27
Recourse	0	0	0
Uncertain	0	0	0
Other Model Elements			
Bounds	18		
Integers	9		
Chance Constraints	0		
Sparsity	30.77		

This type of model commonly arises, but is difficult to solve with the standard Excel Solver, or with Analytic Solver Upgrade. But Analytic Solver Comprehensive, Analytic Solver Optimization, Analytic Solver Upgrade and Analytic Solver Basic in Analytic Solver Desktop or Cloud can *transform* the model to *eliminate* the IF functions, replacing them with additional binary and continuous variables and linear constraints that have the *same effect* on the model as the IF functions. The additional variables and constraints don't appear on the worksheet, but they are handled internally by the PSI Interpreter and the selected Solver engine. To do this, we simply set the **Nonsmooth Model Transformation** option to Automatic:



If we again analyze the model by clicking the **Analyze** button in the Task Pane, or by selecting the dropdown choice **Analyze Transformed Problem** below the **Optimize** button on the Ribbon, Analytic Solver reports that the the *transformed* model has 27 variables (18 of them integer) and 67 constraints, as shown on the next page. But it's now a linear programming (LP) model – so it can be solved by the LP/Quadratic Solver. By solving this transformed model, we can find a solution to the original model on the EXAMPLE5 worksheet.



Model Diagnosis			
Model Type	LP/MIP		
Variables - Functions - Dependencies			
	Vars	Fcns	Dpns
All	27	67	150
Smooth	27	67	150
Linear	27	67	150
Recourse	0	0	0
Uncertain	0	0	0
Other Model Elements			
Bounds	36		
Integers	18		
Chance Constraints	0		
Sparsity	8.29		

When we now click the **Optimize** button, the message "Solver found a solution. All constraints and optimality conditions are satisfied" appears in green at the bottom of the Task Pane, and the objective function value at cell B19 is 2400.

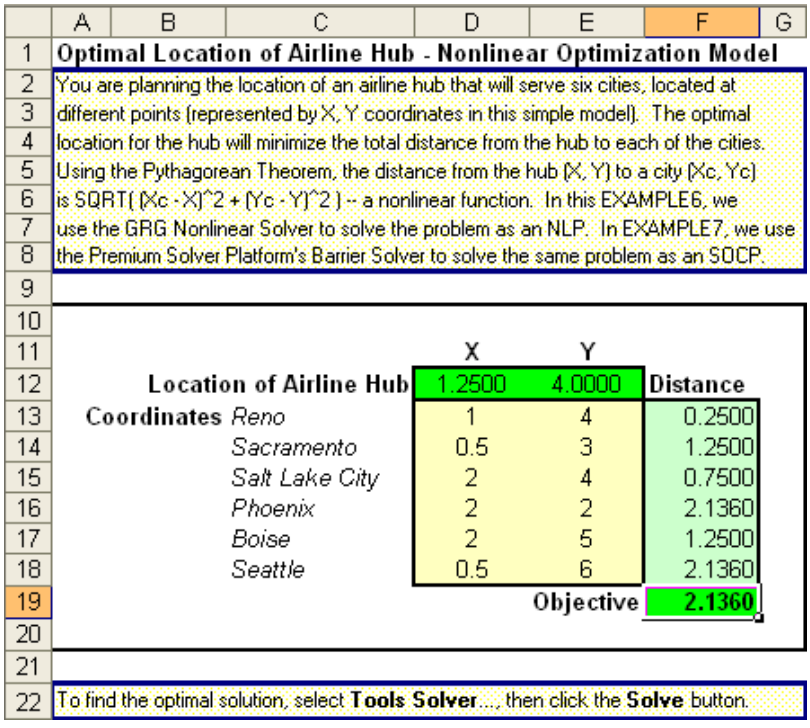
The message indicates that the Solver has found a **proven optimal** solution for the original problem with IF functions.

The PSI Interpreter can automatically transform models containing IF, AND, OR, NOT, ABS, MIN and MAX, and relations <, <=, >= and > into equivalent models where these non-smooth functions are eliminated. When this transformation is sufficient to make the overall model linear – as it was in this case – you can use the LP/Quadratic Solver or a large-scale LP/MIP Solver engine to solve the problem.

A Model with Cone Constraints

In the EXAMPLE6 and EXAMPLE7 worksheets, we wish to solve a model to optimize the location of an airline hub. The hub will serve six cities, each of which is located at some latitude and longitude (in these models, we use simple X, Y coordinates). We want to choose a location (X, Y coordinate) for the airline hub that will minimize the maximum distance from the hub to any of the six cities. The distance from the hub (X, Y) to a city (Xc, Yc) is SQRT((Xc - X)^2 + (Yc - Y)^2). The model is pictured below. In EXAMPLE6, we model and solve the problem using the GRG Nonlinear Solver. In EXAMPLE7, which requires Analytic Solver Comprehensive, Analytic Solver Optimization, Analytic Solver Upgrade or Analytic Solver Basic, we model the problem using **cone constraints**, and solve it using the SOCP Barrier Solver.

Modeling the Problem with Nonlinear Functions



Optimal Location of Airline Hub - Nonlinear Optimization Model

You are planning the location of an airline hub that will serve six cities, located at different points (represented by X, Y coordinates in this simple model). The optimal location for the hub will minimize the total distance from the hub to each of the cities. Using the Pythagorean Theorem, the distance from the hub (X, Y) to a city (Xc, Yc) is SQRT((Xc - X)^2 + (Yc - Y)^2) -- a nonlinear function. In this EXAMPLE6, we use the GRG Nonlinear Solver to solve the problem as an NLP. In EXAMPLE7, we use the Premium Solver Platform's Barrier Solver to solve the same problem as an SOCP.

		X	Y	
Location of Airline Hub		1.2500	4.0000	**Distance**
Coordinates	*Reno*	1	4	0.2500
	Sacramento	0.5	3	1.2500
	Salt Lake City	2	4	0.7500
	Phoenix	2	2	2.1360
	Boise	2	5	1.2500
	Seattle	0.5	6	2.1360
			Objective	**2.1360**

To find the optimal solution, select **Tools Solver**..., then click the **Solve** button.

In EXAMPLE6, our decision variables are the (X, Y) coordinates of the airline hub, at cells D12:E12, and a third decision variable at F19. Cell F19 also serves as the objective function, to be minimized. We calculate the distance from the hub to each of the six cities in cells F13:F18. We define a block of constraints F13:F18 <= F19 – this means that the distance from the hub to each city must be less than or equal to the decision variable F19, which the Solver will minimize.

The effect of these constraints is to cause the Solver to find values for D12:E12 – the (X, Y) coordinates of the hub – that minimize the maximum distance to any of the cities.

Click the EXAMPLE6 tab to display the model, and click Analyze – Analytic Original Problem. We see that the model is diagnosed as smooth nonlinear (NLP), with 3 variables and 7 functions. Notice that the Standard GRG Nonlinear Solver is selected.

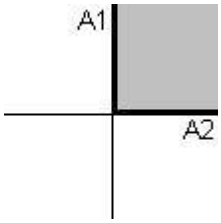
Click the **Optimize** button. The message "Solver found a solution" appears in green at the bottom of the Task Pane. The optimal location for the airline hub is at X = 1.25, Y = 4.0, and the maximum distance from this location to any of the six cities is 2.1360 units.

Modeling the Problem with Cone Constraints

In EXAMPLE4, we solved the simplest kind of nonlinear optimization problem, a portfolio optimization QP model with a quadratic objective and all linear constraints, and a variation that was a QCP model, with a quadratic constraint . We saw that we could solve the problem with the GRG Nonlinear Solver, but we could also solve both variations of the problem with the **SOCP Barrier Solver** – and we learned that we could more easily 'scale up' the SOCP problem to large size, with thousands of stocks or more.

We can do the same thing with the airline hub problem. The model is a little more complex, with more variables and constraints – but this allows the Solver to exploit the structure of the model, and solve it more quickly and reliably. To do this, we will explicitly use cone constraints.

We have actually used a simple kind of cone constraint before – in EXAMPLE1, our first linear programming problem, at the beginning of this chapter. In that model, we used an objective and constraints that were linear functions of the decision variables, and *non-negativity* constraints on the variables. These constraints specified that the variables must lie within a simple kind of cone, called the *non-negative orthant*. This first order cone places a bound on the *L1*-norm of the vector of decision variables:



In our reformulation of the airline hub problem in EXAMPLE7, we'll specify that groups of variables must lie within a *second order cone* (also called a Lorentz cone, or "ice cream cone") – a ***convex*** set that looks like this:

This cone places a bound on the *L2*-norm of the vector of decision variables. If A1:A3 are variables that lie within this cone, then

A1 >= SQRT(SUMSQ(A2:A3)) must hold. A problem with a linear objective and linear or second order cone (SOC) constraints is called a *second order cone programming* (SOCP) problem; it is always a ***convex*** optimization problem.

Second order cone programming is the *natural generalization* of linear programming. It offers the same advantages of convexity and scalability to large problems offered by linear programming – but for a broader class of models. For history buffs, Premium Solver Platform V6.0 was the first commercial software product to offer broad support for second order cone programming.

The EXAMPLE7 worksheet is shown below. In this model, we compute the simple *differences* Xc – X and Yc – Y between the airline hub coordinates and the coordinates of each city. We define new variables F21:F26, G21:G26, and H21:H26. We use constraints to make G21:G26 equal to the Xc – X differences, and H21:H26 equal to the Yc – Y differences.

Then we specify that each set of three variables (for example F21, G21, H21) must belong to a *second order cone* – hence F21 >= SQRT(SUMSQ(G21:H21)) – and likewise for F22, G22, H22, etc. Finally, we use one more variable F27 as the objective to be minimized, and we add a block of constraints F21:F26 <= F27 – much as we did in EXAMPLE6. The effect of these constraints is to cause the Solver to find values for the (X, Y) coordinates of the hub – now at D14:D15 – that minimize the maximum distance to any of the cities.

	A	B	C	D	E	F	G	H	I
1	**Optimal Location of Airline Hub - Conic Optimization Model**								
2	As in EXAMPLE6, you are planning the location of an airline hub that will serve six cities, located at different points								
3	(represented by X, Y coordinates in this simple model). The optimal location for the hub will minimize the total distance from								
4	the hub to each of the cities. In this model, we simply compute the difference between the X coordinates of the hub and								
5	each city at cells D21:D26, and the difference between the Y coordinates at cells E21:E26. We introduce new variables at								
6	F21:H26, and a new variable at cell F27. The variables F21:F26 are each constrained to be less than F27, which will be								
7	minimized. Constraints also make variables G21:G26 equal to the X differences, and variables H21:H26 equal to the Y								
8	differences. Finally, we specify that each set of three variables (F21:H21, F22:H22, etc.) must belong to the second order								
9	cone of dimension 3. By minimizing variable F27, we find the X, Y coordinates for the hub that minimizes the sum of the								
10	distances from the hub to the different cities. This SOCP model can be solved faster and more reliably than the NLP model.								
11									
12									
13					X	Y			
14			**Location of Airline Hub**		1.2501	4.0000			
15		**Coordinates**	*Reno*		1	4			
16			*Sacramento*		0.5	3			
17			*Salt Lake City*		2	4			
18			*Phoenix*		2	2			
19			*Boise*		2	5			
20			*Seattle*		0.5	6	**Cone Constraints**		
21		**Distance**	*Reno*		-0.2501	0.0000	1.1005	-0.2501	0.0000
22			*Sacramento*		-0.7501	-1.0000	1.5781	-0.7501	-1.0000
23			*Salt Lake City*		0.7499	0.0000	1.1863	0.7499	0.0000
24			*Phoenix*		0.7499	-2.0000	2.1360	0.7499	-2.0000
25			*Boise*		0.7499	1.0000	1.5367	0.7499	1.0000
26			*Seattle*		-0.7501	2.0000	2.1360	-0.7501	2.0000
27							**2.1360**	**Objective**	
28									
29									
30	To find the optimal solution, select **Tools Solver**..., then click the **Solve** button.								

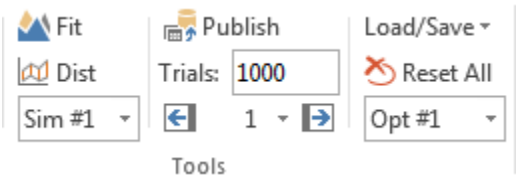
Click the EXAMPLE7 tab to display the model, and click **Analyze – Analyze Original Model**. We see that this formulation of the model is diagnosed as second order cone programming problem (SOCP), with 21 variables and 19 functions. Notice that the SOCP Barrier Solver is selected to solve the problem.

Click the **Optimize** button. After a moment, the same optimal solution as in EXAMPLE6 is found. In this simple example, both the Standard GRG Nonlinear Solver and the SOCP Barrier Solver solve the problem in sub-second time. But if we were to **scale up** this model to large size – say with 1,000 cities – the SOCP Barrier Solver would likely show a speed advantage.

Solving an Optimization Model using Excel Online or Google Sheets

In late 2014, Frontline Systems released Solver App for use with Excel 2013 and Solver Add-on for use with Google Sheets. With the Solver App you can define and solve optimization problems in your Excel workbook, using Excel Online in Office 365, the Excel Web App in SharePoint 2016 or 2013, or desktop Excel 2016 or 2013. With the Solver Add-on, you can define and solve optimization problems in Google Sheets. You can create and solve models on tablets, phones, or anywhere a Web browser can be used. Solver models that you may already have created in old or new versions of Microsoft Excel, are automatically recognized by the Solver App and , after the existing worksheet is published, with the Solver Add-on.

In Analytic Solver Desktop and AnalyticSolver.com, the **Freeze** and **Thaw** buttons were combined into a single **Publish** button, as shown in the screenshot below. (In Premium Solver Pro/Platform where there was no Freeze/Thaw function, the Ribbon now includes a Publish icon.) Note: This functionality is not supported in Analytic Solver Cloud.

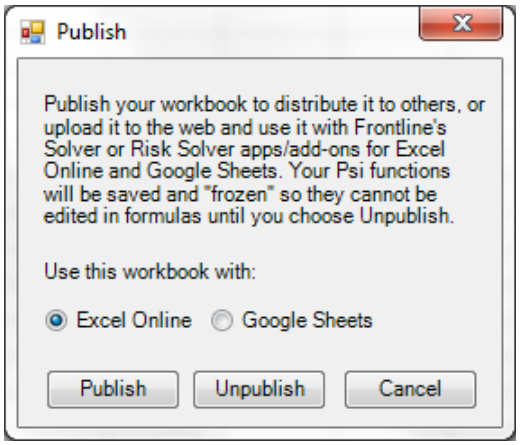


Like the "Freeze" button, the **Publish** button can be used to prepare a workbook for distribution to other users who don't have Analytic Solver or its subsets installed: All formulas containing Psi function calls (which would yield #NAME? for other users) are replaced by their values, and the formulas are saved, so they can be restored later by choosing "Unpublish" (equivalent to the old "Thaw").

But the major use of the **Publish** button in ASP and later, is to prepare a workbook for use with our Solver/Risk Solver Apps for Excel Online and our Solver/Risk Solver Add-on for Google Sheets (the online spreadsheets have limited or no support for user-defined functions).

In *ASP*, when a model is published, the limits for Solver App (for Excel Online) and Solver Add-on (for Google Sheets) will be automatically adjusted to match the problem limits of your license. For example, if you purchased a license for Analytic Solver, then you will be able to solve linear models using the Solver App or Solver Add-on with up to 8,000 variables and constraints and nonlinear or nonsmooth models with up to 1,000 variables and constraints, *if* you publish your model first by clicking the Publish button on the Analytic Solver ribbon.

Let's go back to the model on the Example1 tab used in the section above, click the Publish icon on the Ribbon to display the following dialog.



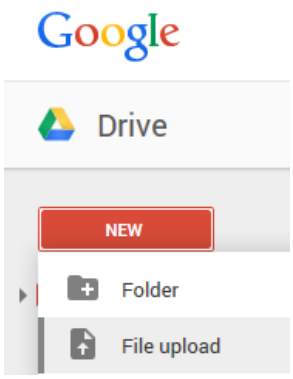
Select **Google Sheets** then **Publish**. (If you are a user of Excel Online, please see the example below.) Make sure to **save** the workbook before uploading to Google Drive.

Note: Only the Active Worksheet is published. To solve a model on a different worksheet within the same Workbook (say Example2), you'll need to publish that worksheet separately. This is important when solving an optimization model. If solving a simulation model, this does not apply. (For an example on how to solve a simulation model with Excel Online or Google Sheets, please see the next chapter.)

Log on to your Google Drive account and upload Standard Example.xls, then open this file in Google Sheets.

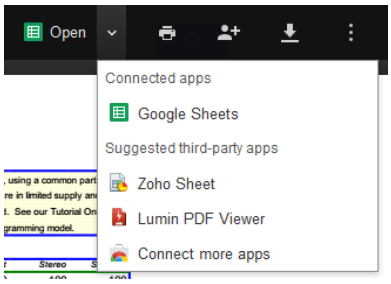
Uploading and Opening Files in Google Sheets

Click the orange New button then select File Upload to upload the StandardExamples.xls spreadsheet to Google Drive.

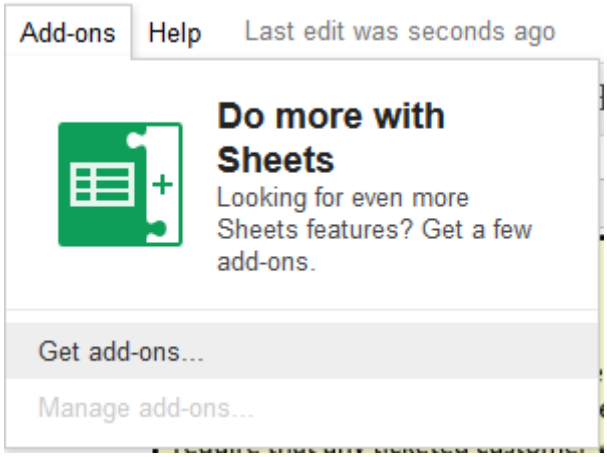


Browse to the location of the file, typically C:\Program Files (x86)\Frontline Systems\Analytic Solver Platform\Examples (if using 32 bit Excel with 64 bit Windows) or C:\Program Files\Analytic Solver Platform\Examples (if using 64 bit Excel or 32 bit Excel with 32 bit Windows). StandardExamples.xls will appear under My Drive.

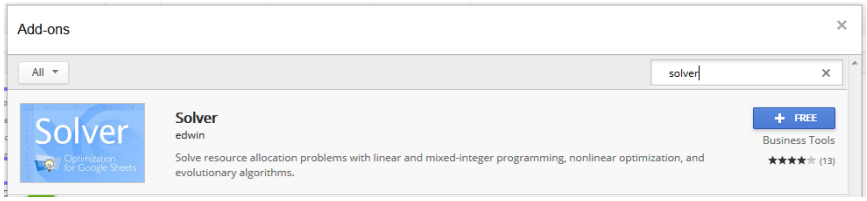
Double click the file to open in Google Drive Preview Viewer (shown below). Click Open – Google Sheets.



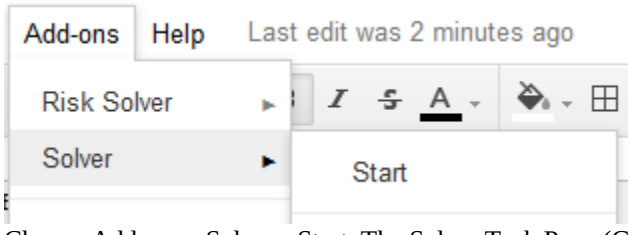
To add the Solver Add-on, choose the menu option Add-ons - Get Add-ons...



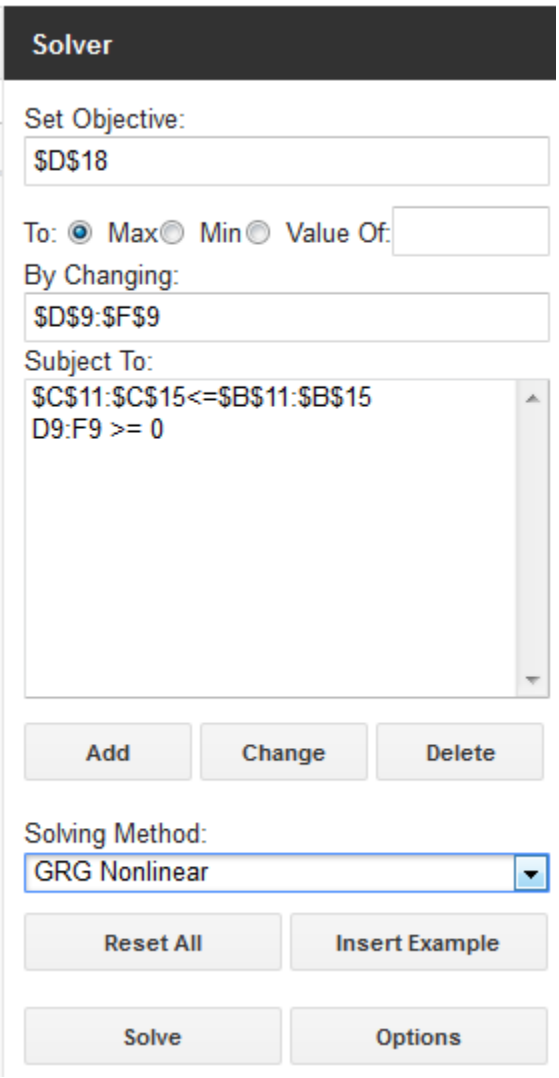
In the Add-ons dialog, scroll until you see *Solver*. Click to select and install.



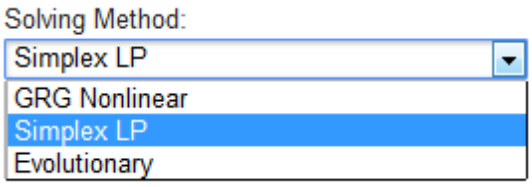
Once these steps are finished, Solver should now appear on the Add-ons menu.



Choose Add-ons - Solver - Start. The Solver Task Pane (Google calls this a Sidebar) will appear containing the Solver model: objective, variables, and constraints.



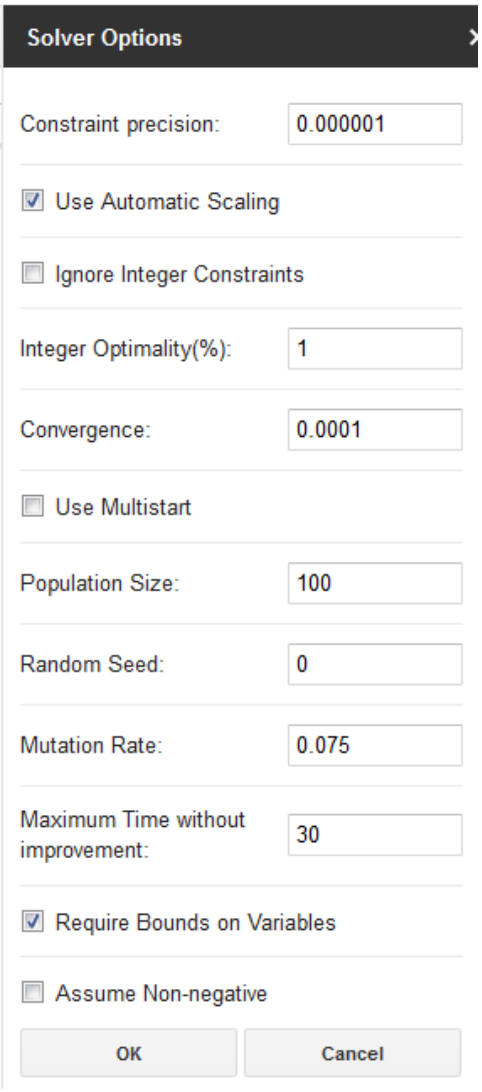
Since this is a linear model, click the down arrow to the right of *GRG Nonlinear* under *Solving Method* to select the **LP/Quadratic** engine.



Click Solve to run the Simplex LP engine to solve the linear model. The Solver Add-on solves the model, inserting the final variable values of 200/200/0 in cells D9:F9 and finding an objective equal to $25,000. Note: Reports, such as Answer Report, Sensitivity Report, and/or Limits reports, are not supported in the Solver Add-on.

The Solver Sidebar behaves much like the Excel Solver dialog. To change a constraint, simply highlight the desired constraint and click *Change*. To delete a constraint, highlight the desired constraint and click *Delete*. Click *Reset All* to clear the objective, all variables and constraints, and all options settings. Select *Options* to change an engine option such as Constraint Precision, Automatic

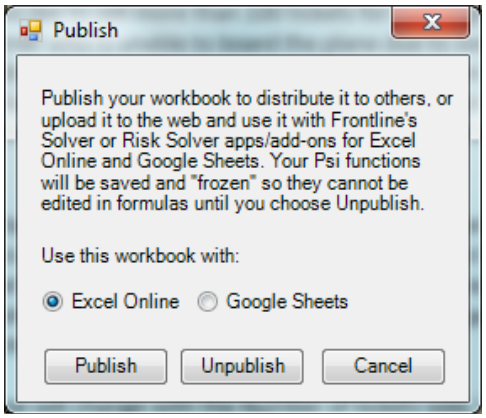
Scaling, Convergence, etc. For more information on each of these options, please see the *Engine Option* chapter in *Frontline Solvers Reference Guide*.



Now let's Publish this same model to Excel Online. Let's go back to Excel and StandardExamples.xls. Click **Publish – Unpublish**.

Reopen the Publish dialog by clicking **Publish**. Confirm that *Excel Online* is selected. Click **Publish** to publish the worksheet to Excel Online.

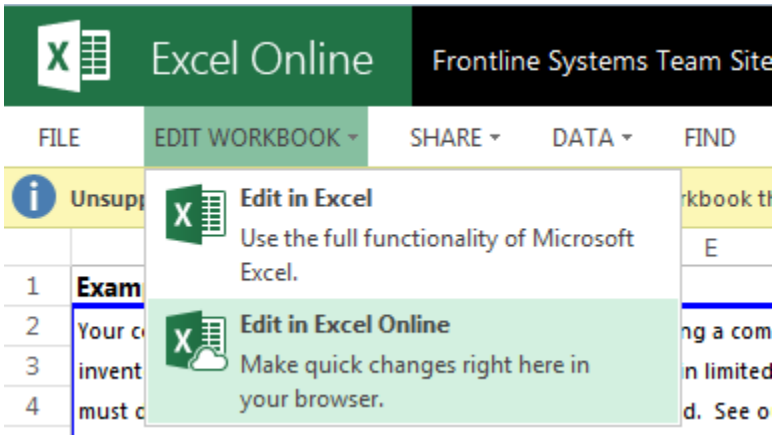
Note: Only the Active Worksheet is published. To solve a model on a different worksheet within the same workbook (say Example2), you'll need to publish that worksheet separately. This is important when solving an optimization model. If solving a simulation model, this does not apply. (For an example on how to solve a simulation model with Excel Online or Google Sheets, please see the next chapter.)



Now **Save** the file as **StandardExamples.xlsx** on your *SharePoint* or *Office 365* site.

Note: In order to use the Solver App, your file must be saved on SharePoint or Office 365 site. This app cannot solve models saved on your local hard drive.

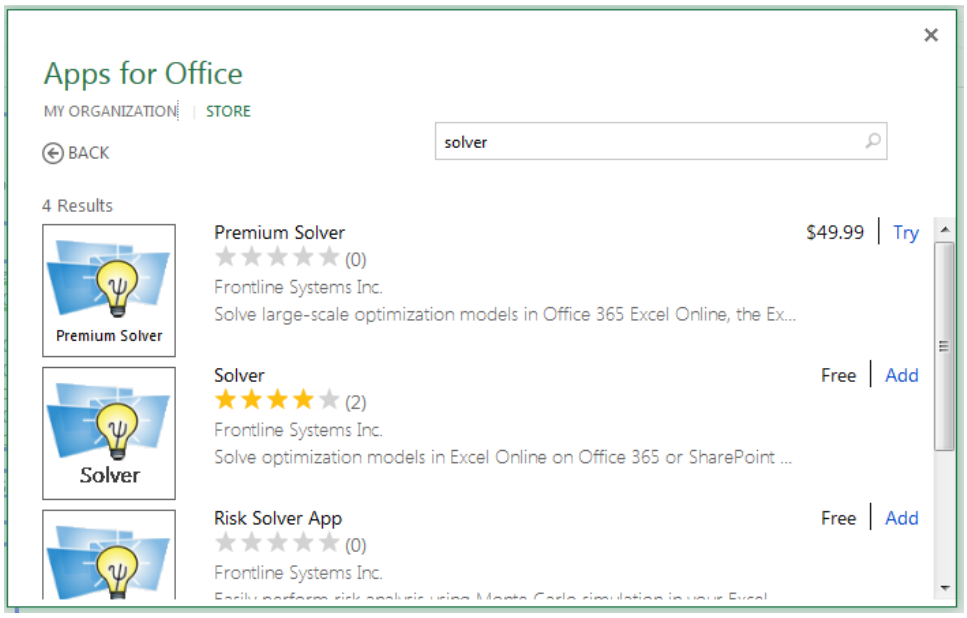
Open the workbook using Excel Online, then click Edit Workbook – Edit in Excel Online.



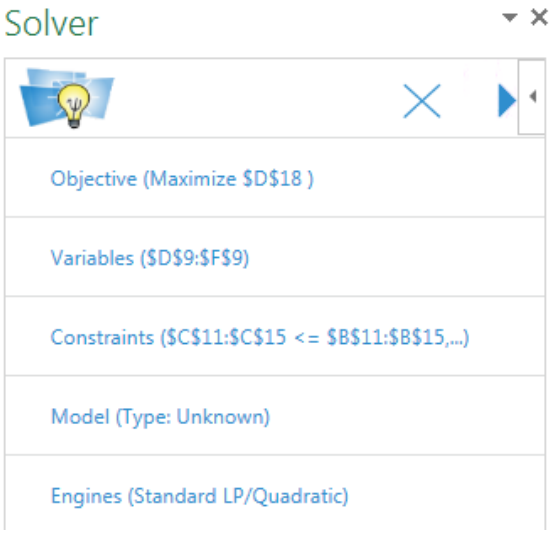
Click Insert – Office Add-ins.

Select the Store tab and search for Solver, then select (2nd app in the list) and Install. Note: A Premium Solver app which solves linear models with more than 200 variables and nonlinear models with more than 200 variables and 200 constraints is available for purchase. Please contact Frontline Systems for more information at sales@solver.com.

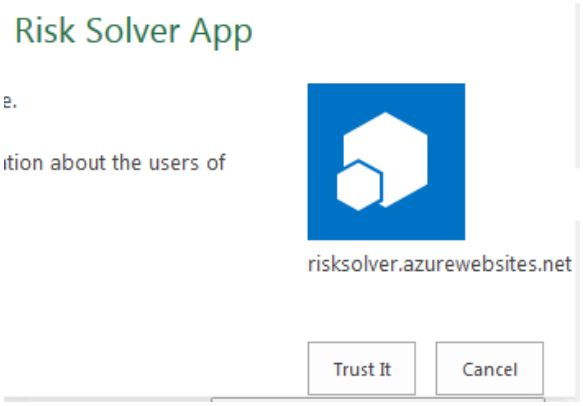
Please see the next chapter for an example on the use of the Risk Solver App.



The Solver App task pane opens to the right on your screen.

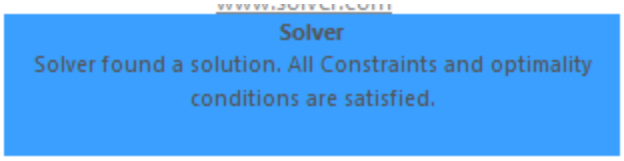


Simplex LP has already been selected for Solving Method. Click *Solve* to run this engine to solve this simple linear model. If running for the first time, you will be asked to **Trust** the App.



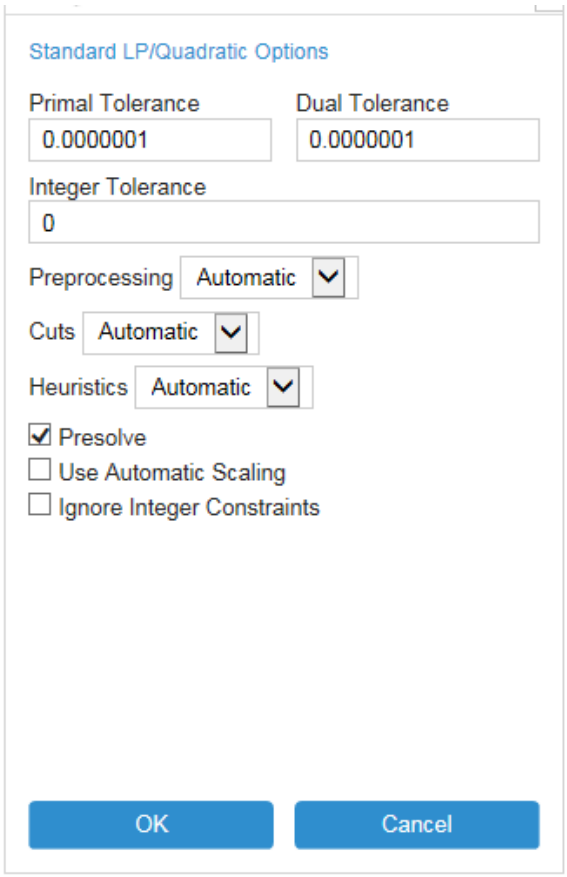
Solver inserts the final variable values 200/200/0 into cells D9:F9 and adds the final result message "Solver found a solution. All Constraints and optimality conditions are satisfied." to the bottom of the Solver pane.

			TV set	*Stereo*	*Speaker*
		Number to Build->	200	200	0
Part Name	*Inventory*	*No. Used*			
Chassis	450	400	1	1	0
Picture Tube	250	200	1	0	0
Speaker Cone	800	800	2	2	1
Power Supply	450	400	1	1	0
Electronics	600	600	2	1	1
		Profits:			
		By Product	$75	$50	$35
		Total	**$25,000**		



Note: The Answer Report and Sensitivity Report are *only* supported when using the Solver App within Excel 2016. You can create the reports after Solver has found a solution by clicking the Create Report icon located in the title bar of the Solver App. If using Excel 2013, Excel for iPad & iPhone or Excel Online, you will not have the option to create reports.

This task pane behaves much like the Excel Solver. To Add a constraint, click *Constraints*, then *Add.* To Change or Delete a constriant, select the desired constraint and click *Change* or *Delete*. To change an engine option, click *Engine* then *Options.* For more information on each of these options, please see the *Engine Option* chapter in *Frontline Solvers Reference Guide*.


Standard LP/Quadratic Options
Primal Tolerance
0.0000001
Dual Tolerance
0.0000001
Integer Tolerance
0
Preprocessing
Automatic
Cuts
Automatic
Heuristics
Automatic
Presolve
Use Automatic Scaling
Ignore Integer Constraints
OK
Cancel

Examples: Simulation and Risk Analysis

Introduction

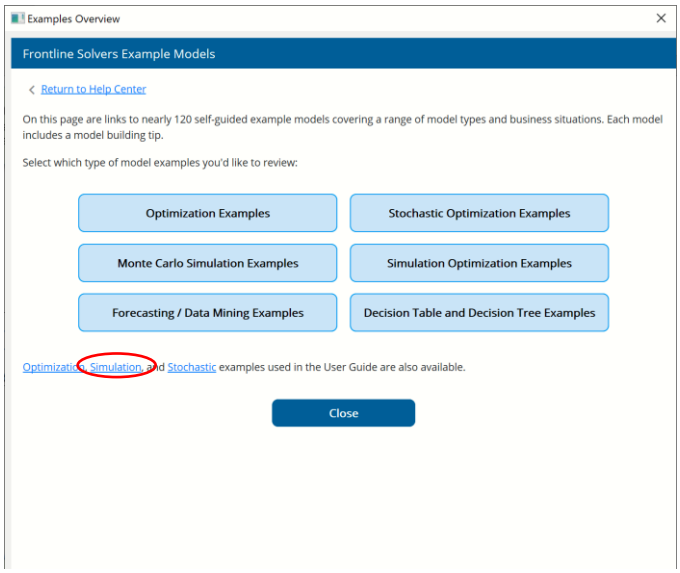
This chapter introduces simulation and risk analysis in Analytic Solver, with a series of examples. Each of these examples with the exception of the last one can be used in Analytic Solver Simulation.

- "A First Simulation Example" takes you step-by-step through the process of building and analyzing a risk analysis model using Monte Carlo simulation.
- "Airline Revenue Management Example" takes you through three versions of an airline yield management problem, to illustrate a single simulation, multiple parameterized simulations, and simulation optimization.

A First Simulation Example

Building a simulation model in Analytic Solver is straightforward: You simply build a conventional spreadsheet model, designed for 'what-if' analysis. Next, you identify the ***inputs*** to your model that are uncertain, and use PSI Distribution functions to describe the uncertainty. Then, you identify the ***outputs*** of special interest (such as Net Profit), and use PSI Statistics functions to examine or summarize how they behave in light of the uncertainty.

To open this example in Analytic Solver Desktop or Analytic Solver Cloud, click **Help – Examples** on the Ribbon, which opens a workbook Frontline Example Models Overview.xls. Click the Simulation link.



To open this example in AnalyticSolver.com click Help – Examples – Simulation Examples – Business Forecast User Guide.

We'll build the simulation model step-by-step in this section using the model in the worksheet, **BusinessForecast**. To view the completed model, see the 2nd tab in the workbook, **BusinessForecastPsi**.

Uncertain Variables

In any problem, there are factors or inputs that you can control – for example, the price you set for a product, and factors or inputs that you *cannot* control – for example, customer demand, interest rates, etc. Analytic Solver uses **uncertain variables** (*random variables* in mathematics) to represent inputs that are uncertain and beyond your control. (It uses decision variables to represent factors or inputs that you *can* control.)

Uncertain Functions

You will also have outputs or results of interest – such as Net Profit – that you can compute, using formulas that depend on the factors influencing the problem – possibly both decision variables and uncertain variables. We'll use the term **uncertain functions** for quantities whose calculation depends on uncertain variables (in mathematics these are called *functions of random variables*).

A Business Planning Example

We'll illustrate the process of building a simulation model step by step, using a simple business planning example. Imagine you are the marketing manager for a firm that is planning to introduce a new product. You need to estimate the first year profit from this product, which will depend on:

- Sales in units
- Price per unit sold
- Unit manufacturing cost
- Fixed costs and overhead

Profit will be calculated as **Profit = Sales * (Price - Unit cost) - Fixed costs**.

Fixed costs are known to be **$120,000**. But the other factors all involve some uncertainty. Sales in units can cover quite a range, and the selling price per unit will depend on competitor actions. Unit manufacturing costs will also vary depending on vendor prices and production experience.

Uncertain Variables: Sales and Price

Based on your market research, you believe that there are equal chances that the market demand will be Slow, OK, or Hot for this product:

- In the Slow market demand scenario, you expect to sell 5**0,000** units at an average price of **$11.00** per unit.
- In the OK market scenario, you expect to sell **75,000** units, but you'll likely realize a lower average selling price of **$10.00** per unit.
- In the Hot market scenario, you expect to sell **100,000** units, but this will bring in competitors who will drive down the average selling price to **$8.00** per unit.

Since the scenarios are equally likely, your *average* volume is **75,000** units, and your *average* price per unit is **$9.67**. But think: How likely is this *average* case? (Will it ever actually occur?)

Uncertain Variables: Unit Cost

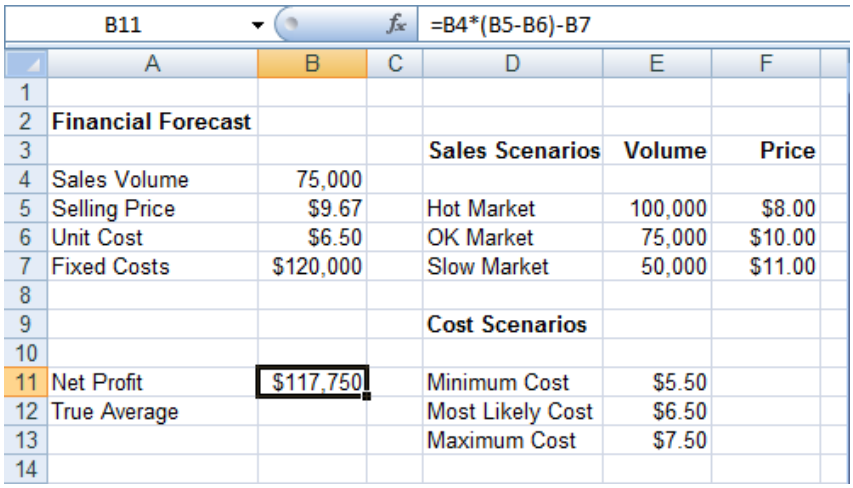
Your firm's production manager advises you that unit costs may be anywhere from **$5.50** to **$7.50**, with a most likely cost of **$6.50**. The most likely cost is also the *average* cost.

Uncertain Function: Net Profit

Net Profit is calculated as **Profit = Sales * (Price - Unit cost) -Fixed costs**. Sales, Price and Unit costs are all uncertain variables, so Net Profit is an uncertain function.

A What-If Spreadsheet Model

At this point, you can summarize the problem in the Excel model pictured below, which calculates Net Profit based on *average* sales, price, and unit cost.



	A	B	C	D	E	F
1						
2	**Financial Forecast**					
3				**Sales Scenarios**	**Volume**	**Price**
4	Sales Volume	75,000				
5	Selling Price	$9.67		Hot Market	100,000	$8.00
6	Unit Cost	$6.50		OK Market	75,000	$10.00
7	Fixed Costs	$120,000		Slow Market	50,000	$11.00
8						
9				**Cost Scenarios**		
10						
11	Net Profit	$117,750		Minimum Cost	$5.50	
12	True Average			Most Likely Cost	$6.50	
13				Maximum Cost	$7.50	
14						

The Net Profit figure of $117,750 (=B4*(B5-B6)-B7) calculated by this model, based on *average* values for the uncertain factors, is quite misleading, as we'll see in a moment. The ***true average*** Net Profit is closer to $93,000! In the spirit of Prof. Sam Savage's book *The Flaw of Averages*, we'll refer to the model above as the Flawed Average model.

Defining a Simulation Model

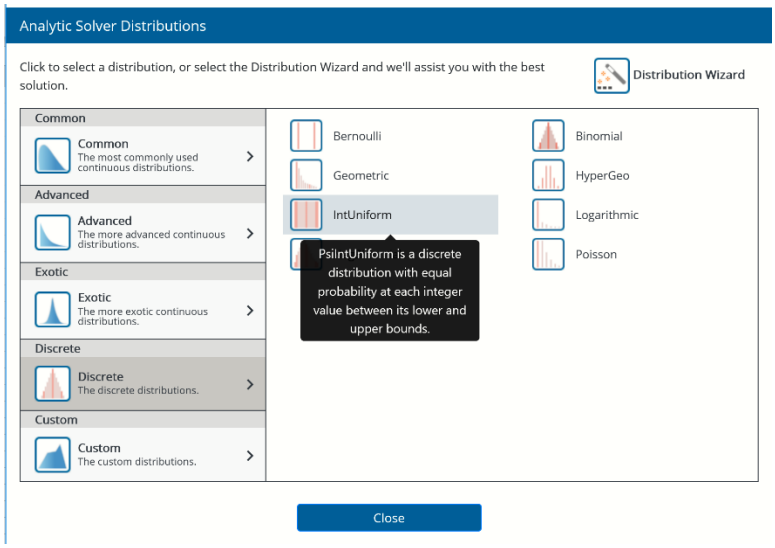
To "stress test" this model, we need to replace the fixed Sales, Price and Unit cost amounts with *variable* amounts that reflect their uncertainty.

Since there are equal chances that the market will be Slow, OK, or Hot, we want to create an uncertain variable that selects among these three possibilities, by drawing a random number – say 1, 2 or 3 – with equal probability. We can do this easily in Analytic Solver using an **integer uniform** probability distribution. We'll then base our Sales Volume and Selling Price on this uncertain variable.

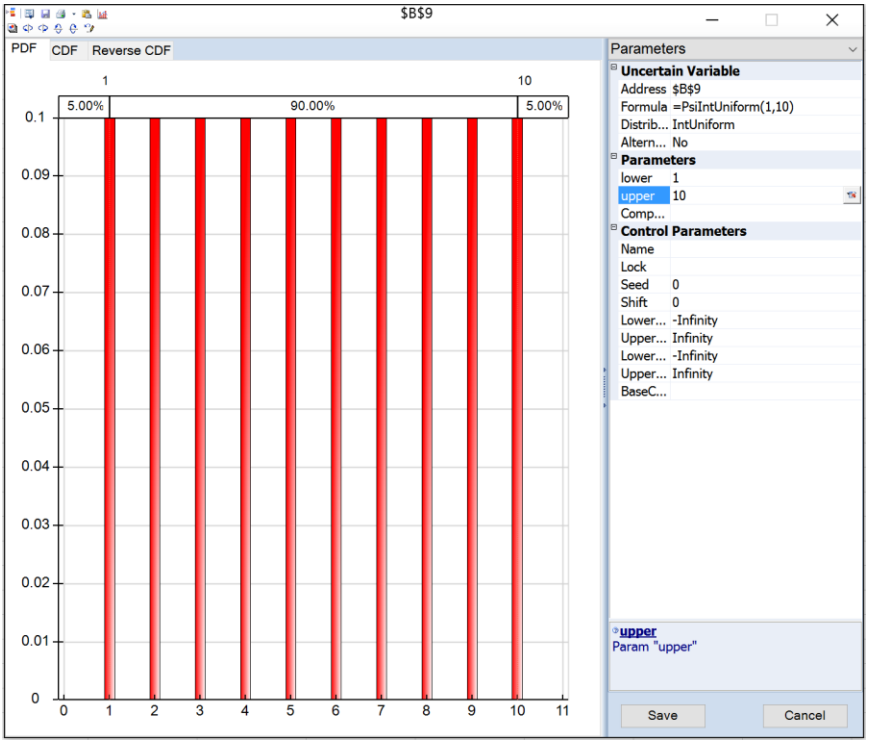
If using Analytic Solver Desktop or AnalyticSolver.com, we'll choose a currently empty cell, B9, to hold this distribution by clicking on it and selecting

Distributions - Discrete on the Ribbon. This displays a cascading menu, as shown on the next page.

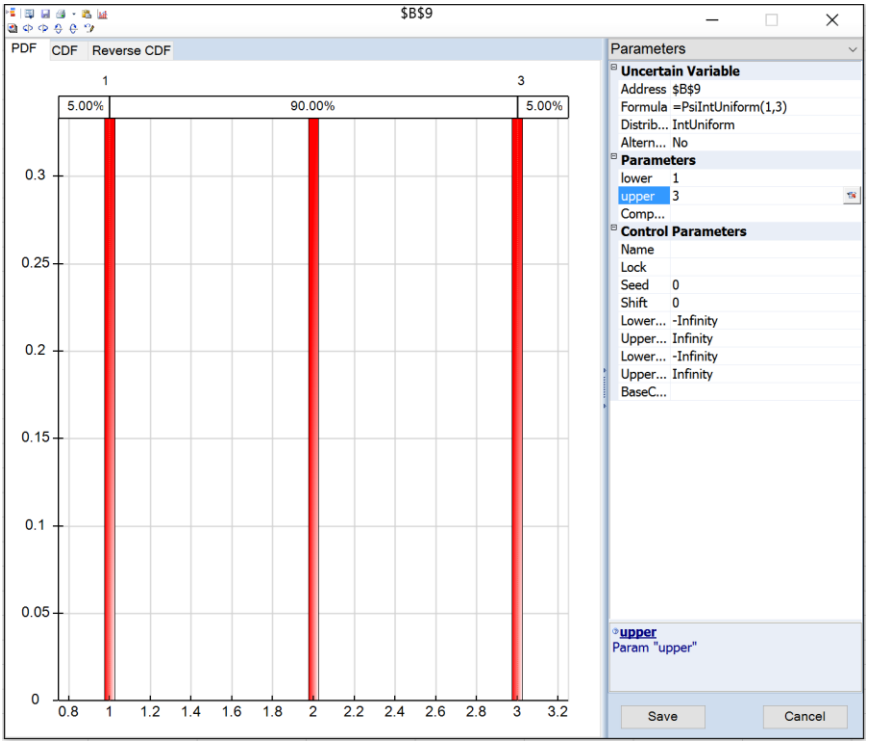
Analytic Solver Desktop



A sample drawn from a *discrete* distribution is always one of a set of discrete values, such as integer numbers. We click to choose **IntUniform** from the gallery or menu. Analytic Solver displays the Uncertain Variable dialog for a integer uniform distribution, initially with parameters lower 0 and upper 10:



We click in the Value column and change the parameters to read **lower** 1 and **upper** 3. This means that on each trial, we'll draw a number 1, 2 or 3 from this distribution. As we do, the chart of probability mass (density) is updated:



When we click the **Save** icon in the dialog toolbar in Analytic Solver Desktop or the Save button at the bottom of the dialog in Analytic Solver Cloud or AnalyticSolver.com, a formula **=PsiIntUniform(1,3)** is written to B9. B9 is now an *uncertain variable*. For each trial of the Monte Carlo simulation, a different value – either 1, 2 or 3 – will appear in cell B9. When we run a Monte Carlo simulation of (say) 1,000 trials, 1,000 different values of 1, 2 or 3 will be sampled for this cell's value.

Now, we need to select one of the three sales scenarios in formulas for Sales Volume and Selling Price. With cell B4 selected, we enter the formula:

=CHOOSE(B9,E5,E6,E7) for Sales Volume

This will cause B4 to return 100,000, 75,000, or 50,000, depending on the value in B9. Next, with cell B5 selected, we enter the formula:

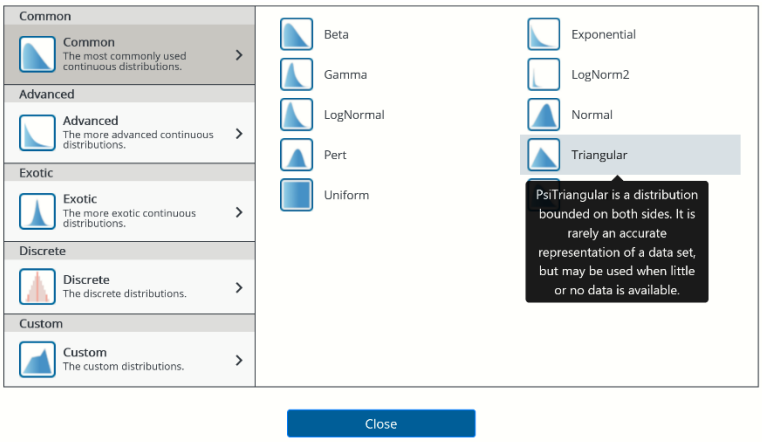
=CHOOSE(B9,F5,F6,F7) for Selling Price

This will cause B5 to return $8, $10 or $11, depending on the value in B9.

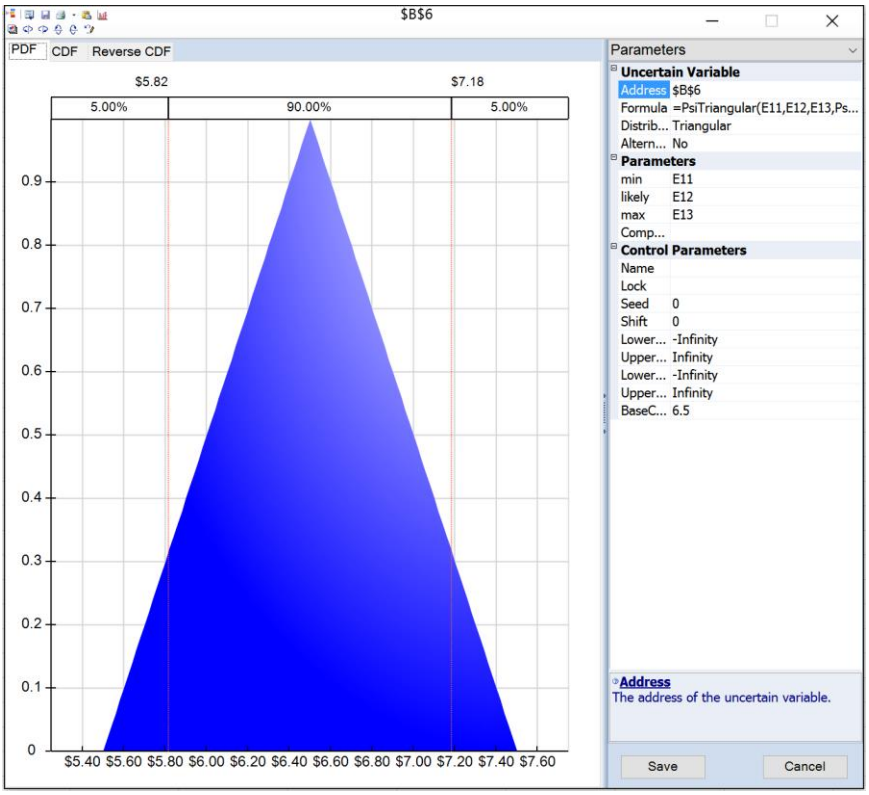
Notice that the values returned by B4 and B5 are related, or ***correlated***: Higher sales volume is accompanied by lower selling prices, and vice versa. If we had scenarios with 100,000 units sold at $11 each, our model would be unrealistic. Analytic Solver has more versatile ways to specify correlation between uncertain variables, but this approach is easy to understand in this example.

Next, we'll deal with Unit Cost. We have not just three, but *many* possible values for this variable: It can be anywhere from $5.50 to $7.50, with a most likely cost of $6.50. A crude but effective way to model this is to use a *triangular* distribution. Analytic Solver provides a function called **PsiTriangular()** for this distribution.

With cell B6 selected, we select **Distributions – Common – Triangular** from the Ribbon.



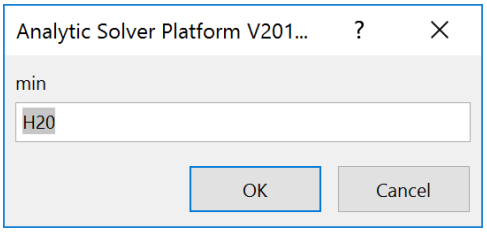
(Unlike a discrete distribution, a sample drawn from a *continuous* distribution can be any numeric value, such as 5.8 or 6.01, in a range.) Analytic Solver displays the Uncertain Variable dialog with a chart of the triangular distribution, initially from 0 to 3, peaking at 1.



To see more of the features of this dialog, try clicking on the Parameters drop down at the top of the right panel. See Frontline Solvers Reference Guide for more information.

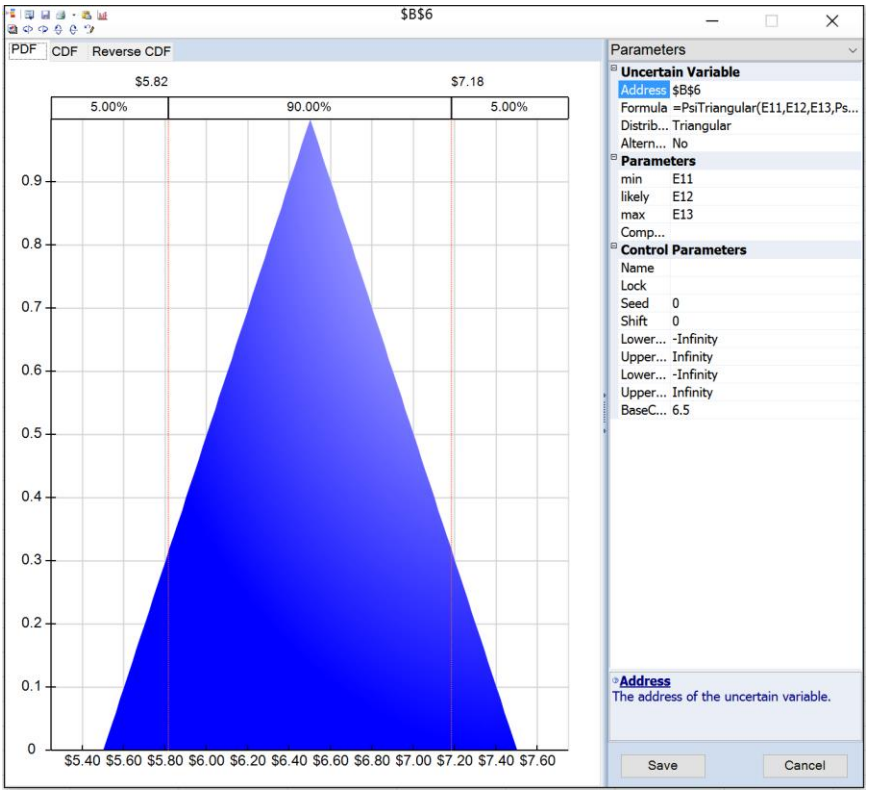
The minimum, most likely, and maximum values for Unit Cost are in cells E11, E12 and E13. If we enter these *cell references* – not just the numbers 5.50, 6.50 and 7.50 – into our PsiTriangular() function call, we'll have a more flexible model. To start, we simply click in the Value field for the **min** parameter.

Now we can either type in a number or cell reference, or we can click the button at the right edge of the field: When we do this, a small dialog appears. Type "E11", then click OK.



If using Analytic Solver Cloud or AnalyticSolver.com, simply type the cell address into the **min** field.

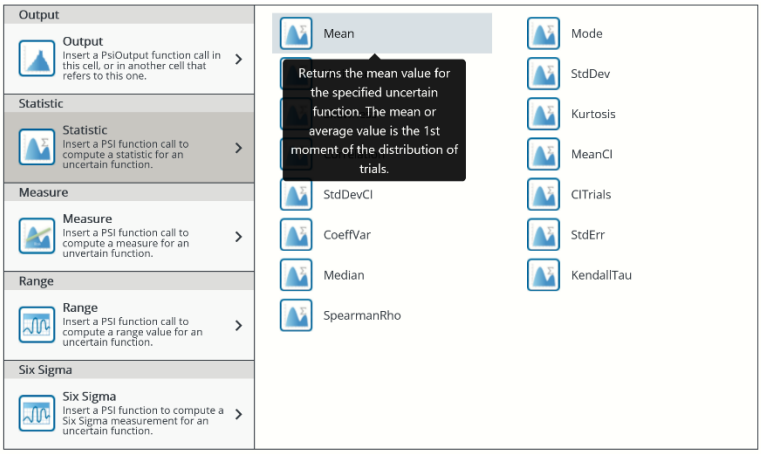
Now E11 appears as the **min (a)** parameter. Since at this moment, the **min (a)** value of 5.50 is greater than the **max (b)** value of 3, the error "The distribution is invalid with the current values of the parameters" is displayed instead of the chart. This is a hint that the parameters are inconsistent. (If using Analytic Solver Cloud, click OK to clear the error and continue editing the Parameter fields.) The chart reappears once we enter references to cell E12 for **likely (c)** and E13 for **max (b)**. When we click the **Save** icon, **=PsiTriangular(E11,E12,E13)** is inserted into cell B6.



We've now defined the **uncertain variables** in our model. Anything calculated from these uncertain variables is an **uncertain function**, but usually we're interested only in specific results such as Net Profit at cell B11. When we run a simulation, B11 will effectively hold an **array of values**, each one calculated from different values sampled for B4, B5, B6 and B7.

What would we like to know about the array of values for Net Profit at cell B11? The simplest summary result is the average (or mean) Net Profit. Note that this will be the ***true average*** of Net Profit across 1,000 or more scenarios or trials – not a single calculation from *average* values of the *inputs.*

Click Results to open the Simulation Results dialog then select Statistics from the left and Mean from the right. Enter the output cell and the cell where the statistic is to be placed, then click Insert.

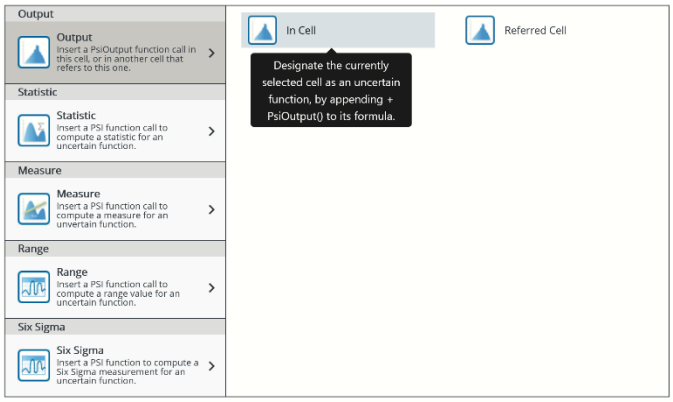


Selecting Uncertain Functions

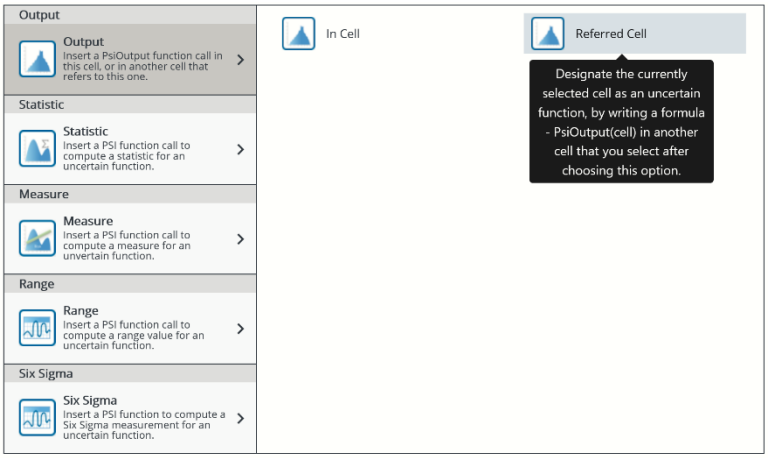
When we define a summary statistic, such as =PsiMean(B11), we've implicitly designated cell B11 as an **uncertain function**. Analytic Solver will keep track of the full range of trial values for B11 during a simulation, and will display frequency and sensitivity charts, statistics and percentiles for it on demand. As noted above, in principle anything calculated from the uncertain variables is an "uncertain function" – but to save time and memory, Analytic Solver keeps track of trial values only for the formula cells that we ***designate*** as uncertain functions.

What if we want to designate cell B11 as an uncertain function without calculating any summary statistic for it on the worksheet?

With cell B11 selected, select Results to open the Result Dialog, then click OK to accept Output for Category and In Cell for Function.

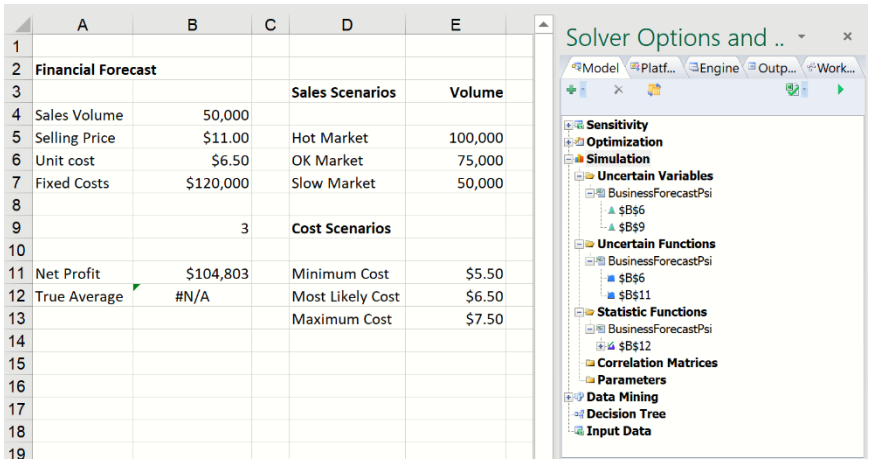


This will modify cell B11's formula =B4*(B5-B6)-B7 to read **=B4*(B5-B6)-B7 + PsiOutput()**. If we don't want to modify this formula, we can instead choose **Results – Output – Referred Cell**.



If we click in cell B12, this cell will contain **=PsiOutput(B11)**. Any **one** of these three actions – defining a summary statistic such as PsiMean() on B11, add PsiOutput() to the formula in cell B11, or placing =PsiOutput(B11) in another cell – is sufficient to designate cell B11 as an uncertain function.

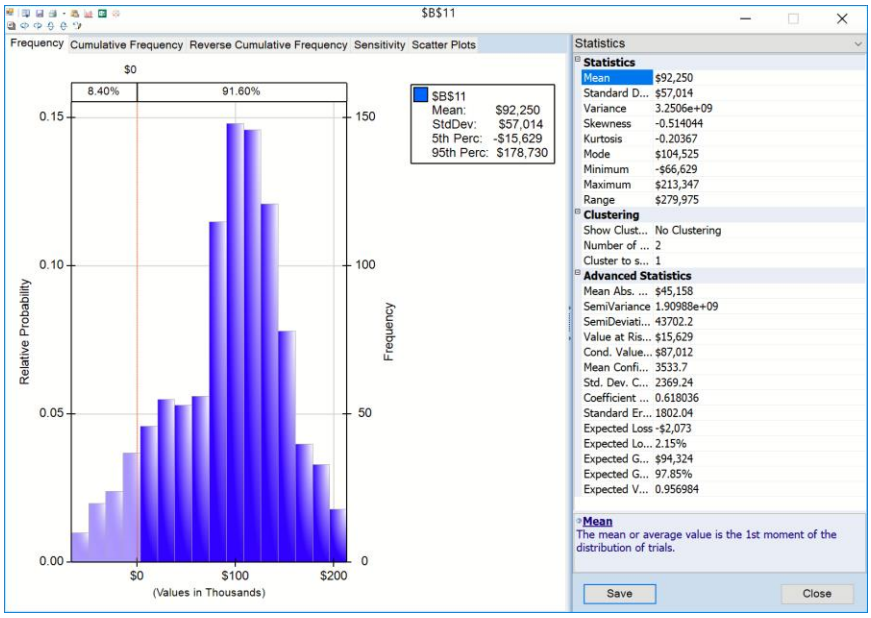
Our model now looks like the one pictured below. Notice that the Task Pane **Model tab** shows our simulation model in outline form, and cell B12, where we placed the **PsiMean()** function, displays as #N/A – because a simulation has not yet been executed.



Running a Simulation

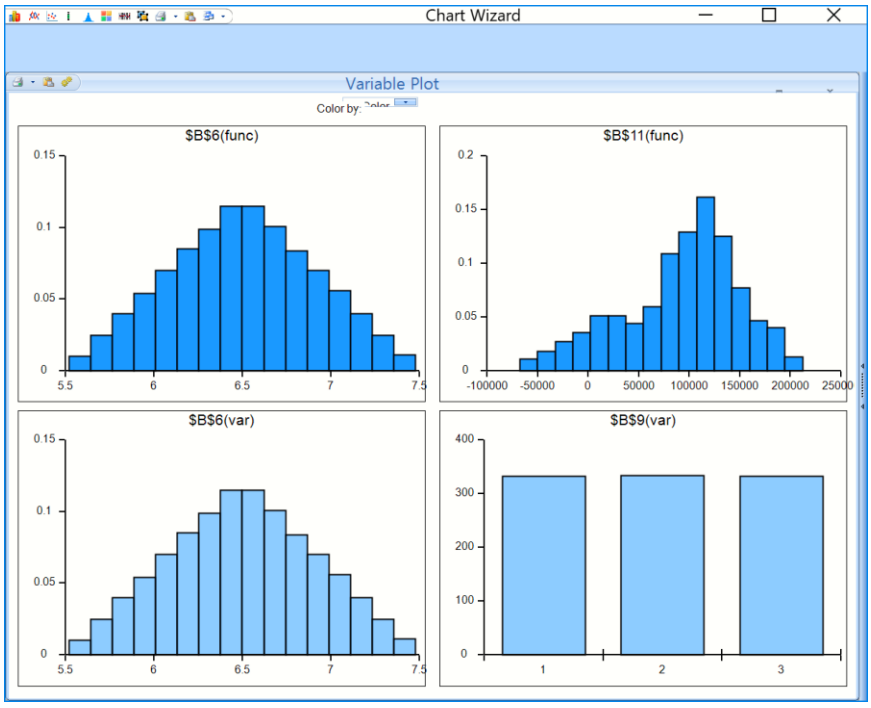
Click the green arrow on the Model tab to start a simulation. With an old-fashioned simulation software package, you'd press a button to start a simulation, then perhaps get a cup of coffee. Because simulations ran slowly, software packages were designed for "batch" operation: You'd spend time getting everything set up just right, run a simulation and wait (sometimes quite a while), then spend time analyzing the results. But with Analytic Solver, you'll find that in the blink of an eye, your first Monte Carlo simulation is complete!

Since there is one uncertain function, and this is the first time a simulation has been performed, the following dialog opens. Subsequent simulations will not produce this report. However, it is possible to reopen this frequency chart simply by double clicking cell B11. (See below for more information on this chart.)



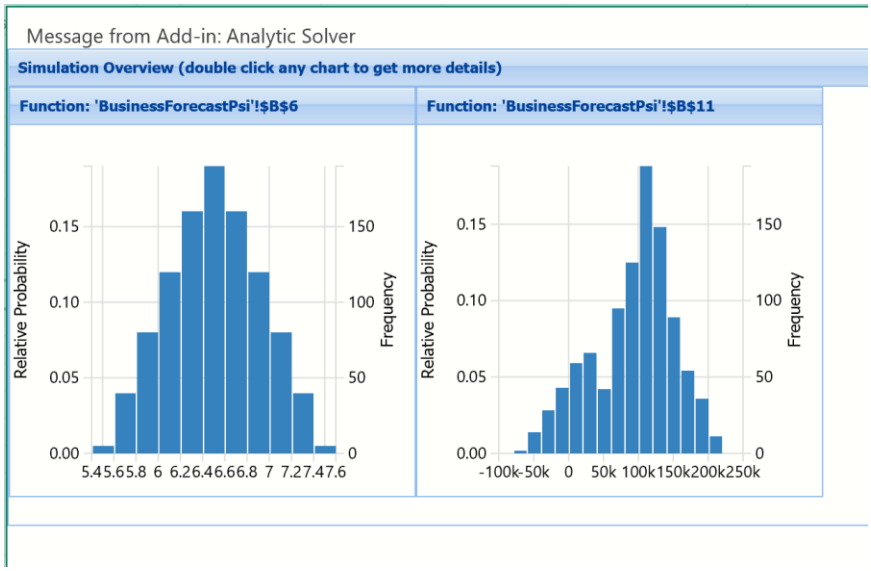
If your simulation model contains more than one output function, then a chart containing frequency graphs of up to 9 output functions and uncertain variables will appear. For example, if the uncertain variable in cell B6 was also selected to be an output cell (B6 = PsiTriangular(0, 1, 3) + PsiOutput()) and a simulation was performed, the following graph would appear at the end of the simulation.

Analytic Solver Desktop

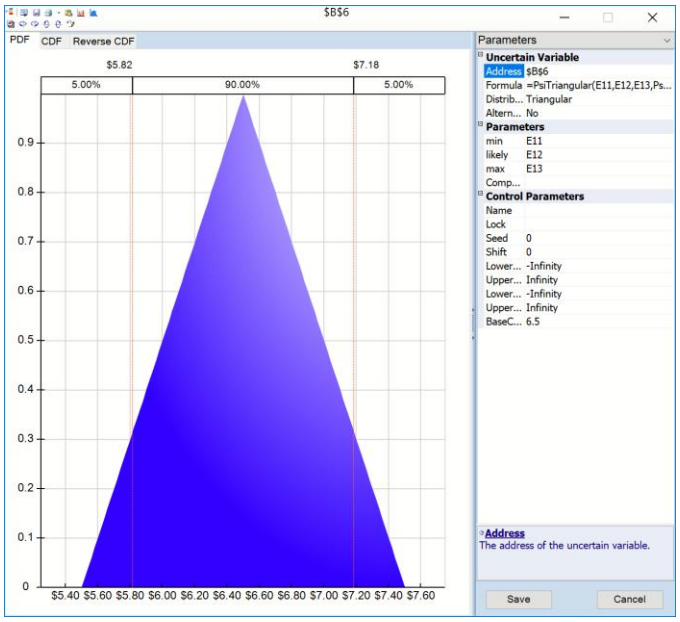


Analytic Solver Cloud and AnalyticSolver.com display only output functions; B6 and B11 in this example.

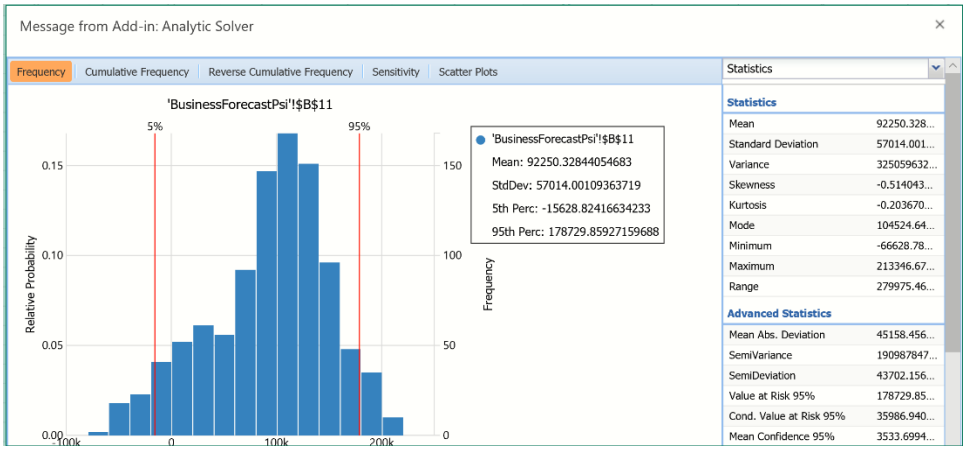
Analytic Solver Cloud



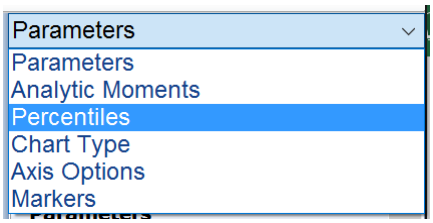
Double clicking the "$B$6(func)" chart in Analytic Solver Desktop will open the B6 uncertain variable dialog, as shown below. To open the uncertain function dialog, click the Show Output icon on the top left of the title bar.

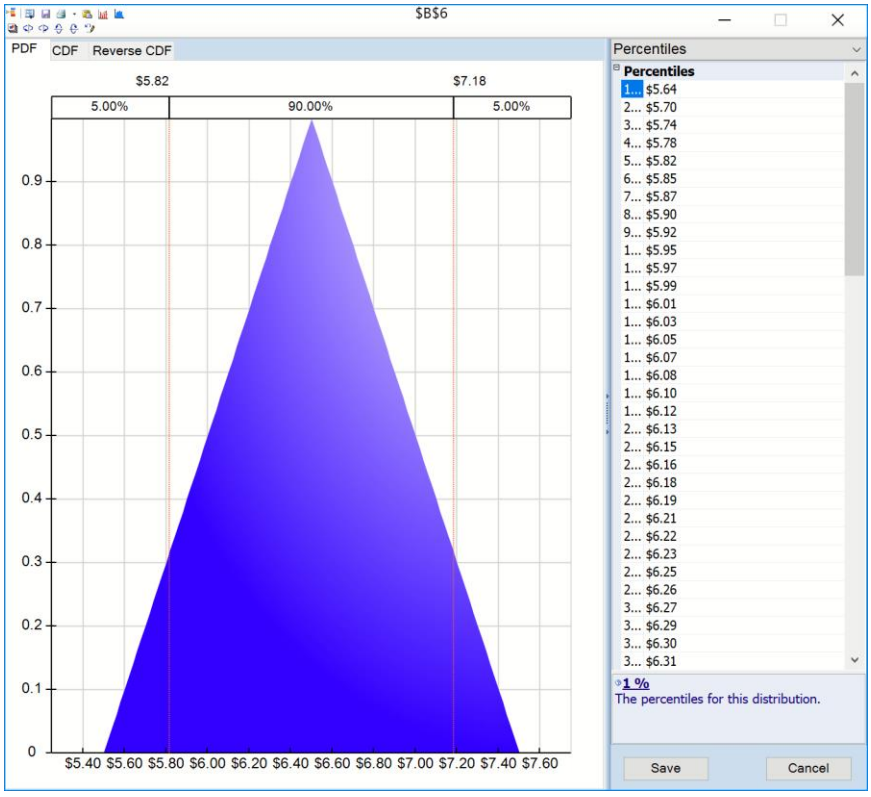


Double clicking "BusinessForecastPsi!B6" in Analytic Solver Cloud will open the uncertain function dialog, as shown below.



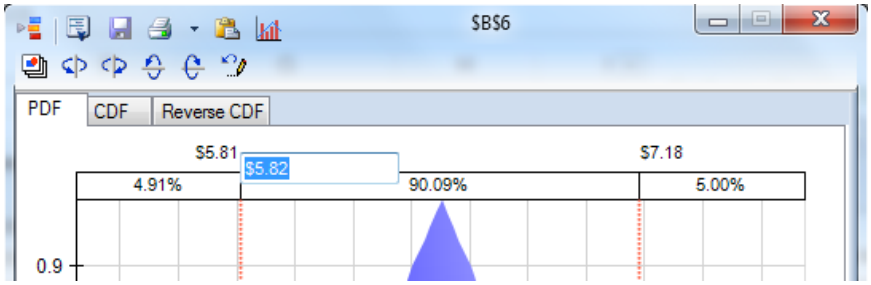
If you select Percentiles from the drop down menu on the top right, you'll notice that the the vertical red lines displayed on the chart denote the 5% and the 95% percentiles values of 5.82 and 7.18, respectively.





Each of the 5 values at the top of the chart can be edited in Analytic Solver Desktop. For example, the red lines can be moved to the left or right until the

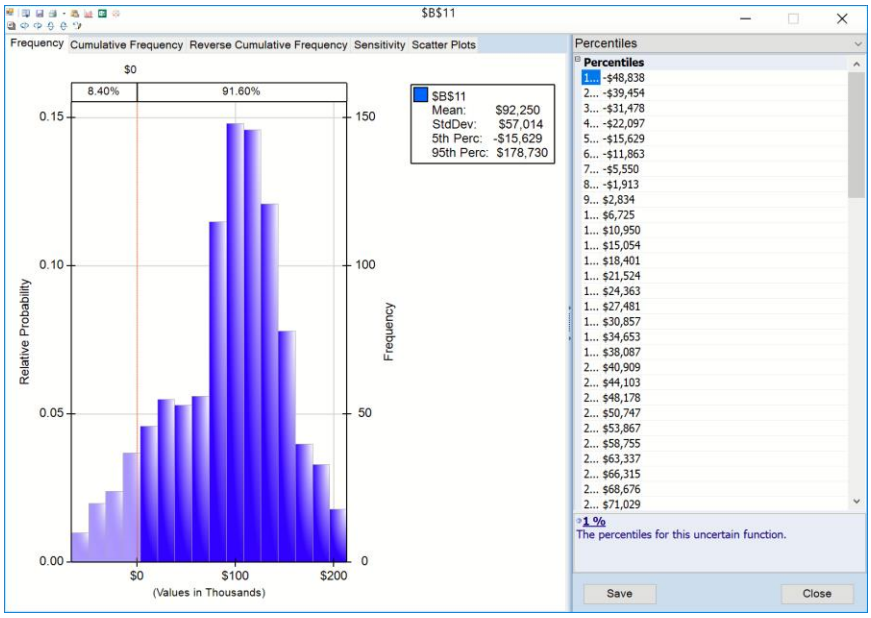
desired percentile is achieved, or you can directly edit the percentile or the percentile's value by clicking the value to be changed. Note: This functionality is not supported in Analytic Solver Cloud or AnalyticSolver.com. The red lines denoting the 5th and 95th percentiles are both stationary in these products.



If you close the uncertain variable dialog for cell B6, (by clicking the X in the top right corner) you will see that cell B12 displays the ***true average*** for Net Profit across these trials – as shown below.

	A	B	C	D	E
1					
2	**Financial Forecast**				
3				**Sales Scenarios**	**Volume**
4	Sales Volume	100,000			
5	Selling Price	$8.00		Hot Market	100,000
6	Unit cost	$6.42		OK Market	75,000
7	Fixed Costs	$120,000		Slow Market	50,000
8					
9		1		**Cost Scenarios**	
10					
11	Net Profit	$37,918		Minimum Cost	$5.50
12	True Average	$92,250		Most Likely Cost	$6.50
13				Maximum Cost	$7.50
14					

The result of "shaking the ladder" is striking: Our ***true average*** Net Profit for these 1,000 trials is $92,250 – quite a bit less than the "Flawed Average" Model figure of $117,750! And we also see that we can **lose money**. Notice that the first eight percentiles are negative in the screenshot below.

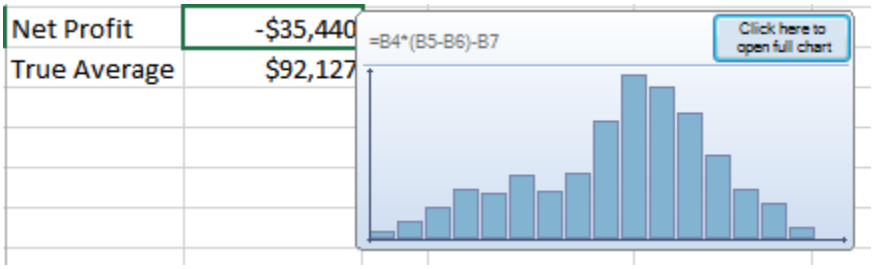


In Analytic Solver Desktop you can try pressing F9 (the Excel recalculate key) on this model: Each time you do, another 1,000 Monte Carlo trials are run, and a slightly different true average Net Profit figure will be displayed – but normally much less than $117,750.

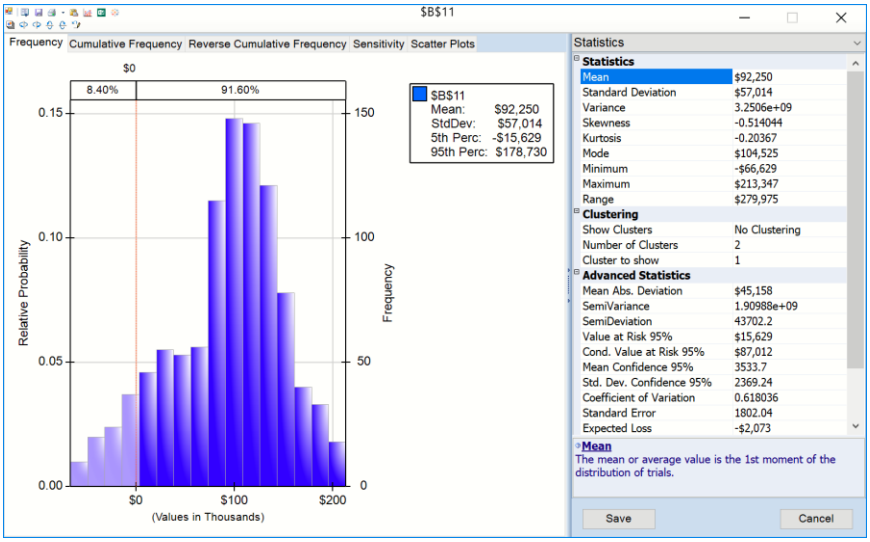
Interactive Simulation in Desktop Solver

We've just seen that the mean or 'True Average' Net Profit, over 1,000 different simulated outcomes, is less than we expected from our naïve "Flawed Average" model. We've also seen that in some outcomes, our Net Profit is actually a loss. A quick look at the dropdown galleries for **Results – Statistic**, **Measure** and **Range** on the Ribbon suggests that we can easily compute and view many other statistics about Net Profit. But we'd really like to see the *full range of outcomes* in this model. This is *very* easy to do in *Analytic Solver Desktop* using Interactive Simulation. Note: Interactive Simulation is not supported in Analytic Solver Cloud or AnalyticSolver.com.

With Interactive Simulation turned on, simply **move the mouse pointer to B11** and wait about 1 second. A ***miniature***, ***live*** frequency distribution chart of the simulation trial values for cell B11 appears automatically:

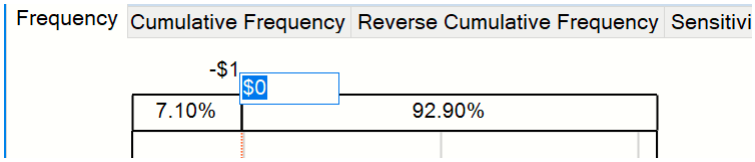


To see and do more, just **double-click on B11**, the output cell calculating Net Profit, to display the same frequency chart that was automatically opened after our first simulation run.

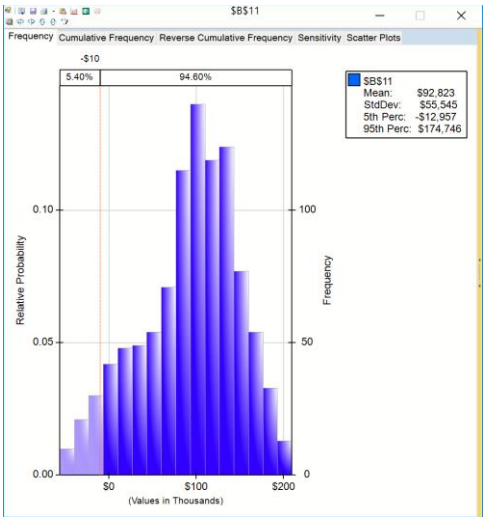


Viewing the Full Range of Profit Outcomes

We see immediately that in some outcomes, we can lose of lot of money – over $60,000! We also see that we make a profit in *most* outcomes – but how many exactly? Analytic Solver automatically sets a **Lower-Cutoff** of "0" in the Frequency chart by displaying a vertical red bar. The probabilities are automatically shown above the chart. In this case there is an 8.4% chance of a loss and a 91.60% chance of a profit. In Analytic Solver Desktop, the lower cutoff can be changed by clicking the $0 at the top of the chart. The percentile values can be edited in the same way.

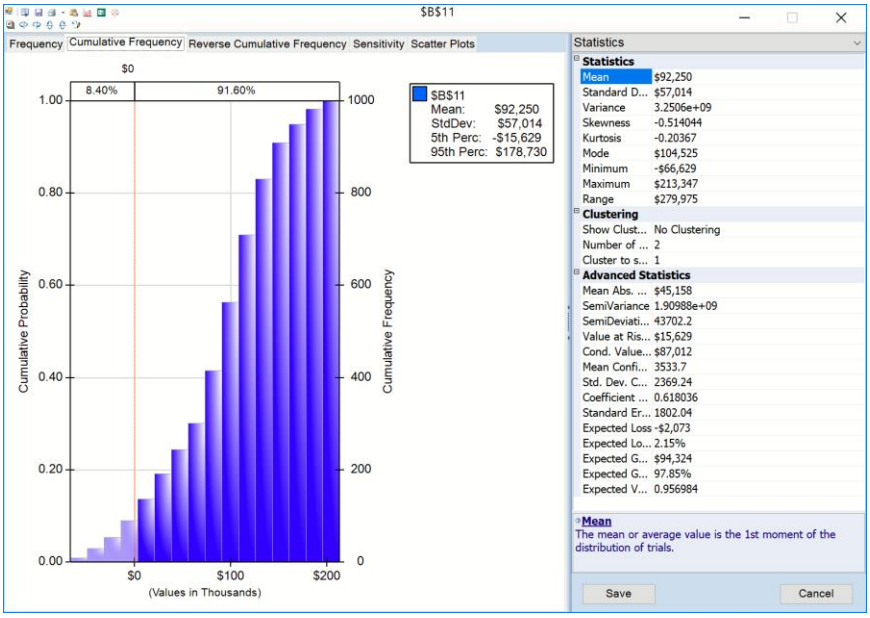


Note: If you change the lower cutoff from 0 to -10, you'll notice the red vertical line denoting the lower cutoff of $0 has now moved to -$10 and the percentile values have also changed accordingly. Percentile values can be edited in the same way or by simply moving the red vertical line to the left or right.

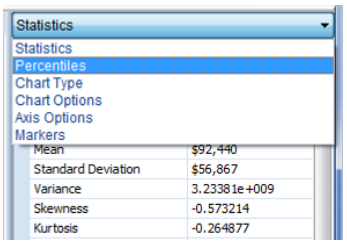


Looking at the right panel you can see the Statistics view, which includes summary statistics for the full range of Net Profit outcomes. We can see that the worst case outcome (Minimum) of this simulation was -$66,629, and the best case outcome (Maximum) was +$213,347. Value at Risk 95% shows that we have a 5% chance of making $15,629 or less. The Conditional Value at Risk 95% value indicates that the average profit we will see (up to the 95% percentile) is $87,012.

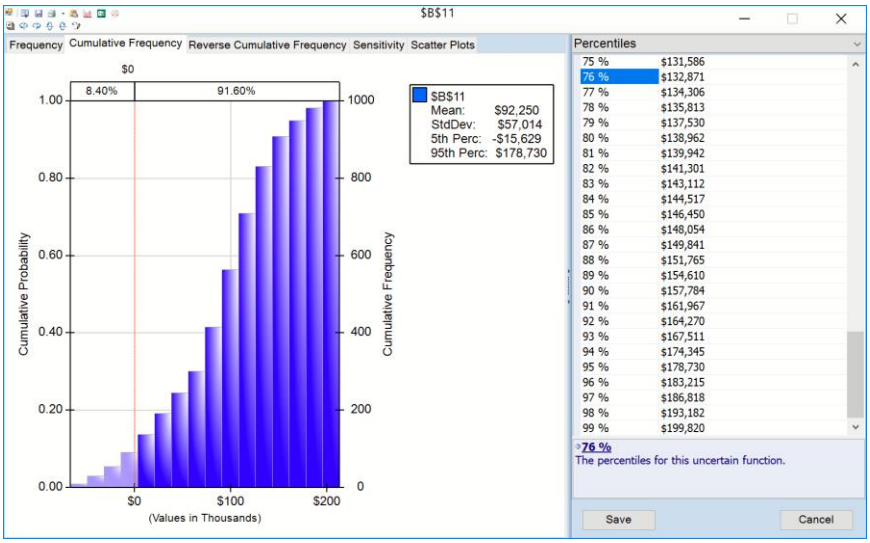
Another view of the full range of outcomes is shown on the Cumulative Frequency tab.



Click on the Statistics drop down at the top of the right panel and choose Percentiles from the list.



The Percentiles tab shows the same information as the Cumulative Frequency tab, but in numeric form. Below, we've shown the 75th through 99th percentiles:



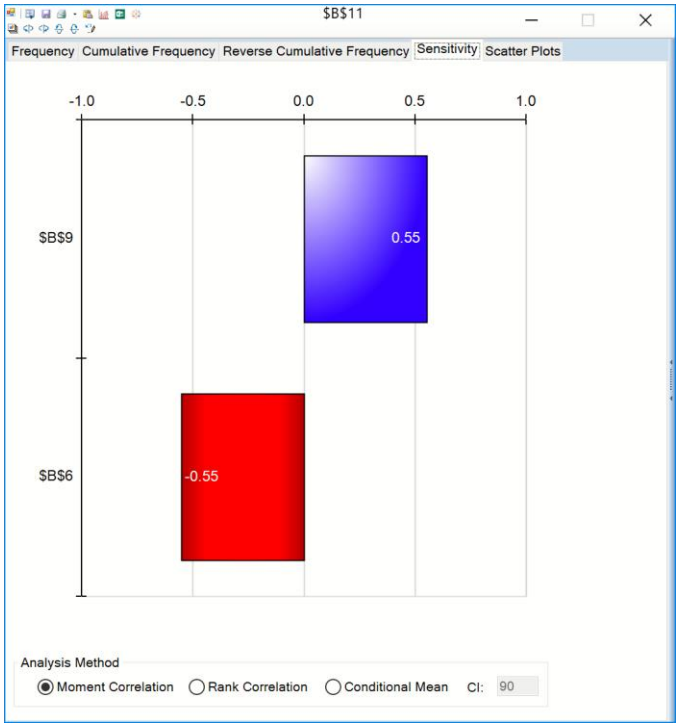
Note that you can close and open the right hand panel simply by clicking on the two arrows on the vertical bar between the chart and the right hand panel.

Analyzing Factors Influencing Net Profit

Other tabs on the Uncertain Function dialog can help us understand how the uncertain variables in our model influence our Net Profit.

Sensitivity Tab

The **Sensitivity tab** displays a "Tornado chart" that shows you how much Net Profit changes with a change in the uncertain variables – the Triangular distribution for Unit Cost at cell B6, and the integer uniform distribution at cell B9. In this model there are only two uncertain variables, but in a large model with many such variables, it's usually not obvious which ones have the greatest impact on outcomes such as Net Profit. A Tornado chart highlights the key variables: B6 has a negative correlation with Net Profit, whereas B9 has a positive correlation.



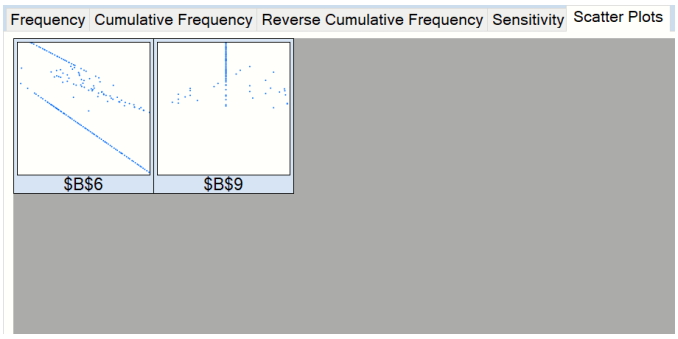
The fact that Net Profit goes down as our Unit Cost at B6 goes up is expected. But why does Net Profit go up as cell B9 goes up? Note that B9 = 1 corresponds to the Hot market scenario, 2 corresponds to the OK market, and 3 corresponds to the Slow market scenario. The fact that B9 is positively correlated with Net Profit is telling us that we make *higher* profits when the market is *slow*, not when it's hot. Our typical Selling Price is lower when the market is hot, and the increased Sales Volume doesn't make up for this.

Scatter Plots Tab

The **Scatter Plots tab**, shown on the next page, gives us a different view of the relationship of Net Profit to our uncertain variables: Unit Cost at cell B6, and the integer uniform distribution at cell B9.

Notice that the scatter plot against Unit Cost has three downward-sloping lines: Each line corresponds to a different market scenario (Hot, OK or Slow), and shows that as Unit Cost rises, our Net Profit drops – dropping fastest in the Hot Market scenario, because our profit margin is so narrow.

The scatter plot against the integer uniform distribution shows three high-low ranges for Net Profit, again corresponding to a different market scenario – Hot, OK, or Slow. We see again that the range of Net Profit is lowest in the Hot Market scenario.

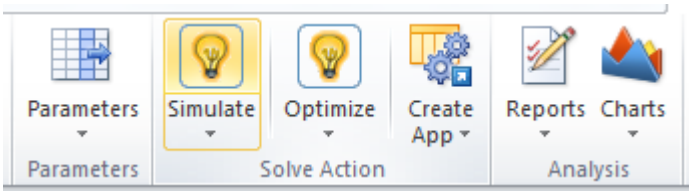


Interactive Simulation with Charts and Graphs

With an old-fashioned simulation software package, you'd press a button to start a simulation, then perhaps get a cup of coffee. Because simulations ran slowly, software packages were designed for "batch" operation: You'd spend time getting everything set up just right, run a simulation and wait (sometimes quite a while), then spend time analyzing the results. But with Analytic Solver, simulations run so fast that *fully Interactive Simulation* is practical.

Now 1,000 Monte Carlo simulation trials (the default number) will be executed *each time we change the spreadsheet*. Since there is one uncertain function, and this is the first time a simulation has been performed, the following dialog opens. Subsequent simulations will not produce this report. However, it is possible to reopen this frequency chart simply by double clicking cell B11. (See below for more information on this chart.)

To turn on **Interactive Simulation**, simply click the **light bulb** on the Ribbon. It will "light up," as shown below.



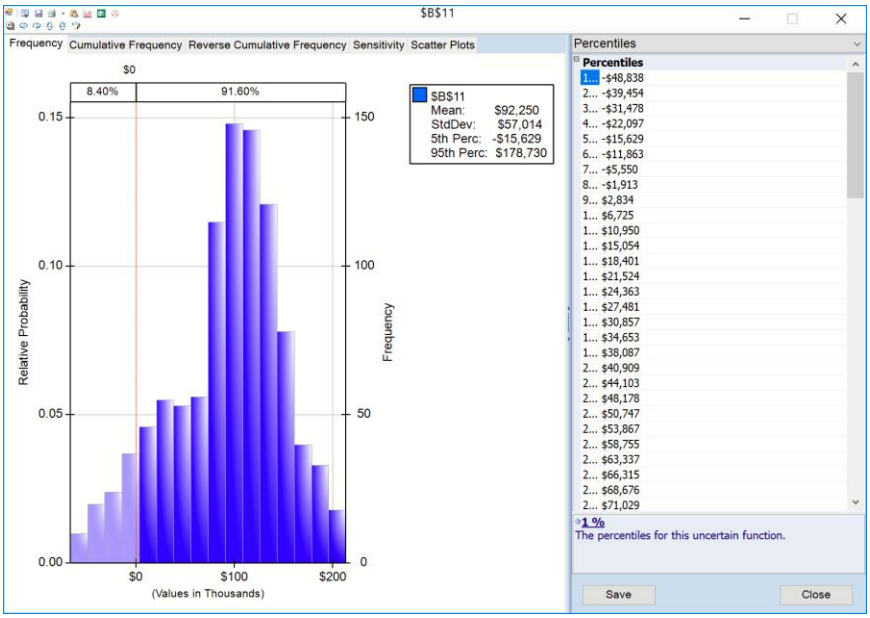
Interactive Simulation makes Analytic Solver Simulation fundamentally different from other Monte Carlo simulation tools for Excel. The kinds of charts we've just seen can be produced by other tools, but only *at the end* of a "simulation run." In contrast, Analytic Solver makes these charts ***live as you play what-if*** with your model.

After seeing this model, your production manager might think of a way to reduce the maximum Unit Cost to $7.00 instead of $7.50. What would be the impact of this change on Net Profit, over the *full range outcomes*? With Analytic Solver Comprehensive or Analytic Solver Simulation, this is as easy as any other 'what-if' question in Excel:

Click the Frequency tab to re-display the frequency chart of outcomes for cell B11. Then simply change the number in cell E13 from 7.50 to 7. ***Immediately***, a thousand Monte Carlo trials are performed, and the chart is updated. The effect is striking: We have a 97.7% chance of making a profit, and – checking the Percentiles tab – we see that instead of a 1% chance of losing about $48,000, we have a 1% chance of losing just $5,285!

But Analytic Solver Simulation is even faster than this: Click the Options button on the Ribbon, and change the number of Monte Carlo trials from 1,000

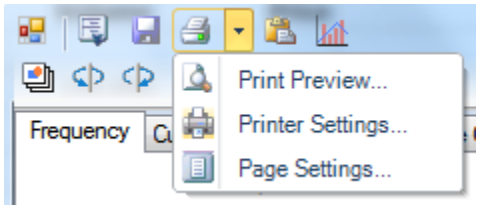
to 100,000 (or more). In a second or less on most modern PCs, ***one hundred thousand*** Monte Carlo trials are performed, and the chart is updated!



The Flawed Average model presented a limited and misleading picture of this business situation. In contrast, the Analytic Solver model has illuminated the situation considerably. We can see what can go *right*, and what can go *wrong*. We can make an informed decision about whether the reward is worth the risk. And – most important – we can interactively explore ways to *improve* the reward and *reduce* the risk. This is risk analysis at work.

Charts and Graphs for Presentations

Often, you may be called up to present your results to others. One great way to do this is in *Excel itself, live!* But at times you may need to print a chart, or copy it into a Word document or PowerPoint presentation. This is *very* easy to do in Analytic Solver Desktop, with the toolbar buttons in the title bar of the Uncertain Variable or Uncertain Function dialog. Note: This functionality is not supported in Analytic Solver Cloud or AnalyticSolver.com.

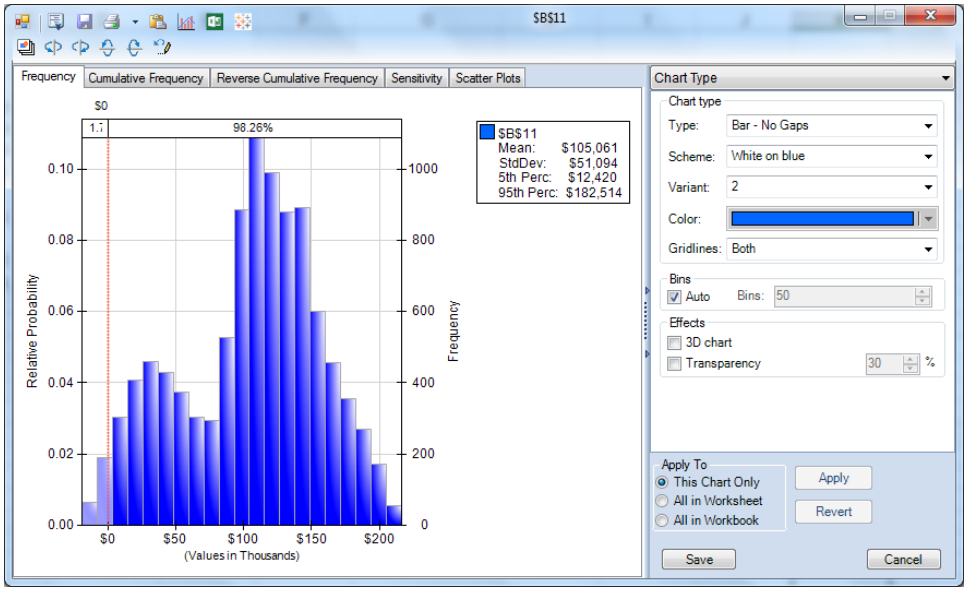


Click the **Clipboard** icon to copy the currently displayed chart to the Windows Clipboard. You can then choose Edit Paste in Word, Excel, PowerPoint and many other applications to paste the chart image into your document. (Choosing Edit Paste in Excel inserts a static, non-updating chart image in the worksheet.)

Click the **Print** icon to immediately print the currently displayed chart on your default printer, or click the down arrow next to this icon to display the menu choices shown above: Print Preview, Printer Settings and Page Settings. You

can choose a printer and set printer options, set page margins, and preview your output using these menu choices.

Analytic Solver also makes it easy to control the format of your charts. Below, we've re-opened the right hand panel and clicked on the drop down menu to choose **Chart Type**.

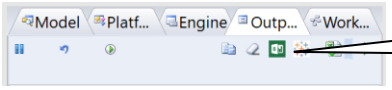


You can control the chart type, color, dimensionality and transparency, bin density, titles and legends, axis labels and number formats, horizontal axis scaling, and more. As you change chart options in the right pane, the chart is *immediately* updated so you can see the results (unlike some other simulation products for Excel). When you're satisfied with the chart format, you can save and apply it to just this chart, to all charts on this worksheet, or to all charts in the workbook when you click the Apply button at the bottom of the right pane.

Exporting Data to Microsoft's Power BI

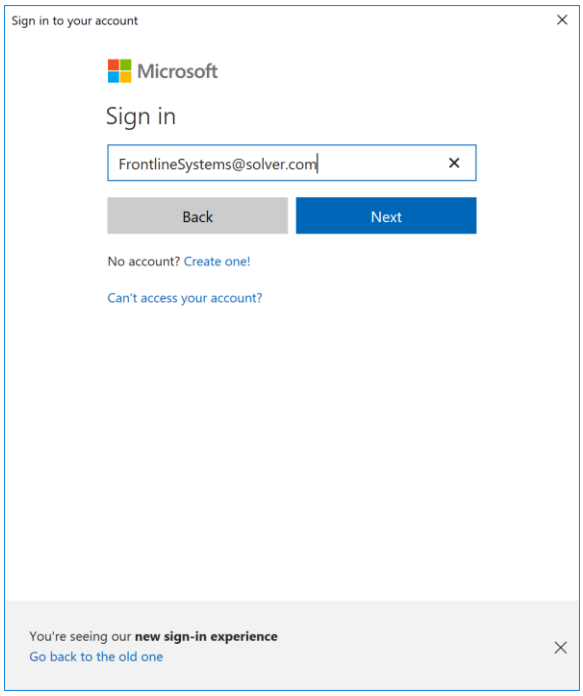
Microsoft's POWER BI, for use with Office 365, is a cloud-based service that works with Excel to help you visualize your data using various charts and reports. Analytic Solver Desktop includes the ability to export a fixed set of data from your simulation model, including all trial values, output function statistics, percentiles, etc., directly into a dataset in Power BI. This functionality is not present in Analytic Solver Cloud or AnalyticSolver.com. See the chapter, Creating Power BI Custom Visuals, that appears later on in this guide for more information on using Power BI with these two products.

Once Solver has stopped with a final result message, click the icon on the Output tab *or* on the Uncertain Function dialog to upload the model results to the Power BI dashboard. If this is the first time that the icon has been clicked within the current Excel instance, you will be asked to log in to Power BI.

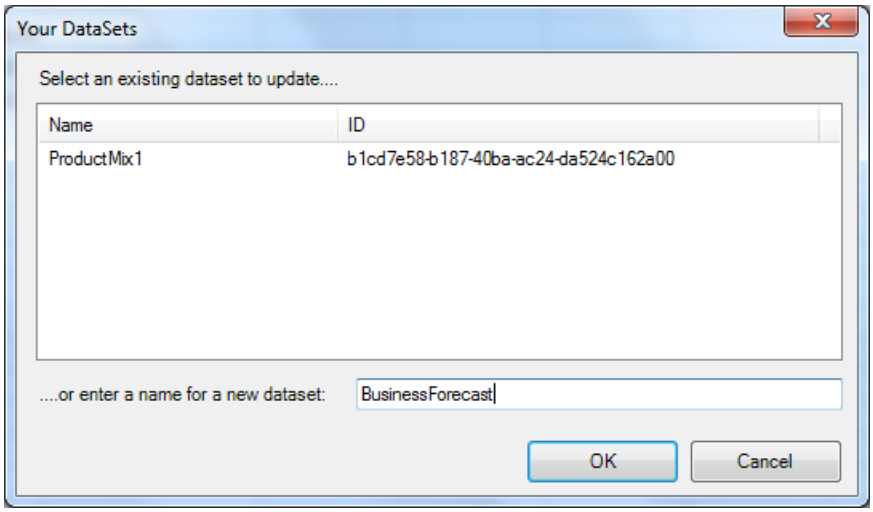


Power BI Icon as shown on the Output tab on the Solver Task Pane.

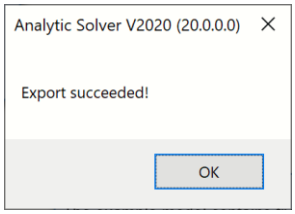
Power BI Icon as shown on the Uncertain Function dialog



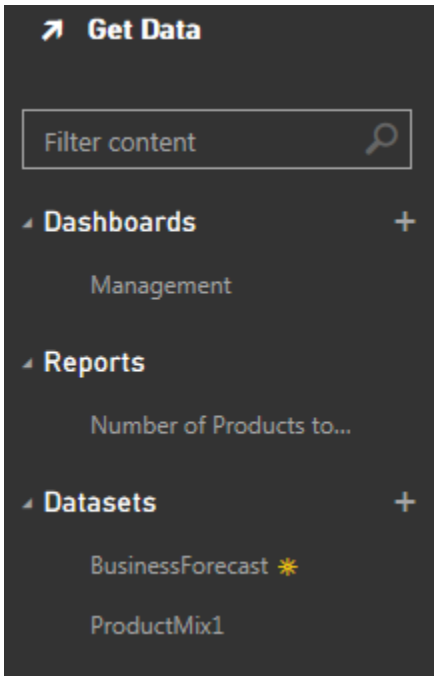
Once logged in, you will be asked to either update an existing dataset or create a new dataset.



In the screenshot above, we have created a new dataset, BusinessForecast, which will contain the uncertain variable and uncertain function trial values, statistics and percentiles, etc from our optimization model. Once the upload is complete, the following message will appear.

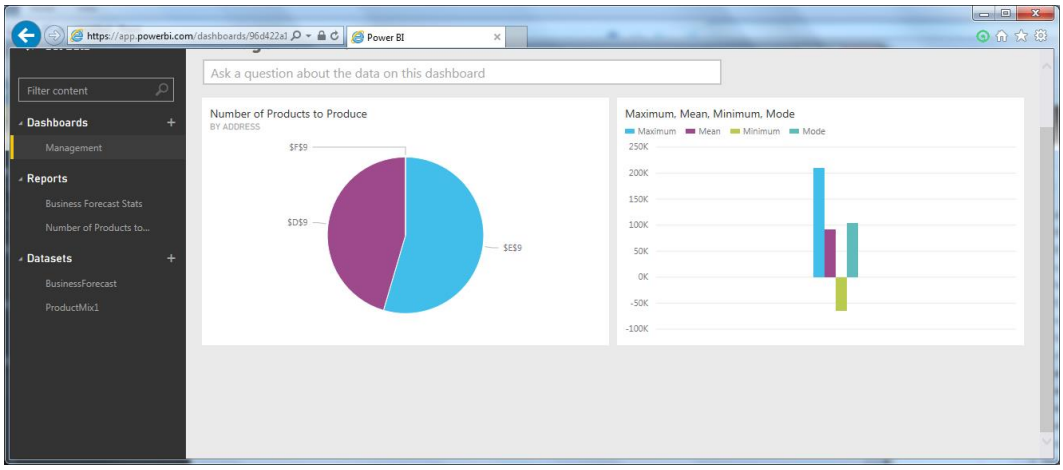


Logon to Power BI (http://powerbi.microsoft.com/). The newly created dataset will be listed under Datasets.



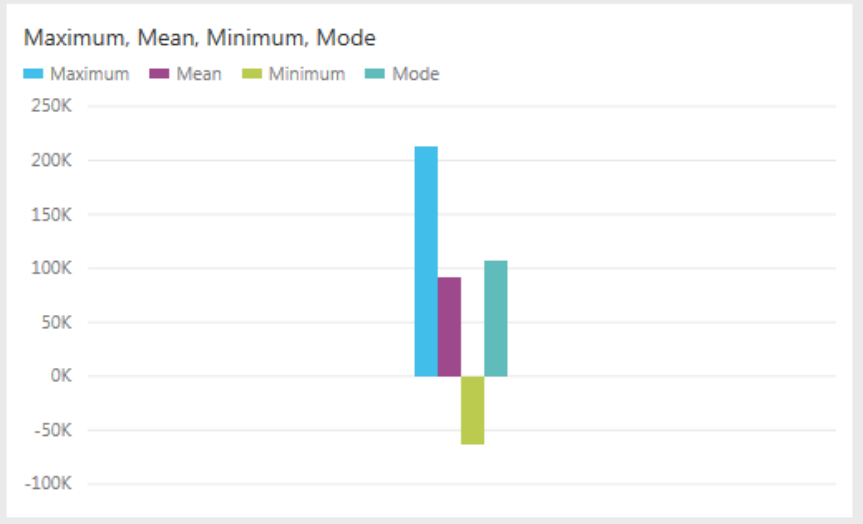
Select BusinessForecast, then determine the components to be included in the graph. In this example, we have created a bar chart by clicking (to the right of the graph) and selecting the Maximum, Mean, Minimum, and Mode Output Statistics.

Use the icon to pin this graph to the Dashboard.



Now, each time the model is solved, the results may be uploaded to your Power BI dashboard. Click back to Excel and change the Price of the Slow Market from $11 to $15, then run a 2nd simulation either by clicking the green arrow on the Model tab in the Solver Task Pane or by clicking the Simulate icon on the

Analytic Solver ribbon. Once Solver stops, click the icon on either the Output tab *or* the Uncertain function dialog to upload the most recent results. Note: We are not asked to log in to the Power BI site a second time since we are using the same instance of Excel. However, we are asked if we would like to select an existing dataset to update. Select BusinessForecast and then click OK. Click back to Power BI in your browser and refresh, the chart will update automatically with the new final statistic values, as shown below.



Exporting Data to Tableau

Tableau is a popular interactive software package that allows you to visually explore and analyze your data. Tableau can import data from a wide range of sources, including Excel workbooks, and it is often used in conjunction with Excel. Because Tableau is designed to import data in table form, it hasn't been easy to import the *results* of a simulation model (such as final values of the uncertain functions, uncertain variables, percentiles and statistic values) into

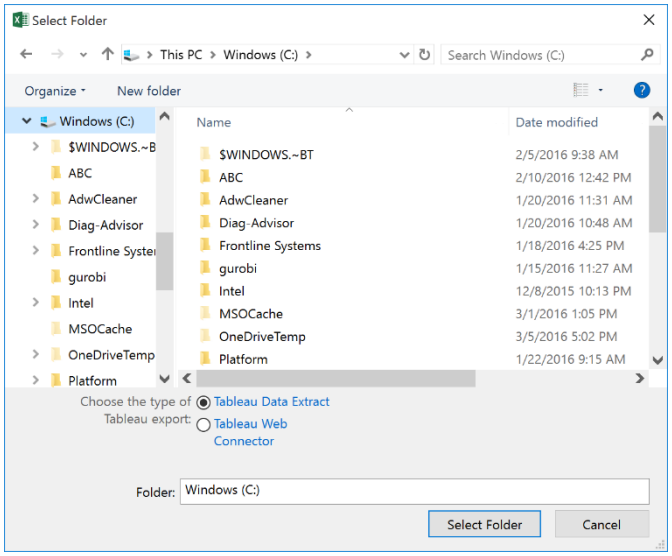
Tableau, unless those model elements occur in table form by themselves in your spreadsheet (which usually isn't the case).

Analytic Solver Desktop simplifies this process considerably. With a single click, you can convert the results of your simulation model into a set of Tableau Data Extract files (*.tde), open them directly in Tableau, and visualize them with a few clicks.

This functionality is not present in Analytic Solver Cloud or AnalyticSolver.com. See the chapter, Creating Custom Extensions in Tableau, that appears later on in this guide for more information on using Tableau with these two products.

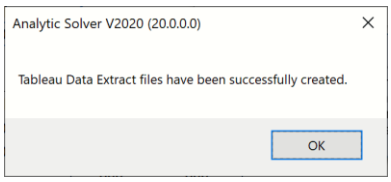
Click the green arrow on the Output tab in the Solver Task Pane to run a simulation. Once Solver has stopped with a final result message, click the icon on the Task Pane Output tab or Uncertain Function dialog to save the values for the uncertain functions, uncertain variables, percentiles and statistics to *.tde files. You will be prompted to select a folder where the Tableau files will be saved along with the type of Tableau export desired: Tableau Data Extract or (*introduced in V2016-R2*) Tableau Web Connector.

Note: If exporting to an existing .tde file, data will be appended rather than overwritten. As a result, when exporting to an existing .tde file, all data must be of the same structure as when the .tde file was first created.



If Tableau Data Extract is selected, static data is exported to files saved on your hard drive.

Once you select a folder, the .tde files will be created, and the following message will appear.



Four files will be saved in the folder you selected: InputTrials.tde, OutputStatistics.tde, OutputTrials.tde, and Percentiles.tde. (Although .tde files are designed to hold multiple tables, currently Tableau's software allows only

one table per file.) When you import this data into Tableau, InputTrials.tde and OutputTrials.tde will have one row for each trial, Percentiles.tde will have one row for percentile and OutputStatistics.tde will have one row for each output function.

- Each row of InputTrials.tde will contain the trial value for each uncertain variable and the simulation index. The number of rows will equal the number of trials.
- Each row of OutputTrials.tde will contain the trial value for each uncertain function and the simulation index. The number of rows will equal the number of trials.
- Each row of Percentiles.tde will contain the percentile value for each uncertain function and the simulation index. The number of rows will equal 99.
- Each row of OutputStatistics.tde will contain the Excel cell address where the uncertain function is located along with 9 statistical functions (mean, standard deviation, variance, kurtosis, skewness, mode, minimum, maximum, and range) and the simulation index.

Note: If exporting to an existing .tde file, data will be appended rather than overwritten. As a result, when exporting to an existing .tde file, all data must be of the same structure as when the .tde file was first created.

To open the files in Tableau, either double click each file (if using Desktop Tableau) or click **Other Files** under *Connect* and open the desired file(s).

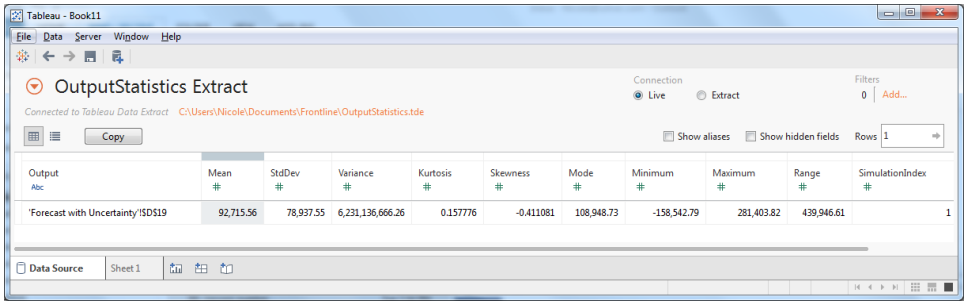
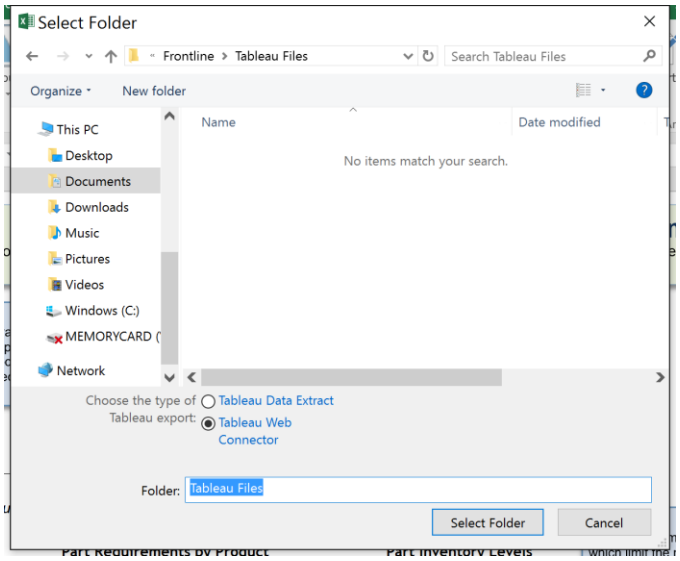


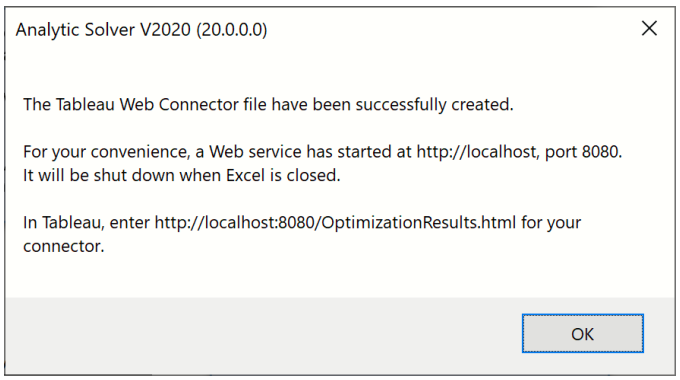
Tableau Web Connector

The Tableau Web Connector offers much more flexibility over Tableau Data Extract by allowing you to refresh your data dynamically inside of Tableau.

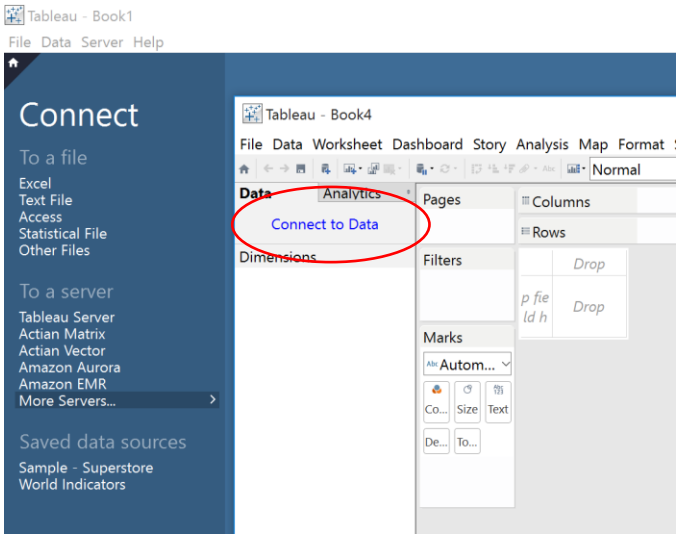


If Tableau Web Connector is selected, you will be prompted to select a folder in which to save SimulationResults.html. This file will hold all contents described above for InputTrials.tde, OutputStatistics.tde, OutputTrials.tde, and Percentiles.tde. The following message will appear.

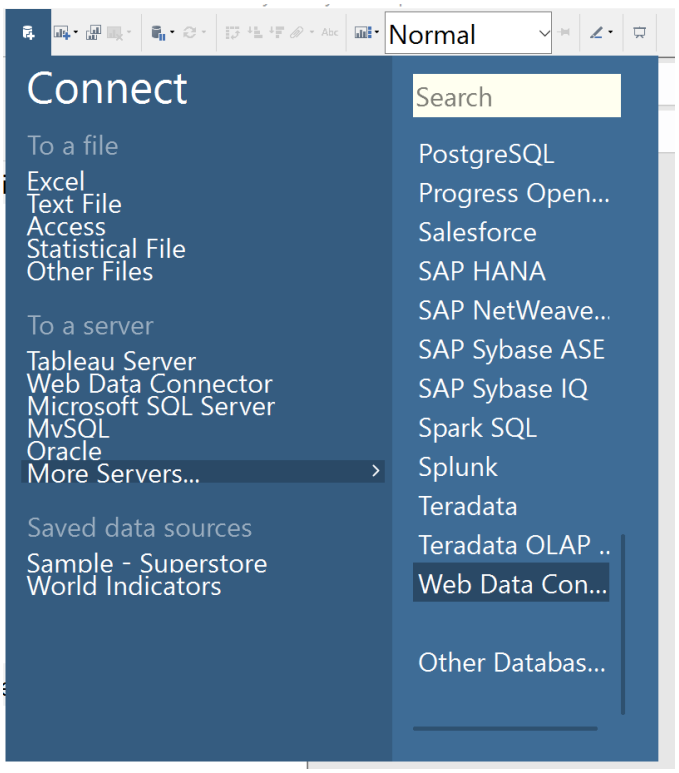
Note: If exporting to an existing .tde file, data will be appended rather than overwritten. As a result, when exporting to an existing .tde file, all data must be of the same structure as when the .tde file was first created.



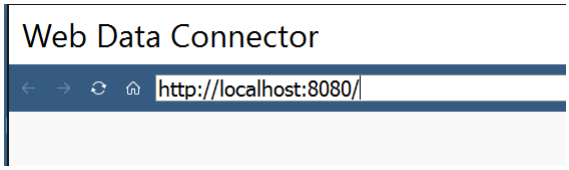
To open the files in Tableau, open a new workbook in Tableau and click **Connect to Data**.



On the Connect menu, select **More Servers – Web Data Connector**.

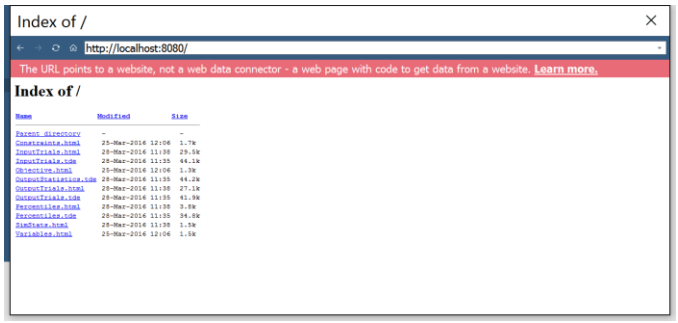


On the Web Data Connector dialog, enter the location displayed on the dialog shown above, i.e. http://localhost:8080/, and press **Enter**.

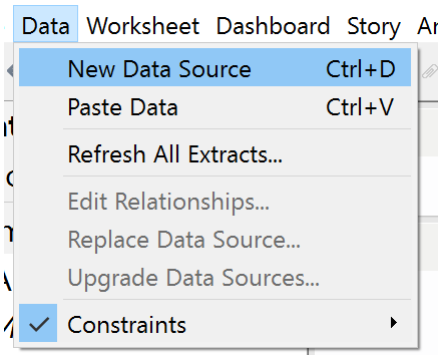


When the following dialog appears, click Constraints.html.

Note: The error highlighted in red is a simple warning that the URL is not pointing to a Tableau Web Data Connector file. If we had entered a file name, such as http://localhost:8080/InputTrials.html, the results would have immediately been uploaded to Tableau.



To add more data, click **Data – New Data Source** on the Tableau ribbon, then repeat the actions described above.



If your Solver results have changed, you'll need to refresh the results within the Tableau Web Connector HTML files. To do so:

1. In ASP, re-run your model
2. Click the Tableau icon on the Output tab in the Solver Task Pane.
3. Select **Tableau Web Connector** and the folder where the files should be saved.
4. Click **OK**.
5. In Tableau, click **Data – Refresh All Extracts** to update your data.

For more information on using Tableau, please refer to the Tableau documentation found at http://www.tableau.com/.

An Airline Revenue Management Model

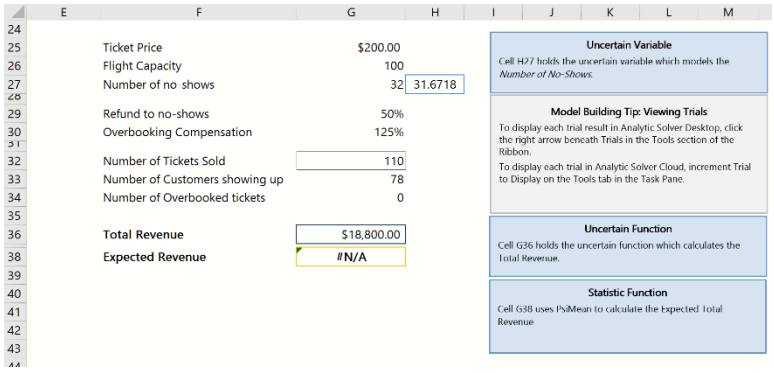
In this section, we'll explore a simple airline revenue management model, also known as a yield management model. We'll start with a simple simulation model, like the one in the previous section. But in this section, we'll see if we can answer further questions by running *multiple parameterized simulations* and by solving a *simulation optimization* model (not available in Analytic Solver Simulation).

To open this example, click **Help – Examples** on the Ribbon, which opens the workbook, Frontline Example Models Overview.xls. Click the **Simulation tab**,

then the **Yield Management Model 1** (a simple simulation model) and **Yield Management Model 2** (a model with multiple parameterized simulations) links. Click the **Simulation Optimization** tab to open **Yield Management Model 3**, a simulation optimization model. In AnalyticSolver.com, click *Help – Examples – Simulation* to open *Yield Management Model 1* and *Yield Management Model 2* and *Help – Examples – Simulation Optimization Examples* to open *Yield Management Model 3*.

A Single Simulation

The model YieldManagement1.xls opened in Analytic Solver Desktop is shown on the next page.



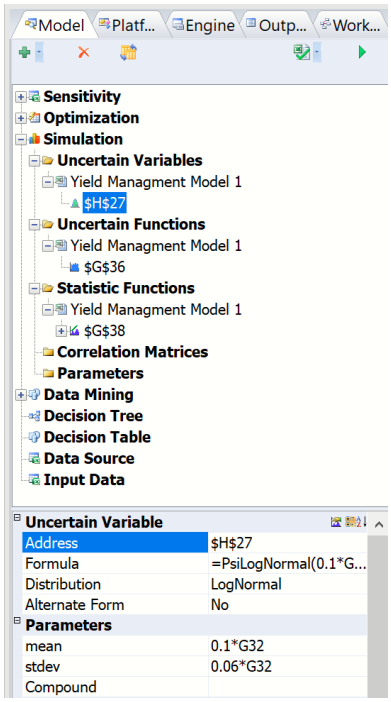
The model depicts a hypothetical airline flight from San Francisco to Seattle. The flight has 100 seats, and tickets are $200 per seat. Some passengers who purchase tickets are "no-shows" whose seats will be empty; in this example we assume that such passengers receive a refund of 50% of their purchase price.

To utilize their 'perishable inventory' of seats, the airline would like to sell more than 100 tickets for each flight. But we assume that Federal regulations require that any ticketed passenger who is unable to board the flight due to overbooking is entitled to compensation of 125% of the ticket price.

The airline would like to know how much revenue it will generate from each flight, less refunds for no-shows and compensation for 'bumped' passengers. As shown above, this total revenue amount is calculated at cell C31, for any specific number of tickets sold (110 above) and number of no-shows (6 above).

The uncertain quantity in this model is the number of no-shows; hence we should model this with an *uncertain variable*. We quickly realize that the **number of no-shows** will depend on the **number of tickets sold**. After some research, we decide that we can use a LogNormal distribution for the number of no-shows: Cell H27 contains the formula **=PsiLogNormal(0.1*G32,0.06*G32)**. Cell G27 contains =ROUND(H27,0) to ensure that the number of no-shows is an integer value – and this is used to compute Total Revenue at cell G36.

Note that the bottom area of the Task Pane is showing the properties of cell H27: for example, the *mean* of the distribution is 10% of the number of tickets sold.

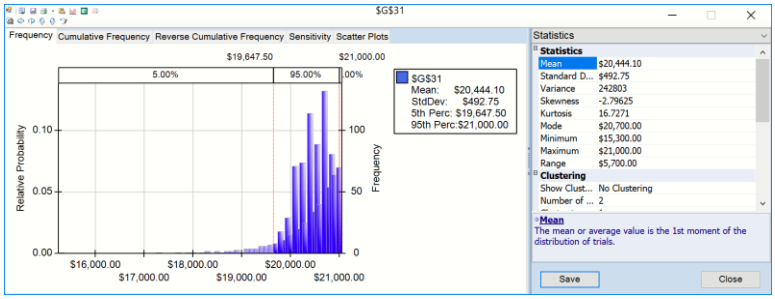


See the chapter "Mastering Simulation and Risk Analysis Concepts" for advice on choosing distributions for your uncertain variables.

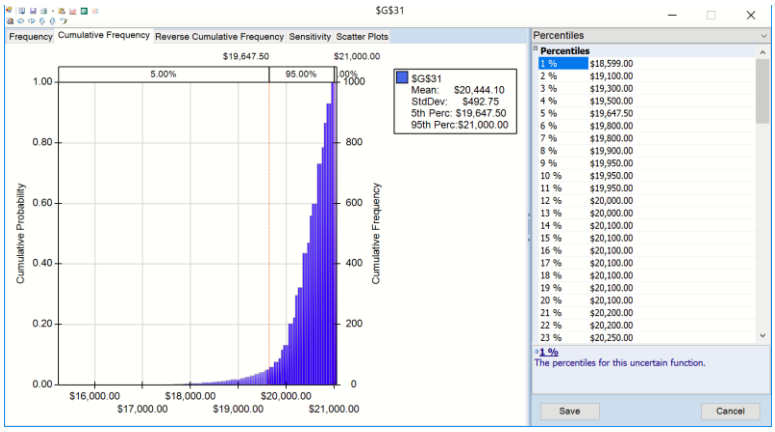
As shown in the Task Pane, cell G36 is an uncertain function; it is defined as such because cell G38 contains =PsiMean(G36) to compute the expected (or average) revenue across all Monte Carlo trials.

Performing the Simulation

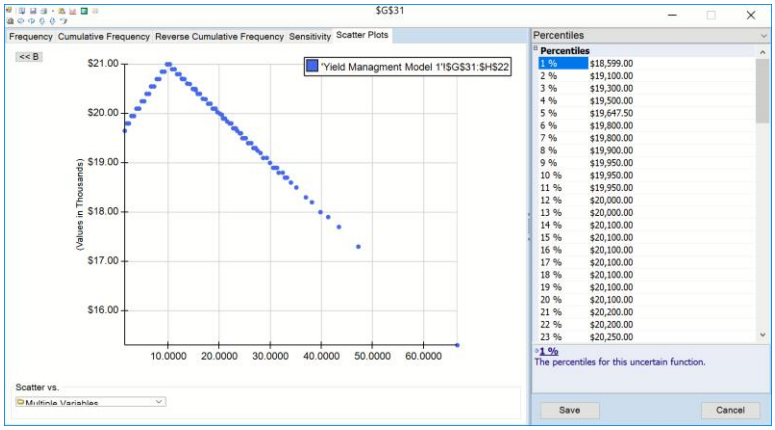
To perform a single simulation (with 1,000 Monte Carlo trials), we click the green arrow on the Model tab of the Solver Task Pane. At the end of the simulation the following dialog appears displaying the distribution of outcomes in the Uncertain Function dialog:



The right hand panel shows the statistics from cell G36. We see that the mean or expected net revenue is about $20,000. From the **Cumulative Frequency tab** over the chart or by clicking on the drop down menu in the right hand panel (currently showing "Statistics") and selecting **Percentiles**, we can see that the 10% percentile is $19,950 – if we sell 110 tickets, we'll earn approximately as much revenue as a full flight (100 seats * $200), 90% of the time. You can see why airlines find that overbooking makes sense as a policy!

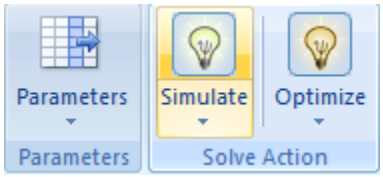


The **Scatter Plots tab** (click the graph to enlarge) shows you a quick scatter plot of this uncertain function against one or more uncertain variables, or other uncertain functions. In this example – shown on the next page – it shows a scatter plot of G36 (net revenue) against H27 (number of no-shows).



Using Interactive Simulation

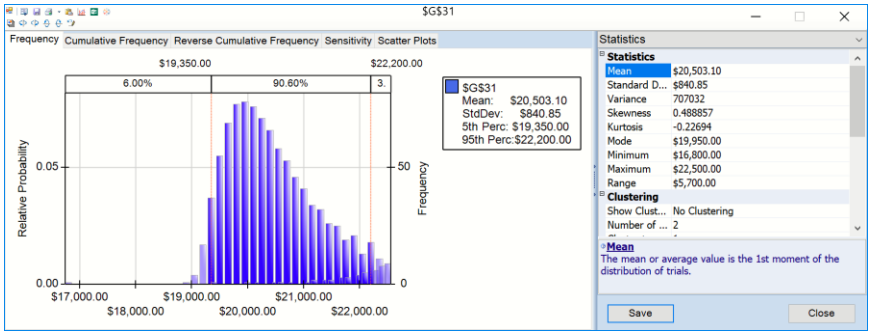
If using Analytic Solver Desktiop, we can explore the question of how many tickets to sell with Interactive Simulation: We simply click the Simulate button to "turn on the lights."



Now we can simply type a new number of Tickets Sold, such as **125**, into cell G32. Instantly, Analytic Solver (Desktop) performs a new simulation of 1,000 Monte Carlo trials, and updates the Uncertain Function dialog and the worksheet with the results – as shown on the next page.

The new distribution of outcomes is quite different – we have more high-revenue data points – but the mean or expected revenue is not so different -- $20,503. Selling 125 tickets does seem to be better than selling 110 tickets, but we're not yet sure that this is the *best* number of tickets to sell. (We'll answer that question in the next two sections.)

In the meantime, however, Interactive Simulation allows us to "play what-if" with this model, changing the parameter that we *can* control (the number of tickets sold), while properly modeling the behavior of the parameter we *cannot* control (the number of no-shows). As Prof. Sam Savage says, "Interactive Simulation does for uncertainty what the spreadsheet did for numbers."



Note: Interactive Simulation is not supported in Analytic Solver Cloud or AnalyticSolver.com. However, you can perform the same type of analysis in either product by simply running a new simulation after making the change to cell G32.

Multiple Parameterized Simulations

After playing "what-if" with Interactive Simulation, we can move to ask Analytic Solver to automate this process: Vary a parameter (the number of tickets sold) over a range, performing a simulation for each different number of tickets sold, and summarize the results.

Choose **Help – Examples** on the Ribbon, click the **Monte Carlo Simulation Examples** button, then scroll down to click the **Yield Management Model 2** link to open YieldManagement2.xlsx. In AnalyticSolver.com, click *Help – Examples – Monte Carlo Simulation Examples – Yield Management Model 2* to open YieldManagement2.xlsx

We can create YieldManagement2.xlsx from YieldManagement1.xls in just three steps:

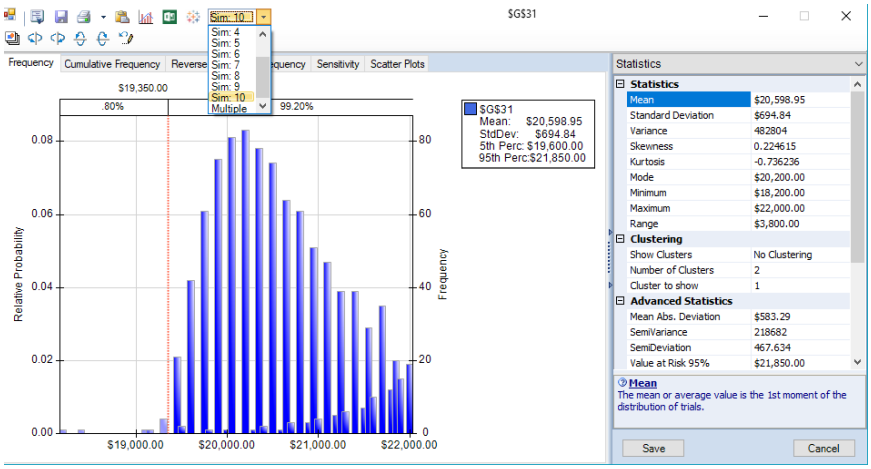
1. Select cell G32, choose **Parameters – Simulation** from the Ribbon, and enter a lower limit of 102 and upper limit of 120 in the dialog. This creates a formula =PsiSimParam(102,120) in cell G32.
2. In the Task Pane Platform tab Simulation group, set the **Number of Simulations** to 10 (the maximum number of simulations allowed by Analytic Solver *Basic*). Cell G32 will take on the value 102 on the first simulation, 104 on the second simulation, 106 on the third simulation and so on, through 120 on the 10th simulation.
3. Select cell G36, choose **Results – Statistic – Mean**, and select a *range* of 10 cells, say G40:G50. Analytic Solver will place =PsiMean(G36,1) in the first cell, =PsiMean(G36,2) in the second cell, and so on for as many cells as you specify.

Now, when you run a simulation either by clicking the **green arrow** on the Model task pane or by using the **Simulate** icon on the Ribbon, Analytic Solver will perform 10 simulations, each with 1,000 Monte Carlo trials, and give you access to *all* of the results. On the worksheet, you'll see the expected revenue

for 100, 102, …, 120 tickets sold. And you can use the Uncertain Function dialog to display the full distribution of outcomes for any of the 10 simulations.

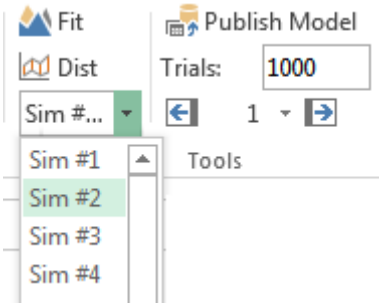
Examining Results Across Simulations

Once the simulation finishes, the uncertain function dialog for cell G36 will open automatically or you can double-click the cell to open.



The dialog now includes a dropdown list that allows you to select a simulation to display. You can examine the Frequency, Cumulative Frequency, Reverse Cumulative Frequency, Sensitivity, or Scatter Plots tabs for any simulation.

The worksheet will initially display values for the last Monte Carlo trial of the last simulation performed (except for the cells containing PSI Statistics function calls such as PsiMean()). But you can display any trial from any simulation, by changing the selections in the Sim # and Trial # controls on the Ribbon:

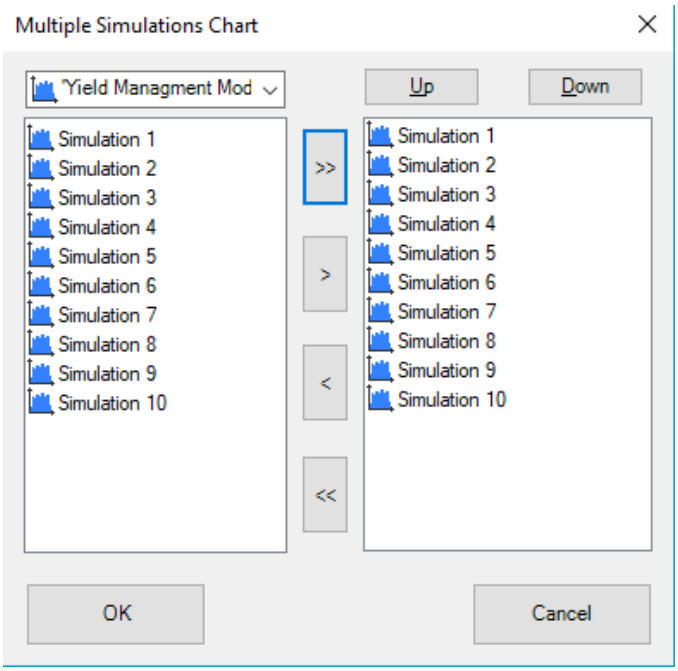


By examining this data, you can get a better idea of how many tickets to sell. But Analytic Solver can help your further.

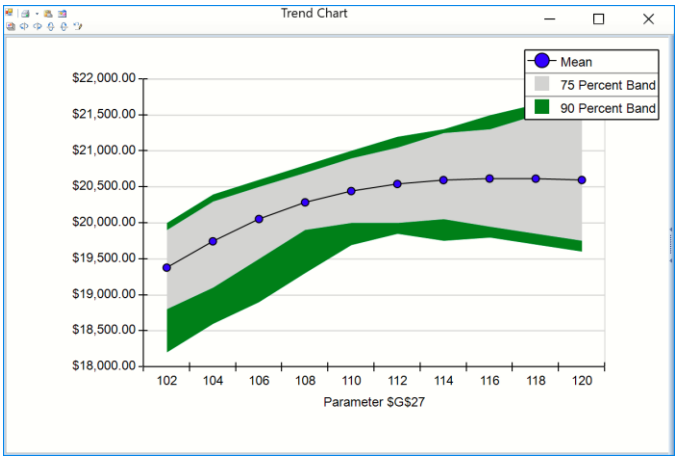
Reports and Charts of Multiple Simulations

Analytic Solver Comprehensive and Analytic Solver Optimization with Analytic Solver Simulation, in Analytic Solver Desktop or Analytic Solver Cloud, has rich facilities for reports and charts across multiple simulations. We'll cover just two chart examples; see the Frontline Solvers Reference Guide for further information.

First, select **Charts – Multiple Simulations – Trend** from the Ribbon. Analytic Solver displays a dialog where you can select one or more simulations to include in the chart. Click the >> button to select all 10 simulations:

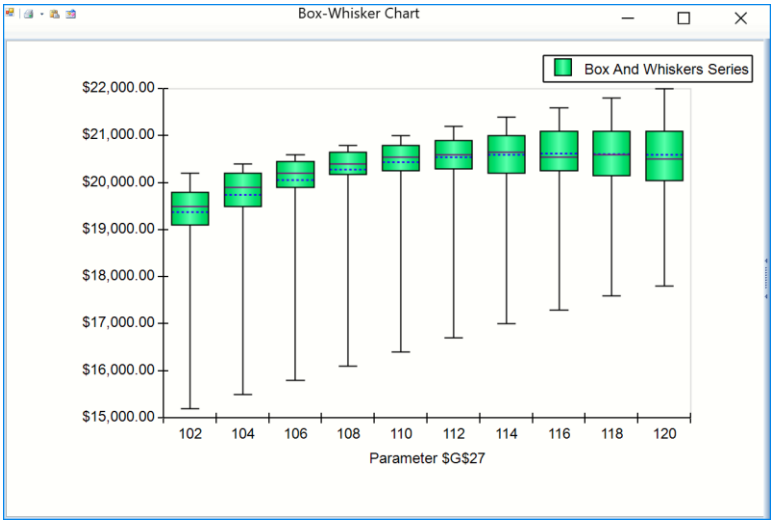


Analytic Solver then draws the Trend Chart:



The number of tickets sold is on the horizontal axis. Analytic Solver shows the mean, 25th and 75th percentile, and 10th and 90th percentile values of net revenue at G36 (this was the only choice in the dropdown list at the top left of the Multiple Simulations dialog). We can see that the mean or expected net revenue peaks at about 116 or 177 tickets sold.

For another view of this information, select **Charts – Multiple Simulations – Box-Whisker** from the Ribbon, and again select all 10 simulations to be included in the chart. Analytic Solver Comprehensive draws the following chart:



This shows a Box-Whisker diagram for each of the 10 simulations, with the mean, median, 25th and 75th percentiles, and the minimum and maximum value for net revenue on each one. In Analytic Solver Desktop, you can click the right edge of the Trend and Box-Whisker charts to open a right panel with options for customizing these charts. You can use the icons on the title toolbar to print the chart, or copy it to the Clipboard, where it can be pasted into another application such as PowerPoint.

Simulation Optimization

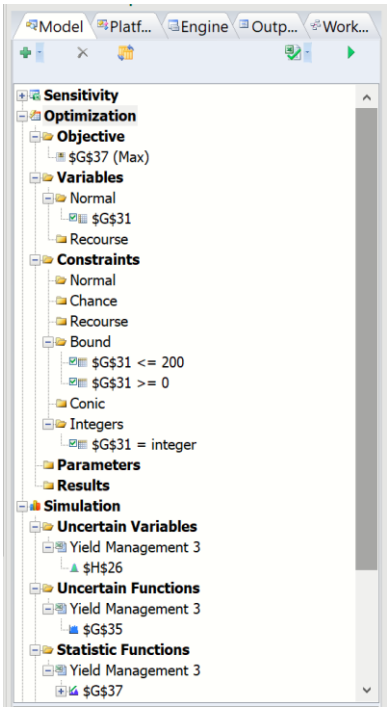
Running multiple parameterized simulations and examining the results on the worksheet and in chart form, has given us a good deal of intuition about the behavior of this simulation model. But Analytic Solver can *directly* answer the question "How many tickets should we sell to realize the *maximum expected* net revenue?"

You can see this by choosing **Help – Examples** on the Ribbon, then clicking the Simulation Optimimization button. Click the link to **Yield Management Model 3** in the list of example workbooks. This example will create YieldManagement3.xlsx from the existing YieldManagement1.xls, used in the previous two examples, in just five steps:

1. Select cell G32 and click **Decisions** on the Ribbon. This makes the number of tickets sold a decision variable for optimization. Alternatively, click the down arrow under Decisions, then select Normal to make the number of tickets sold a decision variable.
2. With G32 still selected, click the down arrow under **Constraints**, then choose **Variable Type/Bound – Integer** from the menu. This specifies that G32 must have an integer value at the optimal solution.
3. With G32 still selected, click the down arrow under **Constraints**, then choose **Variable Type/Bound – <=** from the menu, and enter 200 for the constraint left hand side. This specifies that G32 must have an upper bound of 200.
4. With G32 still selected, click the down arrow under **Constraints**, then choose **Variable Type/Bound – <=** from the menu, and enter 0 for the constraint left hand side. This specifies that G32 must have lower bound of 0.

5. Select cell G38, click the down arrow under **Objective**, then choose **Max – Normal** from the menu. The optimizer will maximize G38: = PsiMean(G31), the expected value of net revenue.

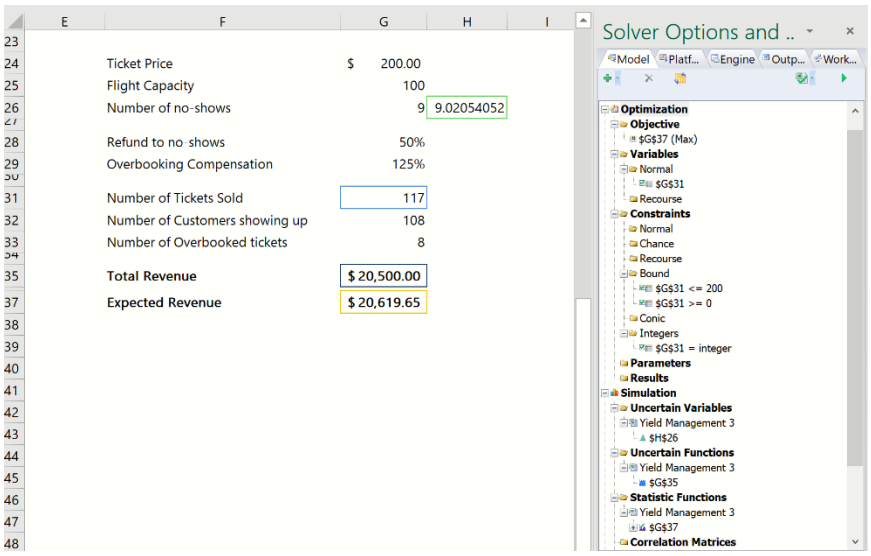
The model in Task Pane will now look like the one pictured below.



In YieldManagement3.xls, we've made just these selections, and we've also chosen the GRG Nonlinear Solver from the dropdown list on the Engine tab, to solve the problem. (Other choices are possible, but this one is simplest for this example problem.)

Now we can simply click the **green arrow** on the Task Pane. After a moment of solving, Analytic Solver returns the solution of 116 or 117 tickets sold appears in G32 (the exact number depends on the simulation Random Seed), and the expected value of net revenue for this number of tickets appears at G32 (about $20,500). "Solver found a solution. All constraints and optimality conditions are satisfied" appears in green in the Output tab of the Task Pane, as shown on the next page.

Note that this required less than a page to explain how you can get answers to questions like "How many tickets should we sell to realize the *maximum expected* net revenue?"



Using a Compound Distribution

Starting with V2016-R2, Analytic Solver Comprehensive and Analytic Solver Simulation within Analytic Solver Desktop include the ability to sum multiple independent random variables using a compound distribution. A compound distribution generates values for the sum of N independent identically distributed uncertain variables. Note: This functionality is not included in Analytic Solver Cloud or AnalyticSolver.com.

There are many common applications for compound distributions in industries across the board. For example, in the insurance industry, compound distributions may be used to estimate the amount of claim payouts to customers or a portfolio of policies over a period of time. In healthcare, compound distributions can be utilized for many reasons including to estimate the total amount of demand for a specific drug over a period of time, the number of days a patient will spend in hospital or to estimate the total amount of exposure to a certain toxin (i.e., radiation or radon) that a group of people might encounter in their lifetime. In addition, compound distributions are used in the food industry to estimate the total number of patients that will become sick due to a food-borne illness.

The incorrect implementation of creating a compound distribution manually is a primary cause of errors in a simulation model. In an effort to reduce these errors, Frontline Systems has implemented compound distributions with the introduction of a single property, PsiCompound(). This property supports any existing Psi Distribution function except the Psi multi-variate functions (PsiMVLogNormal, PsiMVNormal, PsiMVResample, and PsiMVShuffle), PsiSip, and PsiSlurp. PsiCompound is amended to a Psi Distribution, i.e., PsiBeta(3,2, PsiCompound(100)) The signature of this property is:

```
PsiCompound(number_cell, deduction, limit)
```

A compound distribution is made up of a "severity" distribution and a "frequency" distribution. Assume the following compound distribution, =PsiBeta(3, 2, PsiCompound(A2)), where A2 = PsiPoisson(100). PsiBeta(3,2)

is referred to as the "severity" distribution. The severity distribution is the distribution to be added N times. PsiPoisson(100) is referred to as the "frequency" distribution. The frequency distribution determines the size N of the sum (i.e, how many PsiBeta to sum). N can be a constant but can also be computed at each trial by drawing from a discrete distribution.

- The **number_cell** argument passes the number of random trial values to be summed. Number_cell can be an integer, a cell containing an integer, a formula evaluating to an integer, or a cell containing a discrete distribution.

  If a fractional value is passed directly or indirectly (by using a formula) or a continuous distribution is passed to this argument, the result will be rounded down to the nearest integer.

  Note: If a discrete distribution is passed to the number_cell argument, the frequency distribution must be formulated in such a way that the trial values generated by the distribution must be greater than 1. If not, trial values < 1 will be set equal to 1.

- The value passed to the **deduction** argument is subtracted from every term of the compound sum which results in a shift of the compound distribution by -N * *deduction*.

- If a trial value is larger than a specified **limit**, then the trial value is reset to the limit.

Depending on what is passed to the number_cell argument, PsiCompound() automatically selects from several different compounding methods.

- First, ASP tries to compute the distribution analytically. For example "=PsiExponential(par, PsiCompund(N))" can be computed as PsiGamma(N, par). Analytic Solver can immediately sample from this "shortcut" distribution.

- If Analytic Solver is unable to compute a compound distribution analytically, but the frequency of the severity function (N) is greater than the value for the CLT Threshold option, then the distribution will be computed according to the Central Limit Theorem as PsiNormal(m, s). The parameters m and s will be computed analytically from the corresponding analytical moments of the severity distribution. The maximum value allowed for the CLT Threshold option is 1000 while the minimum value allowed is 1. The default setting is 100.

- Otherwise, the compound distribution will be computed using Monte Carlo simulation to sum up N independent variates of the severity distribution.

The following examples illustrate how to use the PsiCompound() property when a discrete distribution or a constant value is passed to the number_cell argument

Discrete Distribution passed to 1st Argument

Imagine an insurance policy has two basic classes of insured members, class A and class B; there are 50 class A members and 10 class B members. The number of claims from class A members follows a Negative Binomial distribution with parameters (5, 0.25), and the number of claims from class B members follows a geometric distribution with parameter 0.25. The size of a claim from class A members follows an exponential distribution with mean $40,000, and the claim size from class B members is distributed with a Pearson 5 distribution with parameters (10, 2000000). In other words, if there are six Class A claims, the size of the payout for each of the six claims will follow the PsiExponential(40000) distribution. Calculate the expected claim payment for both classes.

1. Let's start by formulating the compound distribution for the Class A members. Recall that the number of Class A claims follows a Negative Binomial distribution using a success parameter = 5 and probability parameter = 0.25 while the size of a Class A claim follows an exponential distribution with mean $40,000.

   In this example, PsiExponential(40000) is the severity distribution. This is the distribution that will be added together. If there are six claims, then PsiExponential(40000) will be compounded six times. The frequency distribution is the number of Class A claims, =PsiNegBinomial(5, 0.25, PsiTruncate(0, 50)).

   Note: Since there are 50 class A members, the PsiTruncate property is used to ensure that sample values *always* lie within the range from 0 to 50.

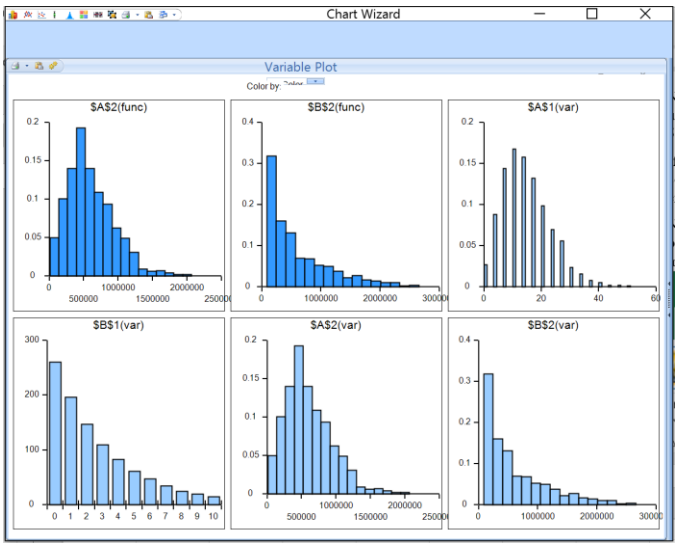
   If A1 = PsiNegBinomial(5, 0.25, PsiTruncate(0, 50), the full compounding formula for the amount paid to Class A claims can be entered into cell A2 as "=PsiExponential(40000, PsiCompound(A1))".

2. Now we can formulate the compound distribution to calculate the payouts for the Class B members. The second compound distribution may be formulated in the same manner. PsiPearson5(10, 2000000) is the severity distribution while =PsiGeometric(0.25, PsiTruncate(0, 10)) is the frequency function. Since there are 10 class B members, PsiTruncate is used to ensure that sample values lie within the range 0 to 10.

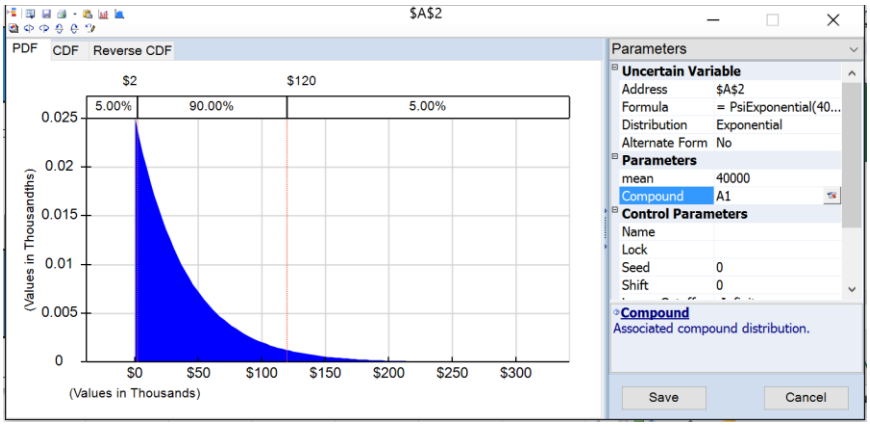
   If B1 = PsiGeometric(0.25, PsiTruncate(0, 10), the full compounding formula for the amount paid to Class B claims can be entered into cell B2 as "= PsiPearson5(10,2000000, PsiCompound(B1))".

3. Enter =PsiMean(A1) and =PsiMean(A2) in cells A3 and B3, respectively, to calculate the total expected payout to each class.

Run a simulation by clicking the green arrow on the Output tab on the Solver Task Pane. Instantly, Analytic Solver performs a new simulation of 1,000 Monte Carlo trials, and updates the Uncertain Function dialog and the worksheet with the results – as shown on the next page.



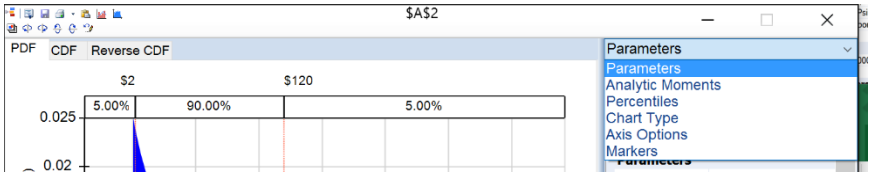
Double click the distribution for $A$2(var) to open the uncertain function dialog for cell A2.



If an uncertain variable uses the PsiCompound() property to create a compound distribution, you will see added fields on both the Parameter and Analytic Moments menus. Curves displayed in the Uncertain Variable dialog and statistics listed under the Parameters tab are related to the "severity" distribution.

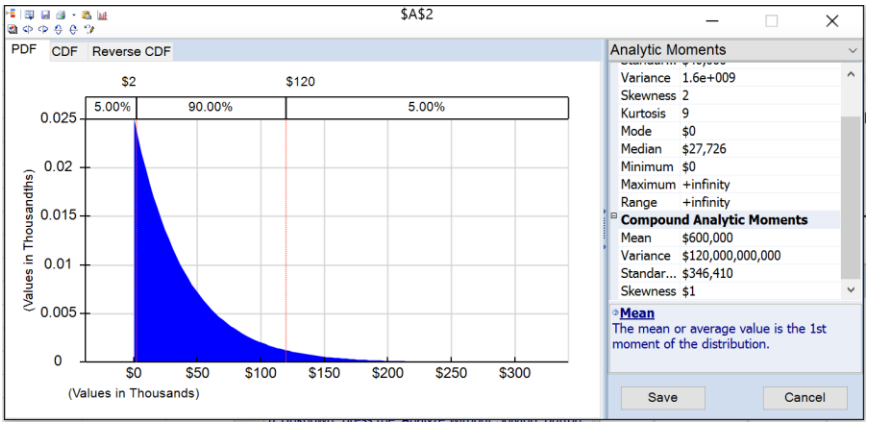
On the Parameter tab, the Compound field will appear under Parameters. (If the distribution is not a compound distribution, this field will be blank.) This field holds the arguments passed to the PsiCompound property.

Click the down arrow next to Parameters and select Analytic Moments from the menu.



On the Analytic Moments menu, four additional statistics relating to the compound distribution appear under Compound Analytic Moments: Mean,

Variance, Standard Deviation and Skewness. Statistics listed under Analytic Moments relate to the severity distribution.



Constant passed to 1st Argument

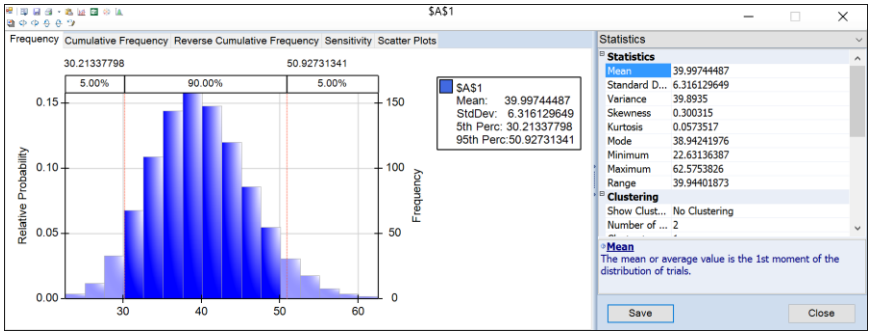
Recall that it is also possible to pass an integer, a cell containing an integer or a formula evaluating to an integer to the number_cell argument, the first argument of PsiCompound().

Imagine a department store manager predicting demand for snowboards for the coming winter season. From past analysis, she knows that the purchasing behavior of customers that visit her store follow the PsiGamma distribution with parameters of shape = 4 and scale = 1. She expects 1000 customers in the month of October. Using a compound distribution, calculate the expected number of snowboard purchases.

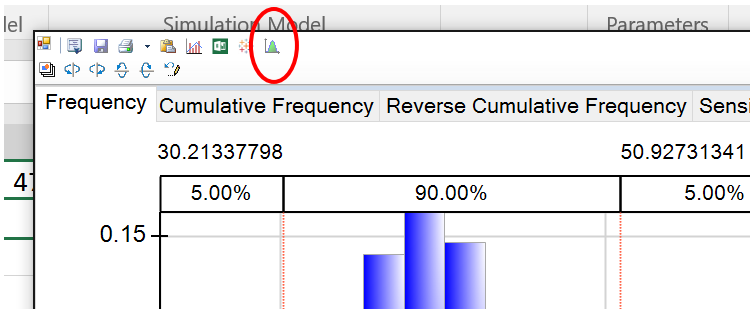
The severity distribution in this example is PsiGamma(4,1). Since N = 1000, a constant, no frequency distribution exists. Therefore, the syntax for this compound distribution would be =PsiGamma(4, 1, PsiCompound(1000).

Select the cell containing the compound distribution, then click **Results – Output – In Cell** on the Analytic Solver ribbon; "+ PsiOutput()" will be amended to the existing formula.

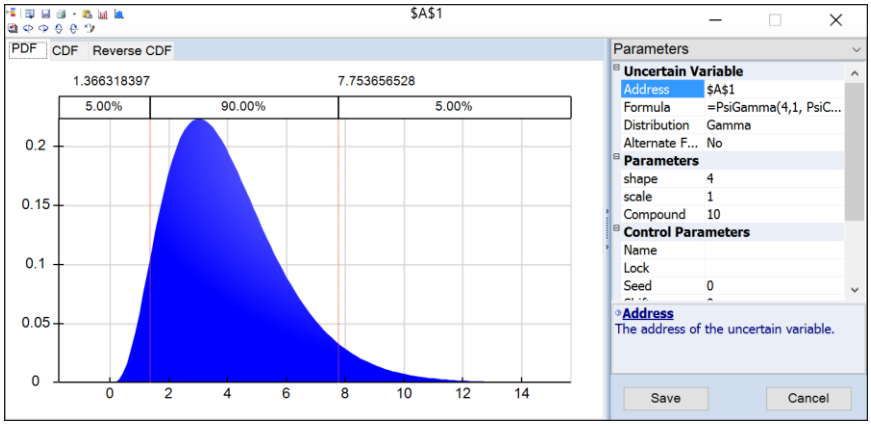
Again, run a simulation by clicking the green arrow on the Output tab of the Solver Task Pane. Instantly, Analytic Solver Simulation performs a new simulation of 1,000 Monte Carlo trials, and updates the Uncertain Function dialog and the worksheet with the results. If the worksheet only contains this one output function, the following dialog appears.



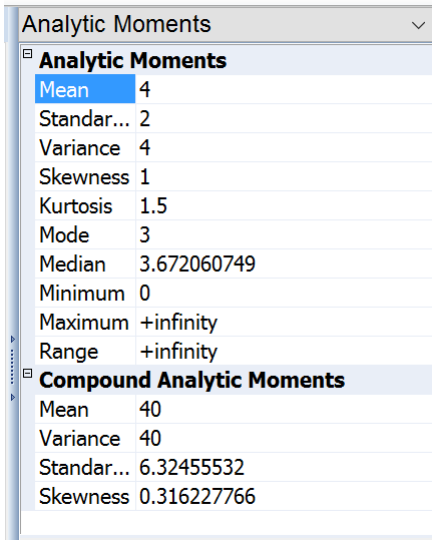
To view the compound distribution results, click the Show Input icon, circled below.



The Uncertain Variable dialog opens. Again, we see the Compound field, but this time, the constant 10 appears here.



Click the down arrow next to Parameters to view the Analytic Moments for both the severity distribution (under Analytic Moments) and the compound distribution (under Compound Analytic Moments).

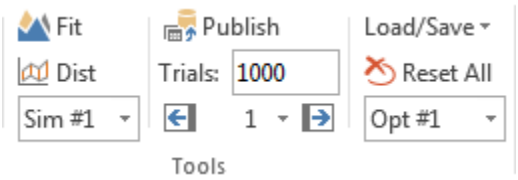


Publishing a Simulation Model to Excel Online or Google Sheets

In late 2014, Frontline Systems released Solver App for use with Excel 2013 and Solver Add-on for use with Google Sheets. With the Solver App you can define

and solve simulation problems in your Excel workbook, using Excel Online in Office 365, the Excel Web App in SharePoint 2016 or 2013, or desktop Excel 2016 or 2013. With the Solver Add-on, you can define and solve simulation problems in Google Sheets. You can create and solve models on tablets, phones, or anywhere a Web browser can be used. Solver models that you may already have created in old or new versions of Microsoft Excel, are automatically recognized by the Solver App and , after the existing worksheet is published, with the Solver Add-on.

In Analytic Solver Desktop and AnalyticSolver.com, the **Freeze** and **Thaw** buttons have been combined into a single **Publish** button, as shown in the screenshot below. (In Premium Solver Pro/Platform where there was no Freeze/Thaw function, the Ribbon now includes a Publish icon.)



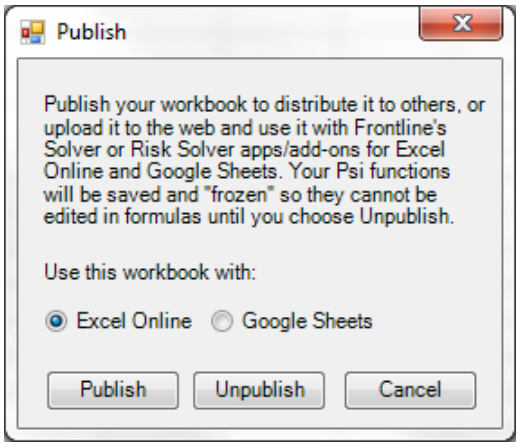
Note: This functionality is not supported in Analytic Solver Cloud.

Like the "Freeze" button, the **Publish** button can be used to prepare a workbook for distribution to other users who don't have Analytic Solver or its subsets installed: All formulas containing Psi function calls (which would yield #NAME? for other users) are replaced by their values, and the formulas are saved, so they can be restored later by choosing "Unpublish" (equivalent to the old "Thaw").

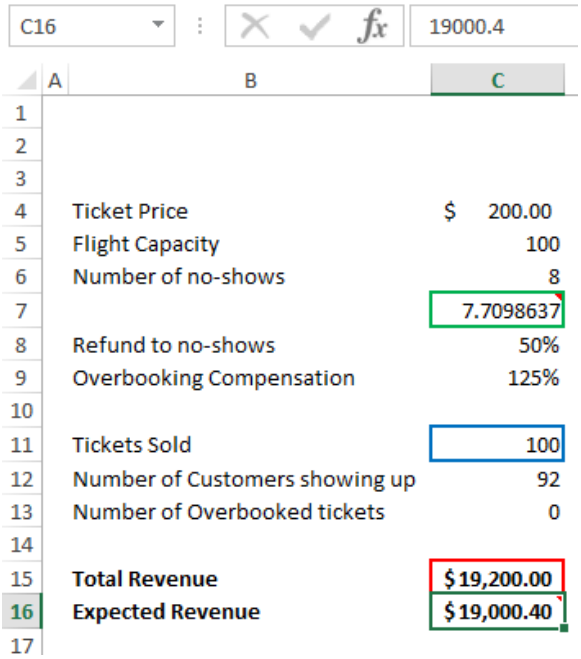
But the major use of the **Publish** button is to prepare a workbook for use with our Risk Solver App for Excel Online and our Risk Solver Add-on for Google Sheets (the online spreadsheets have limited or no support for user-defined functions).

In *Analytic Solver*, when a model is published, the limits for Solver App (for Excel Online) and Solver Add-on (for Google Sheets) will be automatically adjusted to match the problem limits of your license. For example, if you purchased a license for Analytic Solver, then you will be able to run simulation models with an unlimited number of uncertain variables and functions, *if* you publish your model first by clicking the Publish button on the Analytic Solver ribbon.

Let's go back to the YieldManagement1.xls example used in the section above, click the Publish icon on the Ribbon to display the following dialog.



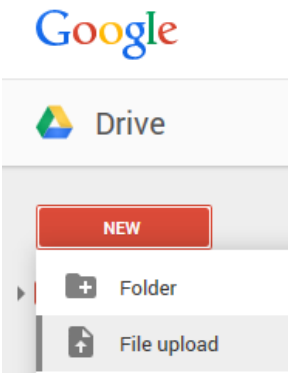
Select **Google Sheets** then **Publish**. (If you are a user of Excel Online, please see the example below.) If you inspect the worksheet, you'll notice that all Psi functions have been replaced with actual values. For example, cell C16 which used to contain the PsiMean() function, now contains a value of $19,00.40. Make sure to **save** the workbook before uploading to Google Drive.



Log on to your Google Drive account and upload YieldManagement1.xls, then open this file in Google Sheets.

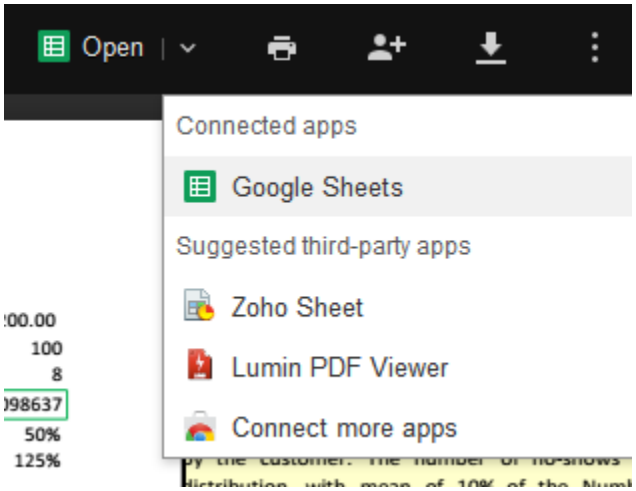
Uploading and Opening Files in Google Sheets

Click the orange New button then select File Upload to upload the YieldManagement1.xls spreadsheet to Google Drive.

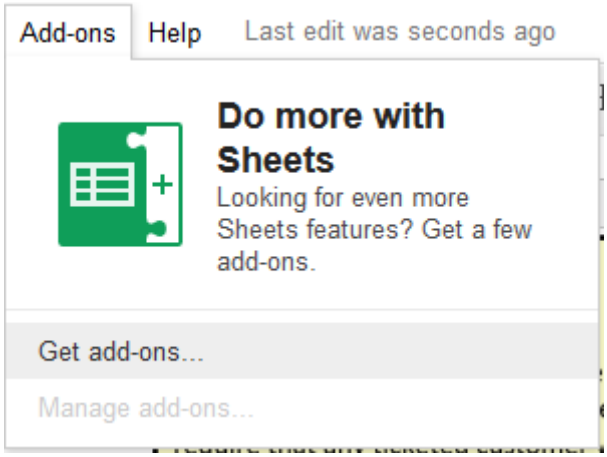


Browse to the location of the file, typically C:\Program Files (x86)\Frontline Systems\Analytic Solver Platform\Examples (if using 32 bit Excel with 64 bit Windows) or C:\Program Files\Analytic Solver Platform\Examples (if using 64 bit Excel or 32 bit Excel with 32 bit Windows). The YieldManagementModel1.xls will appear under My Drive.

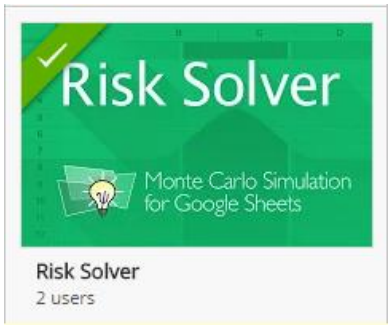
Double click YieldManagementModel1.xls, the file opens in Google Drive Preview Viewer (shown below). Click Open – Google Sheets.



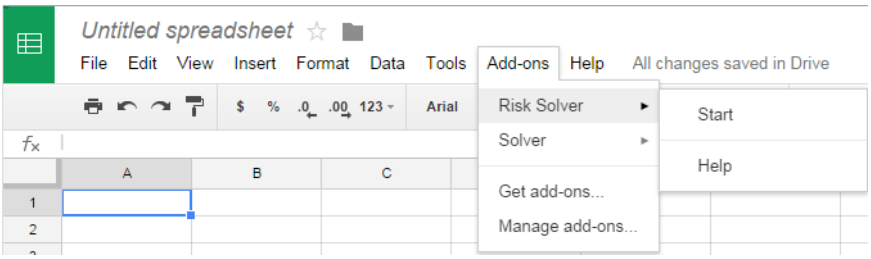
To add the Solver Add-on, choose the menu option Add-ons - Get Add-ons...



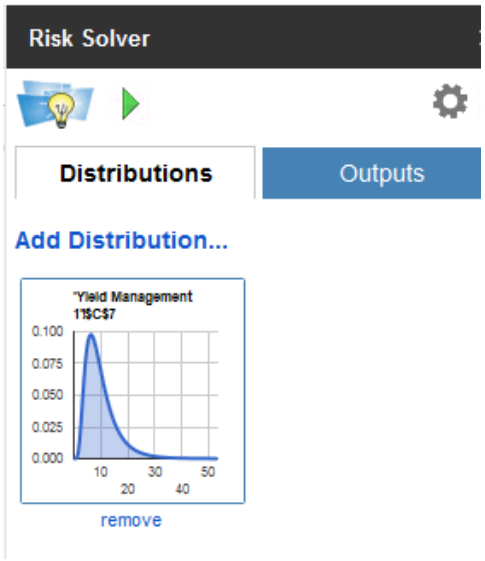
In the Add-ons dialog, scroll until you see Risk Solver. Click to select and install.



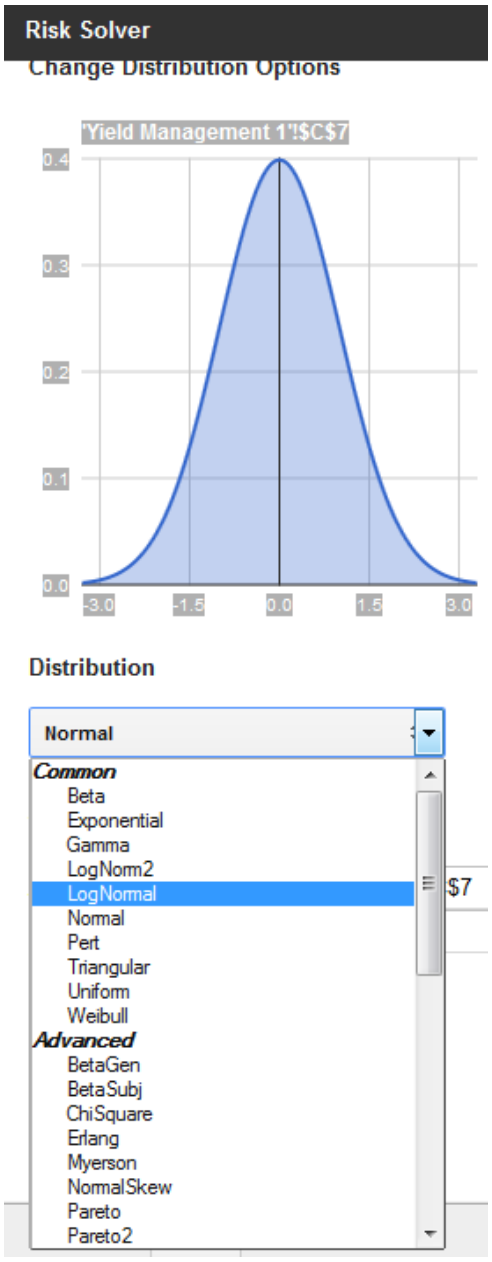
Once these steps are finished, Risk Solver should now appear on the Add-ons menu.



Choose Add-ons - Risk Solver - Start. The Risk Solver Task Pane (Google calls this a Sidebar) will appear. The uncertain variable that appears in cell C7 is displayed in this tab.

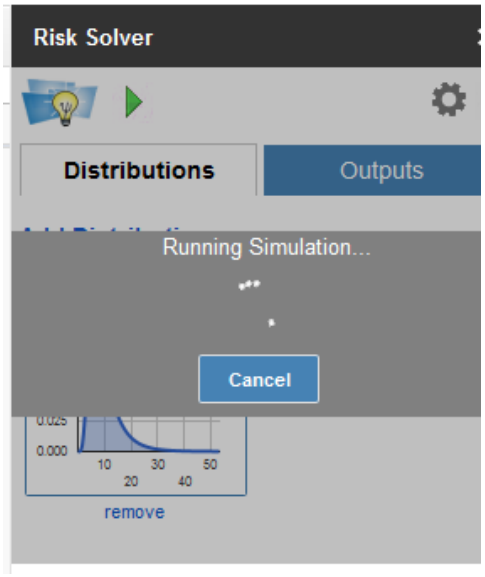


Click the distribution to change the distribution type and parameters or to view the cell formula and address.

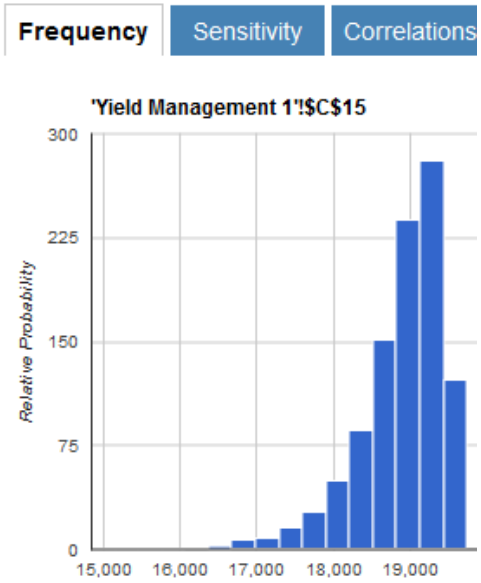


Click Cancel to leave everything "as is" or OK for Risk Solver to accept any changes. For this example, we'll click the Cancel button to leave the Distribution as PsiLogNormal.

Click the green arrow at the top of the sidebar to run a simulation. (Click the Cancel button to stop the simulation before finishing.)



In the sidebar, the Output tab appears with a small frequency chart containing the uncertain function in cell C15. Click the chart to enlarge it. Click the Frequency tab to view statistics (mean, standard deviation, variance, skewness, kurtosis, mode, minimum, maximum, and range) or Percentiles (1 – 100).



Statistics | Percentiles

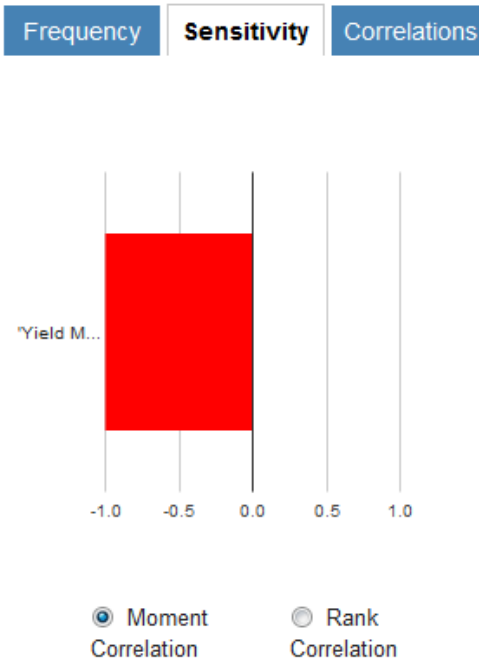
Mean	19000.1
StdDev	597.869
Variance	357447
Skewness	-1.85547
Kurtosis	5.68925
Mode	19400
Minimum	15000
Maximum	19900
Range	4900

Statistics | **Percentiles**

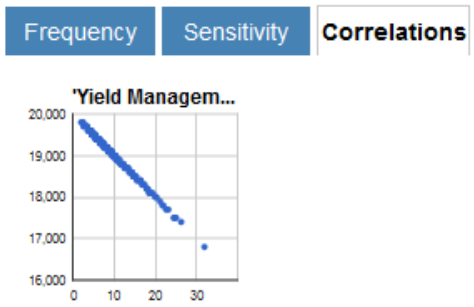
%	Value
1	16900
2	17300
3	17597
4	17700
5	17900
6	18000
7	18100
8	18100
9	18200
10	18300
11	18300
12	18400

For more information on the statistics, please see the corresponding Psi function (PsiMean, PsiMean, PsiStdDev (Standard Deviation), PsiVariance, PsiSkewness, PsiKurtosis, PsiMode, PsiMin, PsiMax or PsiRange) in *the Psi Function Reference* chapter in *Frontline Solvers Reference Guide*.

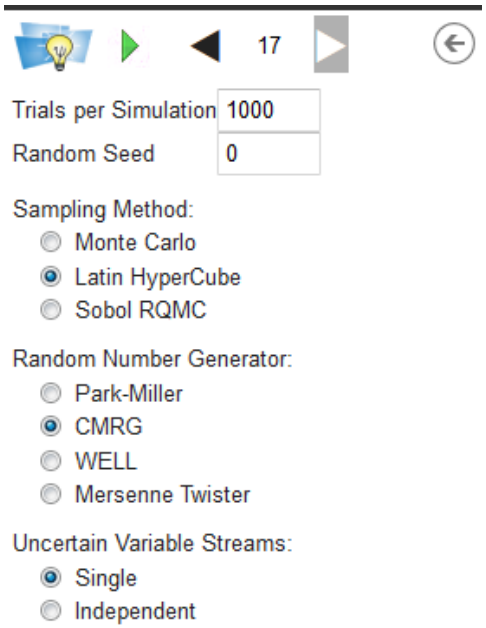
Click the Sensitivity tab to view a "Tornado chart" that shows you how much Total Revenue changes with a change in the uncertain variable in cell C7. In this model there is only one uncertain variable. This chart shows a negative correlation between the Number of No-Shows and Total Revenue. For more information on this tab, please see the section, "A First Simulation Example" above.



Select the Correlations tab to view the same negative correlation between the uncertain variable in cell C7 and the uncertain function in cell C15. For more information on this tab, please see the section above.

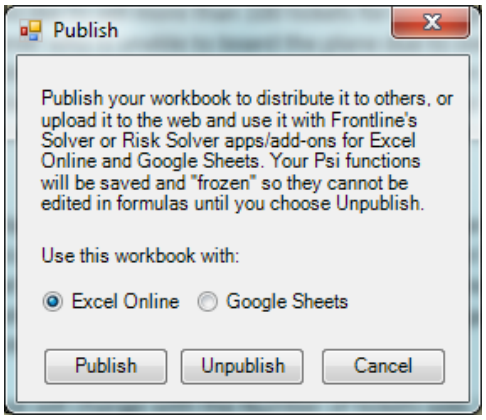


Click the icon to go back to the Output tab or click the left and right arrow icons to increment through each of the simulation trials. (The default is 1000.) To change the number of trials per simulation or other option settings, click the icon in the upper right corner of the Sidebar. For more information on these options, please see the chapter *Platform Solver Options* in the *Frontline Solvers Reference Guide*.



Now let's Publish this same model to Excel Online. Let's go back to Excel and YieldManagement1.xls. Afterwards, click **Publish – Unpublish**. Immediately, all PsiFunctions are restored in cells C7 and C16.

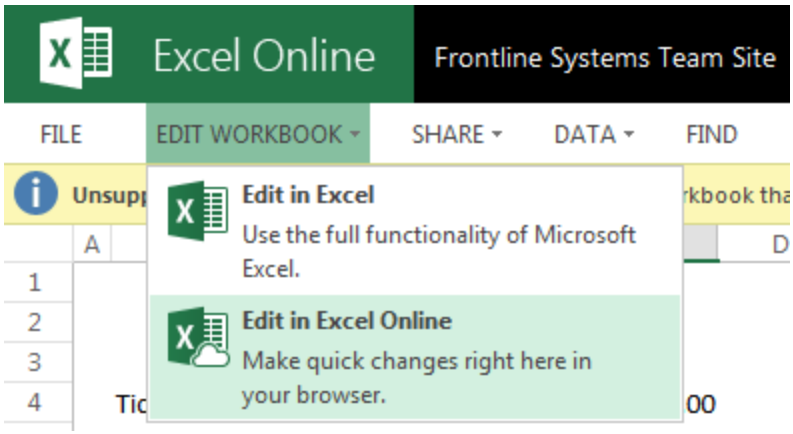
Click **Publish – Publish** again, but this time select **Excel Online**, then click **Publish.**



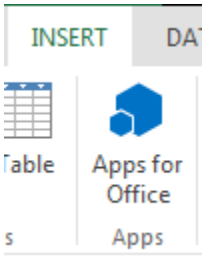
Click **File – Save As** and save this file as **YieldManagement1.xlsx** on your *SharePoint* or *Office 365* site.

Note: In order to use the Risk Solver App, your file must be saved on SharePoint or Office 365 site. This app cannot solve models saved on your local hard drive.

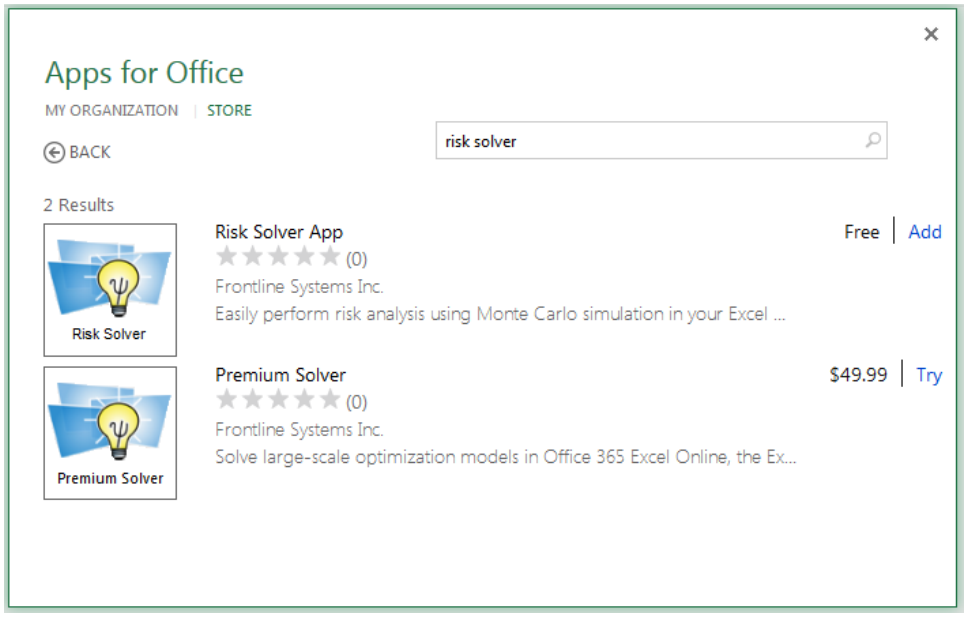
Open the workbook using Excel Online, then click **Edit Workbook – Edit in Excel Online**.



Click Insert – Apps for Office.



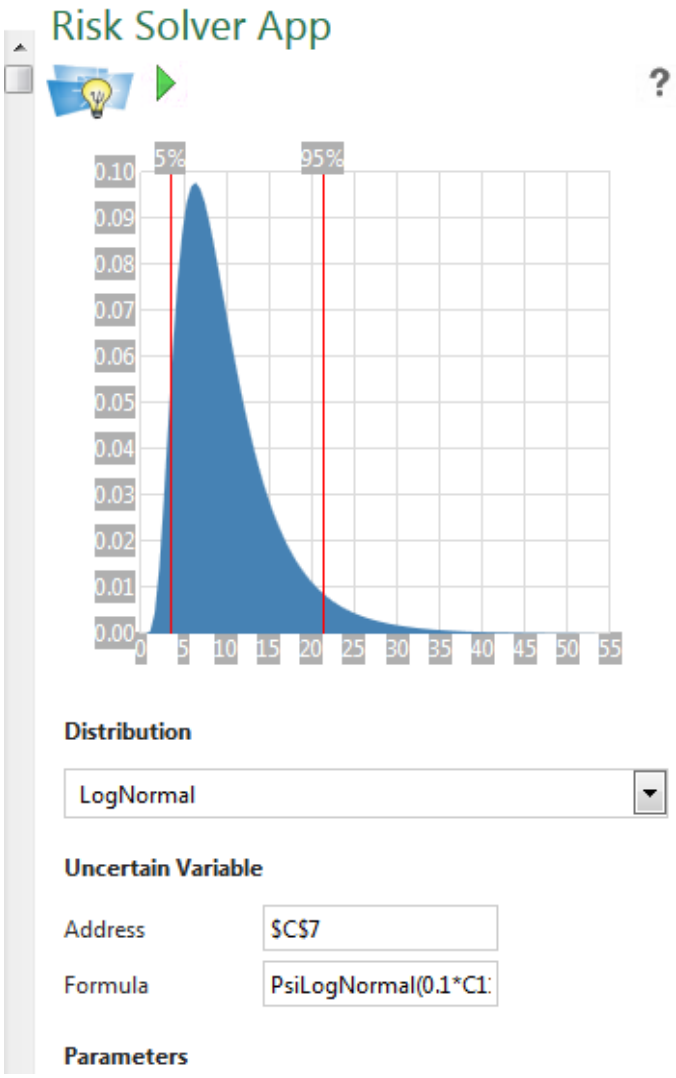
Select the Store tab and search for Risk Solver, then select (1st app in the list) and Install. Note: A Premium Solver app which solves linear models with more than 200 variables and nonlinear models with more than 200 variables and 200 constraints is available for purchase. Please contact Frontline Systems for more information at sales@solver.com.



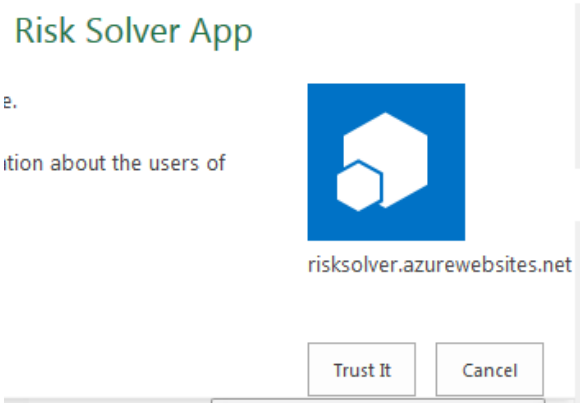
The Risk Solver App task pane opens on the right of your screen.

The uncertain variable that appears in cell C7 is displayed in this tab. Click the distribution to change the distribution type and parameters or to view the cell formula and address as shown in the Google Sheets example above.

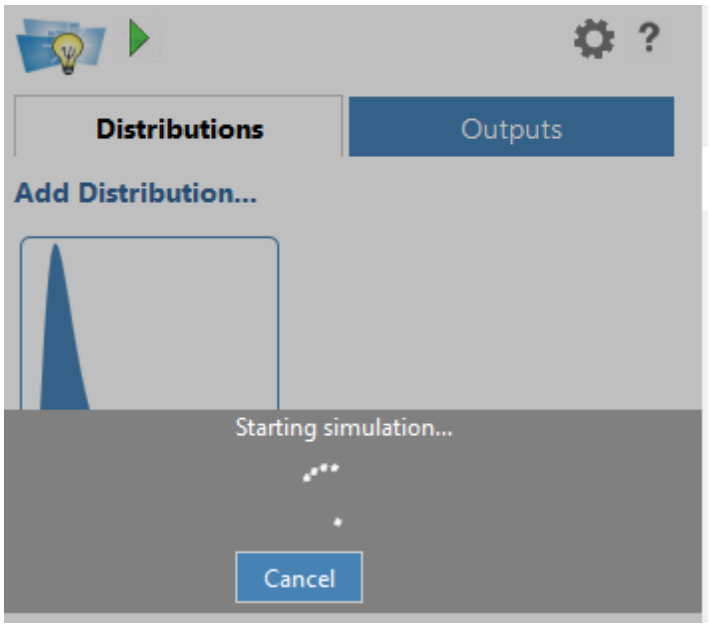
Note: In the Solver App red vertical lines have been drawn at the 5% and 95% percentiles.



Click the green arrow at the top of the task pane to run a simulation. (Click the Cancel button to stop the simulation before finishing.) If running for the first time, you will be asked to "Trust" the app.



To cancel the simulation before completion, click Cancel.



In the sidebar, the Output tab appears with a small frequency chart containing the uncertain function in cell C15. Click the chart to enlarge it. Click the Frequency tab to view statistics (mean, standard deviation, variance, skewness, kurtosis, mode, minimum, maximum, and range) or Percentiles (1 – 100). Click the Sensitivity tab to view a "Tornado chart" which illustrates the negative correlation between the Number of no-shows (uncertain variables) and Total Revenue (uncertain function) and the Correlations tab to view the relationship between the uncertain variable in cell C7 and the uncertain function in cell C15 as a scatter chart. For more information on either of these tabs, please see the Google Sheets example above.

Click the icon to go back to the Output tab or click the left and right arrow icons to increment through each of the simulation trials. (The default is 1000.) To change the number of trials per simulation or other option settings, click the icon in the upper right corner of the Task Pane. For more information on these options, please see the chapter *Platform Solver Options* in the *Frontline Solvers Reference Guide*.

Examples: Stochastic Optimization

Introduction

This chapter introduces stochastic optimization in Analytic Solver Comprehensive (Desktop or Cloud) with a series of examples.

We use the term stochastic optimization to mean optimization of models that include *uncertainty*, using any solution method. Analytic Solver offers an exceptional level of power to find robust optimal solutions to models with uncertainty, using three different solution methods:

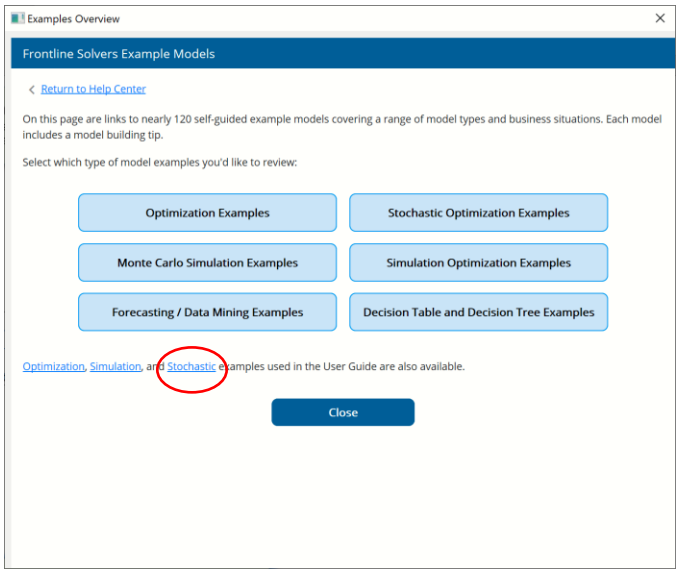
- Simulation optimization
- Stochastic programming
- Robust optimization

The first method, **simulation optimization**, is also available in Analytic Solver Optimization with Analytic Solver Simulation, Analytic Solver Upgrade and Analytic Solver Basic (Desktop or Cloud), and is the only method in other software products such as Crystal Ball Professional and @RISK Industrial. It handles very general models, but it is not scalable to large models (with thousands of variables and constraints), and it doesn't support the important modeling concept of recourse decisions.

Stochastic programming and **robust optimization** can be applied only to linear and quadratic programming models with uncertainty, but they are scalable to large models. Either Analytic Solver Comprehensive, Analytic Solver Simulation with Analytic Solver Optimization, Analytic Solver Upgrade or Analytic Solver Basic (Desktop or Cloud) are required to use these methods.

A Project Selection Model

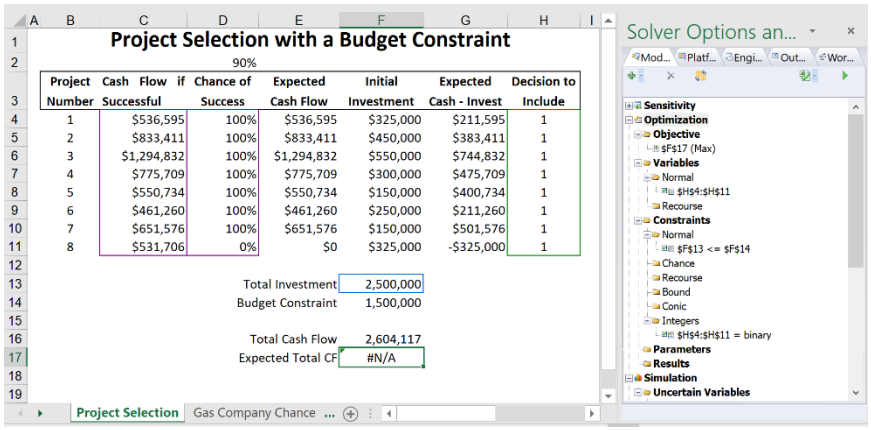
To open the examples, click **Help – Examples** on the ribbon. Click the Stochastic link on the Overview tab to open the workbook StochasticExamples.xls which includes three worksheets. In AnalyticSolver.com, click *Help – Examples – Stochastic Optimization Examples*, then scroll down to the *Stochastic Examples* link.



Click the Project Selection tab within the StochasticExamples.xls workbook to open the first example, which may surprise you: It is a capital budgeting problem, where the projects being considered for funding have uncertain future cash flows. Models similar to **Project Selection** have been used with other software products for many years to illustrate how **simulation optimization** can be used to optimize models with uncertainty. We'll show how to do this in Analytic Solver Comprehensive, Analytic Solver Simulation with Analytic Solver Optimization, Analytic Solver Upgrade, or Analytic Solver Basic, using simulation optimization and the Evolutionary Solver – with much better performance. But when we use Analytic Solver to *analyze the structure* of this model, we'll see that this model *doesn't require simulation optimization at all.* We can solve this model in a fraction of a second – using the LP/Quadratic Solver!

In **Project Selection**, eight different capital projects are proposed for funding. Each one has a known initial investment. Each project has a 90% chance of success, and if a project succeeds, it will have an uncertain (but positive) future cash flow. Funding all eight projects would require a total initial investment of $2.5 million, but our capital budget is only $1.5 million. Hence, we must choose a subset of the projects to fund that will maximize our expected total future cash flow, while ensuring that our total initial investment doesn't exceed our $1.5 million budget.

Click the tab for the Projection Selection model, shown below.



Project Selection with a Budget Constraint

90%

Project Number	Cash Flow if Successful	Chance of Success	Expected Cash Flow	Initial Investment	Expected Cash - Invest	Decision to Include
1	$536,595	100%	$536,595	$325,000	$211,595	1
2	$833,411	100%	$833,411	$450,000	$383,411	1
3	$1,294,832	100%	$1,294,832	$550,000	$744,832	1
4	$775,709	100%	$775,709	$300,000	$475,709	1
5	$550,734	100%	$550,734	$150,000	$400,734	1
6	$461,260	100%	$461,260	$250,000	$211,260	1
7	$651,576	100%	$651,576	$150,000	$501,576	1
8	$531,706	0%	$0	$325,000	-$325,000	1

Total Investment	2,500,000
Budget Constraint	1,500,000
Total Cash Flow	2,604,117
Expected Total CF	#N/A

To model the uncertainty in this problem, we use PSI functions that define *uncertain variables* with certain probability distributions. We can create these functions via the Distributions dropdown gallery and the Uncertain Variable dialog, as shown in the last chapter, or we can just type in the formulas.

To model the "Cash Flow if Successful" in column C, we use the **PsiTriangular()** function, specifying a minimum, most likely, and maximum cash flow. For example, the formula in C4 is =PsiTriangular(400000, 500000, 900000).

To model the "Chance of Success" in column D, we use **=PsiBinomial(1,D2) where D2=.9**. On each trial, this distribution returns 1 with probability 90% and 0 with probability 10%. In column E we multiply the "Cash Flow if Successful" and the "Chance of Success" to obtain the "Expected Cash Flow."

Column G computes the *net* cash flow – the "Expected Cash Flow" in column E minus the "Initial Investment" in column F. Column H holds our decision variables, which are constrained to be binary integer (0 or 1 at the solution).

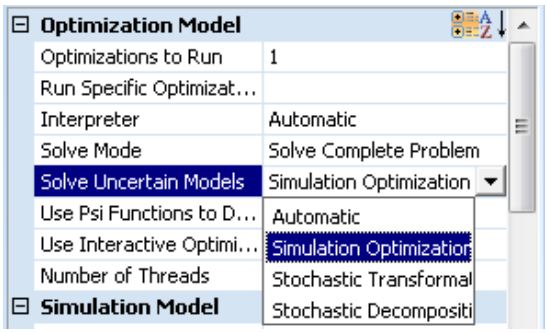
Cell F13 computes the total initial investment as the SUMPRODUCT of the project initial investments (column F) and the 0-1 variables in column H. In the model, F13 is constrained to be less than the $1.5 million budget in F14.

Cell F16 computes the total cash flow as the SUMPRODUCT of the project net cash flows and the 0-1 variables in column H. Cell F17 – unique to a model with uncertainty – contains =PsiMean(F16): It computes the mean (*expected*) value of total net cash flow. This is the objective function we want to maximize.

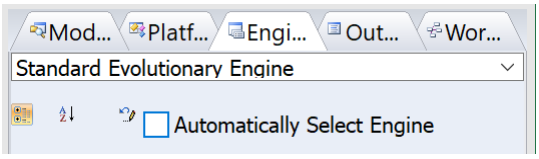
We're asking Analytic Solver to find the best combination of projects – by finding 0 or 1 values for the selection variables at H4:H11 – to maximize cell F17, the expected value of total net cash flow, subject to the constraint that the total initial investment doesn't exceed our $1.5 million budget.

Solving with Simulation Optimization

We'll first solve this problem using **simulation optimization**. To do this, go to the Task Pane Platform tab, and change the **Solve Uncertain Models** option to **Simulation Optimization**. (We'll see later what happens when we allow Analytic Solver to choose the solution method automatically.)



On the Engine tab, select the **Evolutionary Solver** from the dropdown list.

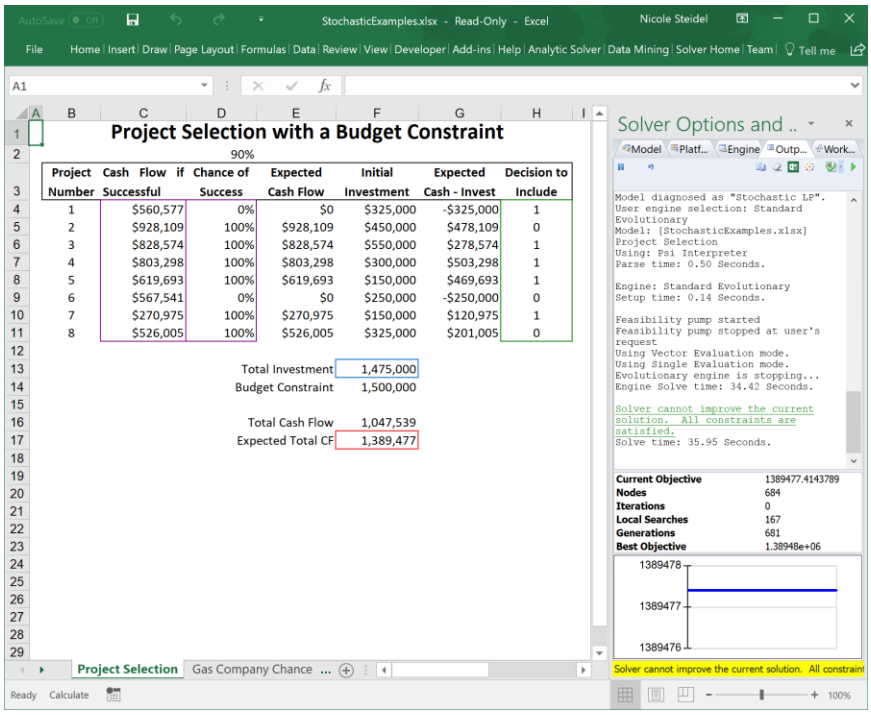


Why do we choose these settings? In the case of other software products, it's because simulation optimization is the only technology they have – and "if your only tool is a hammer, every problem looks like a nail." Simulation optimization is also a very general approach that can handle nonlinear and non-smooth functions, and it's comparatively easy to understand.

The idea behind simulation optimization is straightforward: **For each** set of values for the decision variables considered by the optimizer, we perform **one simulation**, a compute user-specified *summary measures* – such as =PsiMean(F16) in the Project Selection model – for the constraints and/or objective that depend on uncertainty. The optimizer uses these summary measures to decide what set of values it should try *next* for the decision variables – and the process is repeated.

The great strength of simulation optimization is its **generality** – but this is also its weakness: It requires a new simulation **at each step** of the optimization, and because the method assumes no structure in the model, in general the **number of step**s can grow **exponentially** with the number of variables and constraints.

Now click the green arrow in the Task Pane to run a simulation. If you are using Analytic Solver Desktop, after a second or two (much faster than other software products), you can press ESC to stop the Evolutionary Solver and display the best solution found so far – as shown on the next page.



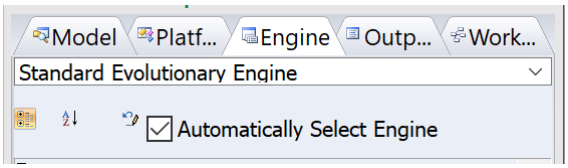
We've decided to fund projects #1, 3, 4, 5, and 7 for an expected total net cash flow of $1,389,477. That's a great result. But – *how much work* did we do to solve this model, and did we *need* to do that much work? It might not matter for a small model like this one – but for a 'scaled-up' model that might involve hundreds or thousands of projects, the solution might have taken far more time.

Solving Automatically

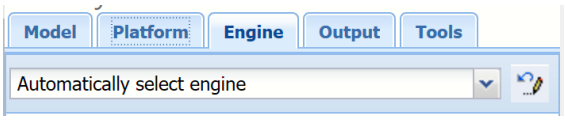
Let's allow Analytic Solver Comprehensive (or Analytic Solver Simulation with Analytic Solver Optimization) to choose the solution method and the Solver Engine automatically. To do this, go to the Task Pane Platform tab, and change the **Solve Uncertain Models** option to **Automatic**.

On the Engine tab, check the box to automatically select a Solver Engine in Analytic Solver Deskop or select Automaticaly select engine at the top of the menu for Analytic Solver Cloud or AnalyticSolver.com.

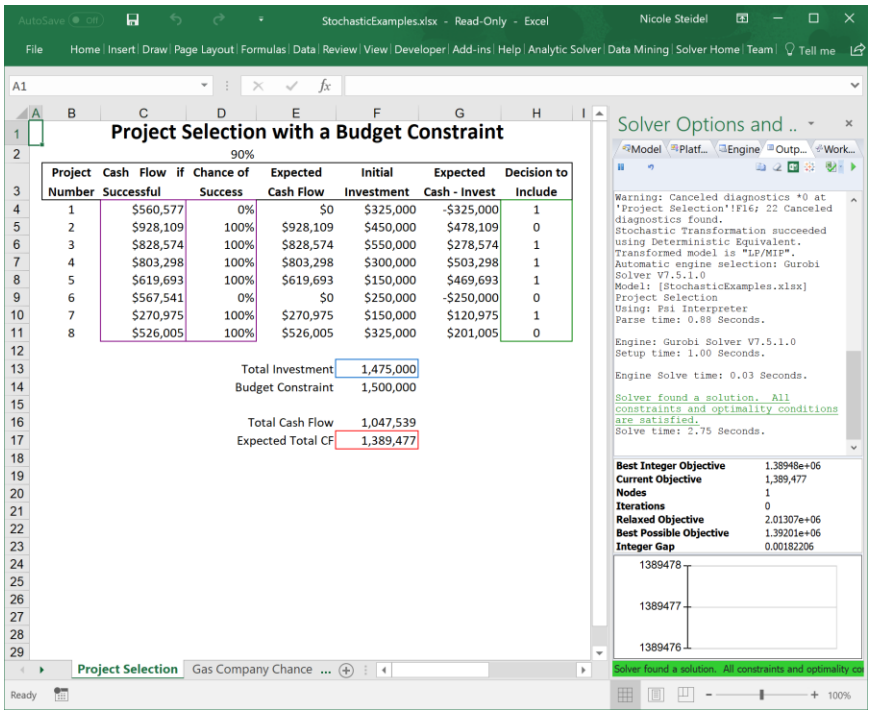
Analytic Solver Desktop



Analytic Solver Cloud



Now click the green arrow on the Task Pane. The results are shown on the next page.



In a *fraction of a second*, a solution appears with the *same* objective value of $1,389,477 and the same projects selected, with the message "Solver found a solution. All constraints and optimality conditions are satisfied." This means that Analytic Solver found a *proven* globally optimal solution – whereas with simulation optimization, we never know whether the solution we found is optimal. How did this happen?

If you examine the solution log, you'll see these messages:

```
---- Start Solve ----
Using: Full Reparse.
Parsing started...
Diagnosis started...
Warning: Canceled diagnostics *0 at 'Project Selection'!F16;
6 Canceled diagnostics found.
Uncertain input cells detected.
Attempting Stochastic Transformations...
Using: Full Reparse.
Parsing started...
Diagnosis started...
Convexity testing started...
Warning: Canceled diagnostics *0 at 'Project Selection'!F16;
22 Canceled diagnostics found.
Stochastic Transformation succeeded using Deterministic
Equivalent.
Transformed model is "LP/MIP".
Automatic engine selection: Standard LP/Quadratic
Model: [StochasticExamples.xlsx]Project Selection
Using: Psi Interpreter
Parse time: 0.66 Seconds.

Engine: Standard LP/Quadratic
Setup time: 0.01 Seconds.

Engine Solve time: 0.33 Seconds.

Solver found a solution.  All constraints and optimality
conditions are satisfied.
```

```
Solve time: 1.56 Seconds.
```

Analytic Solver Comprehensive analyzed the model and diagnosed it as a Stochastic LP (linear programming) problem, with 8 variables, 2 functions (objective and budget constraint), and 16 uncertainties (the PsiTriangular() and PsiBinomial() functions) that affect the objective. As you'll see in the chapter "Mastering Simulation and Risk Analysis Topics," Analytic Solver can solve a Stochastic LP using two *other* methods besides simulation optimization – stochastic programming and robust optimization. For this model, it chose a transformation to Stochastic Programming Deterministic Equivalent form.

But this model is so simple that Analytic Solver determined that *no* transformations were needed to solve the problem. Despite the presence of uncertainty, this model *doesn't require simulation optimization at all*. There was *no need* to run hundreds of Monte Carlo simulations (or many more, with some alternative software products). It was sufficient to run *one* Monte Carlo simulation at the beginning, to compute the *constant* linear coefficients of the objective function. Project Selection is simply an LP/MIP (linear mixed-integer programming) model!

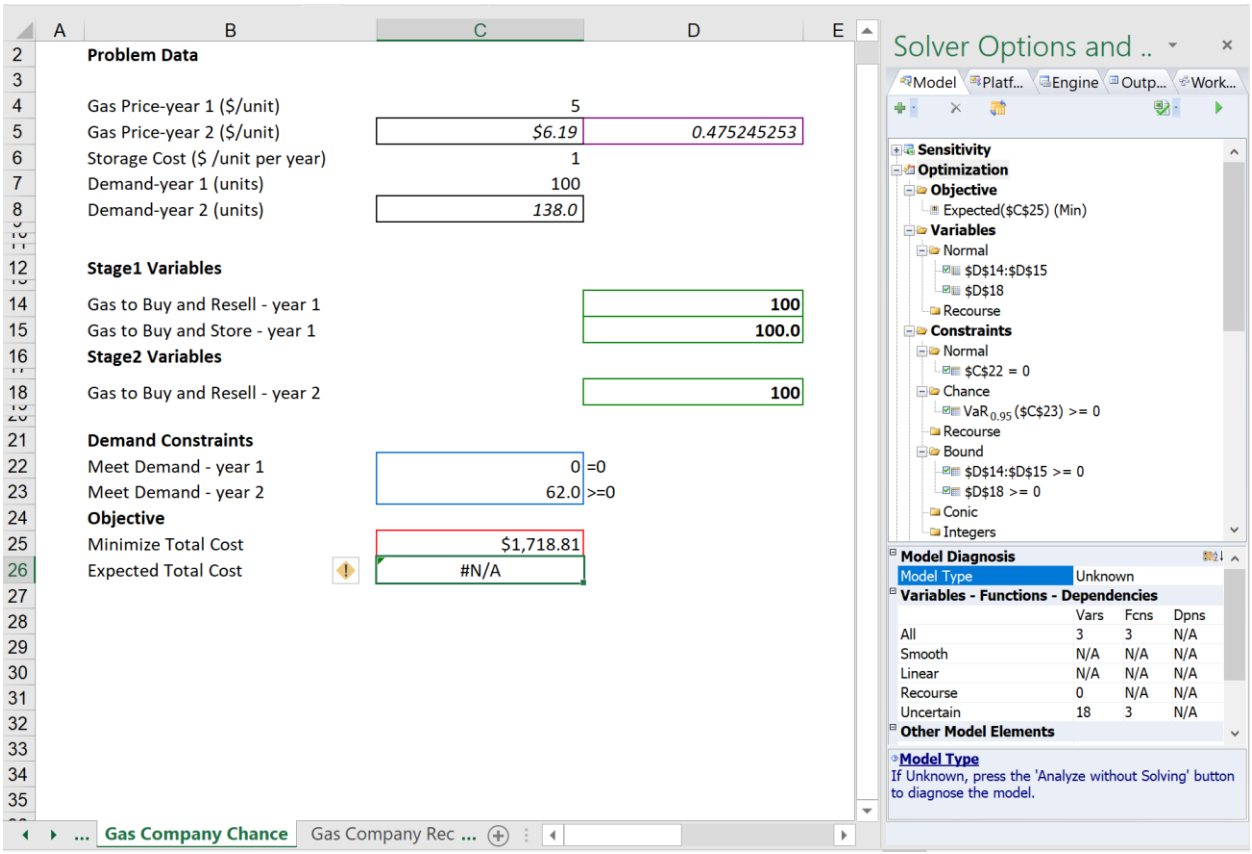
In this small model, we found the same solution within seconds using both methods. But in a 'scaled-up' model in a large company, with hundreds or even thousands of projects, Analytic Solver's ability to *analyze the structure* of the model could make all the difference – between a solution of unknown quality, found after a long wait using the *wrong approach* – and a proven optimal solution, found within seconds using the *right approach.*

A Model with Chance Constraints

The worksheets Gas Company Chance and Gas Company Recourse in **StochasticExamples.xls** are related – they both describe the same problem, but with different assumptions about *when* a certain decision must be made. With Gas Company Chance, we'll show how a problem with uncertainty can be formulated with a *chance constraint* and solved using robust optimization methods. With Gas Company Recourse, we'll show how to use a "wait and see" or **recourse decision** – a capability *not available at all* with simulation optimization – to obtain a *better* optimal solution.

> We hope these examples will motivate you to read the chapter "Mastering Simulation and Risk Analysis Topics," which will give you a *unified view* of the crucial characteristics of models with uncertainty, and the options of solving them with simulation optimization, stochastic programming, and robust optimization methods.

Click the **Gas Company Chance** tab to display the model, which is pictured on the next page.



In this model, a gas company purchases natural gas from suppliers and resells it to consumers in its service area. Consumer demand is known to be 100 units this year (cell C7) but is uncertain for next year (cell C8); the company must meet this demand with high probability, or it will encounter public relations and regulatory problems. The price of gas is known to be $5.00/unit this year (cell C4), but is uncertain for next year (cell C5): If the weather is very cold, demand may reach 180 units, and the price may reach $7.50/unit, but if the weather is warm, demand may remain at 100 units, and the price may remain at $5.00/unit. The company's goal is to minimize its total cost of purchased and stored gas (cell C25). It's decisions are:

- How much gas to purchase and resell to consumers *this year* (cell D14)
- How much gas to purchase *this year* and store (cell D15) , at a cost of $1 per unit, for use *next year*
- How much to purchase and resell to consumers *next year* (cell D18)

In Gas Company Chance, we assume that the gas company must commit to all of its gas purchases this year, *before* next year's demand is known: All three decision variables D14, D15 and D18 are normal or 'here and now' decisions. (In the next section, we'll consider Gas Company Recourse, where we assume that next year's gas purchases can be determined on a 'wait and see' basis.)

Gas Company Chance has a constraint that the company must have enough gas to meet next year's *uncertain* demand "with high probability." We'll model this in Analytic Solver Comprehensive with a ***chance constraint***. Our objective function – total cost, to be minimized – depends in part on next year's uncertain gas price. We will therefore seek to minimize the ***expected value* of total cost**.

The **objective** appears as "Expected($C$25) (Min)" – in Gas Company Chance, we used the Ribbon to define the objective interactively, rather than a PsiMean() function on the worksheet, as we did earlier in Project Selection. The decision variables are cells D14, D15 and D18, as explained earlier; each of these is constrained to be non-negative, as shown in the Bound section of the outline.

At C22 we calculate =D14-C7 (this year's gas purchases minus this year's demand), and at C23 we calculate =D15+D18-C8 (gas purchased and stored this year, plus gas purchased next year, minus next year's uncertain demand).

The **normal constraint** $C$22 = 0 specifies that we must meet this year's consumer demand exactly (forcing D14 to 100). The **chance constraint $\mathbf{VaR_{0.95}}$($C$23) >= 0** requires that the 95th percentile of C23, over *all* realizations of the uncertainty, must be non-negative – in other words, we must meet demand with 95% probability.

We *could* express this chance constraint by placing =PsiPercentile(D15+D18-C8,0.95) in cell C23, and using the Ribbon to define a *normal* constraint C23 >= 0. But while PsiPercentile and other PSI Statistics functions are acceptable for simulation optimization, the transformation for *robust optimization* requires that we express the chance property directly in the constraint itself, not in a formula.

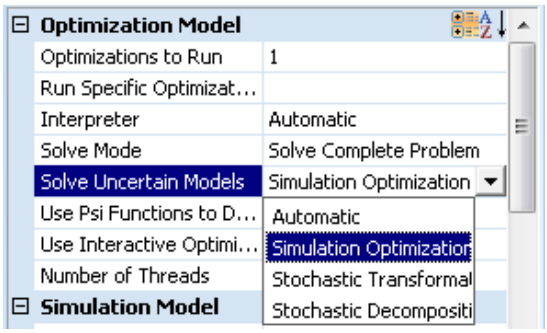
Solving with Robust Optimization

We could solve this model using *simulation optimization*, as we did for Project Selection in the previous section. But here, we want to show how Analytic Solver Comprehensive (or Analytic Solver Simulation with Analytic Solver Optimization) can automatically *transform* this stochastic linear programming problem – with its expected value objective and chance constraint – into a larger conventional optimization model, using the methods of ***robust optimization***.

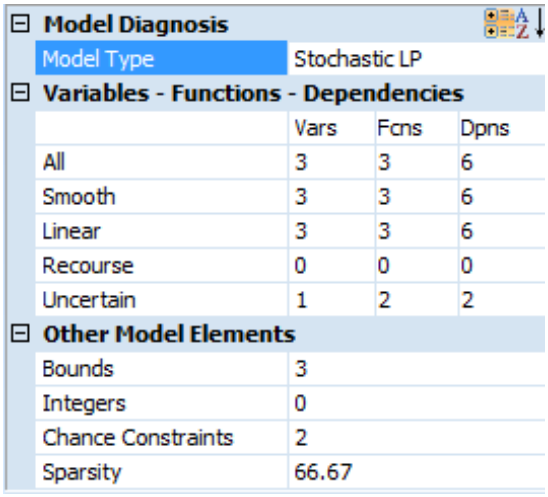
The idea behind robust optimization is to *transform* an optimization problem with known *structure* – such as a stochastic linear programming problem – into a larger, *conventional* 'robust counterpart' problem that accounts for the impact of *bounded* uncertainty on the constraints and objective. Analytic Solver performs **one simulation** at the outset, to assess the impact of uncertainty and construct the robust counterpart problem. Solving the robust counterpart – a **single LP or SOCP problem** – gives us an approximate solution to the original stochastic problem.

The strength of robust optimization is its **scalability** to very large problems – since only one simulation and one optimization of an LP or SOCP problem is required. But robust optimization cannot solve more general nonlinear, non-convex problems.

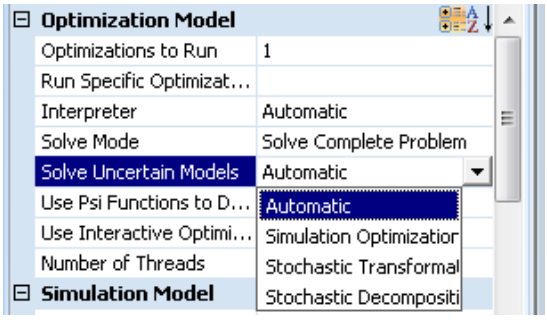
As saved, the model is ready to be solved using robust optimization. But to see the difference between the original model – a stochastic linear programming model – and the robust counterpart model that is the result of the transformation, we'll first set the **Solve Uncertain Models** option to **Simulation Optimization**:



and then click **Analyze – Analyze Transformed Model** (on the Model tab) to analyze the structure of the model. The Model Diagnosis section of the Task Pane Model tab "pops up" to show the results, as shown below.



The model is diagnosed as a Stochastic LP, with 3 variables, 3 functions, and 1 uncertainty (the Beta distribution at cell D5, which models the weather). Now, we'll set the **Solve Uncertain Models** option to **Automatic**:



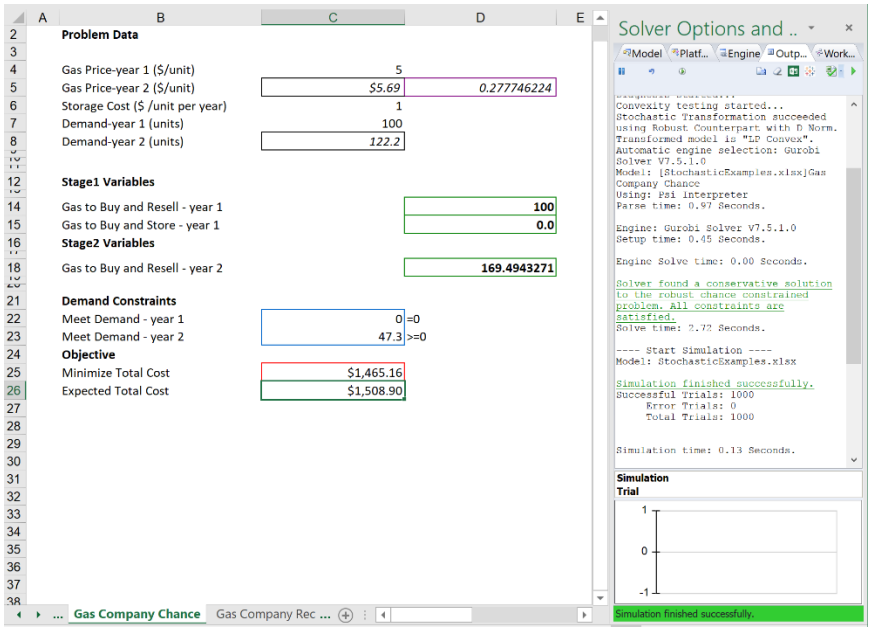
and click the **Analyze – Analyze Transformed model** again – this will analyze the structure of the *transformed* robust counterpart model.

Model Diagnosis			
Model Type	LP Convex		
Variables - Functions - Dependencies			
	Vars	Fcns	Dpns
All	9	8	19
Smooth	9	8	19
Linear	9	8	19
Recourse	0	0	0
Uncertain	0	0	0
Other Model Elements			
Bounds	7		
Integers	0		
Chance Constraints	0		
Sparsity	26.39		

The *transformed* model has 9 variables and 8 functions (instead of 3 and 3), but it has *0 uncertainties* – it's a conventional linear programming model. Solving this robust counterpart model will give us an *approximate* (and somewhat conservative) solution to the original stochastic LP problem.

Technical note, explained in the chapter "Mastering Simulation and Risk Analysis Topics:" The robust counterpart model is an LP because the Platform tab Chance Constraints Use option is set to D Norm. If it had been set to L2 Norm, the robust counterpart model would have been an SOCP.

Now click the green arrow on the Task Pane. In a fraction of a second, the solution appears, with the message "Solver found a conservative solution to the robust chance constrained problem. All constraints are satisfied." You can **click this message to display Help** with a more complete explanation of what this means. To resolve the formula in cell C26, click the Simulate icon to run a simulation. The results are shown below.



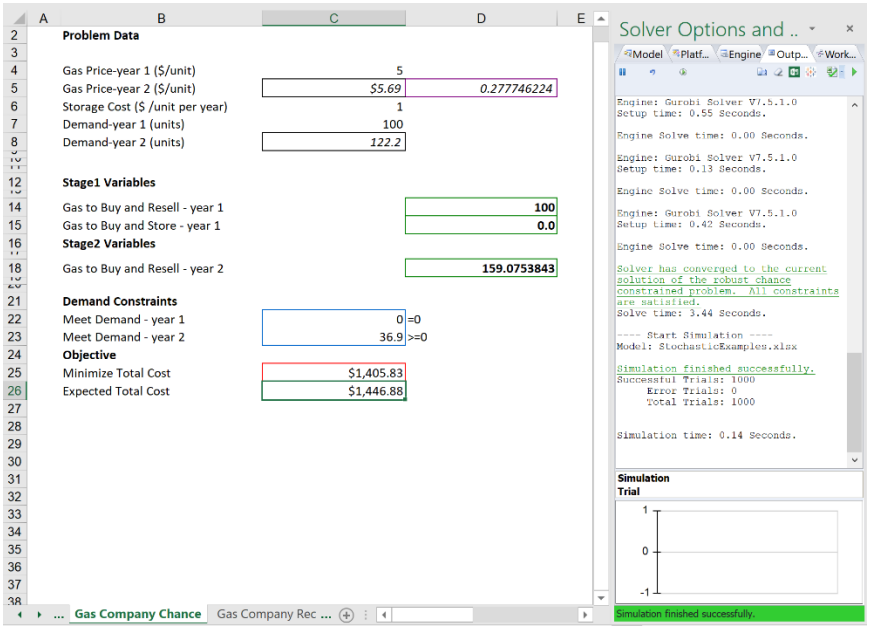
We run one simulation to see the expected value of the objective, which is about $1,509, lower than the initial value of $1,693. But our chance constraint is not only satisfied but

over-satisfied – we meet consumer demand about 99% of the time, when we asked for only 95%. This solution is more conservative than necessary.

But Analytic Solver Comprehensive within Analytic Solver Desktop can *automatically improve* this solution, by adjusting the size of the uncertainty set for the chance constraint. To do this, click the special button to "Auto Adjust Chance Constraints" that appears at the top of the Task Pane. After a moment, a new solution appears with the message "Solver has converged to the current solution of the robust chance constrained problem. All constraints are satisfied." To resolve cell C26, double click cell C25 and click "Yes" to run a simulation.

To find this same solution in Analytic Solver Cloud, click the Platform tab and set **Auto Adjust Chance Constraints** to True and then resolve by clicking the green arrow on the Model tab. To resolve cell C26, click the Simulation button to run a simulation.

The results are shown on the next page.



We run one simulation to see the expected value of the objective, which is about $1,447. As noted earlier, this very simple model could have been solved via simulation optimization; but with robust optimization, we can *scale up* a model like this one to large size, and solve it efficiently using the LP/Quadratic Solver, or any of several large-scale Solver Engines.

A Model with Recourse Decisions

We now have a good solution to the Gas Company problem, found with either simulation optimization or robust optimization. But *we can do better than this* – we can reduce our expected total cost to $1,276, a significant improvement.

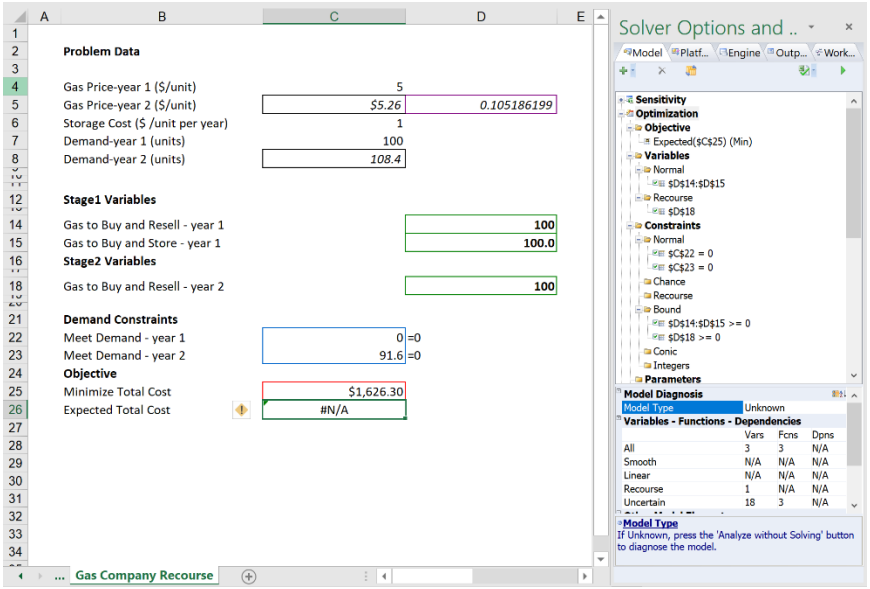
We can do this provided that *the business situation permits us* to make the decision of how much gas to purchase next year on a 'wait and see' basis, *after* the uncertainty of the weather is resolved – a so-called **recourse decision**. In this example, our gas supplier must accept our purchase order next year, and not require us to commit to a specific amount of gas this year for delivery next year.

One of the most important messages we can convey is this: **If the business situation permits you to make some decisions on a 'wait and see' basis, it's**

crucial to *include* this in your optimization model. If you *don't* do this, you may find an optimal solution to *the wrong model* for the actual business problem.

We emphasize this because so many people have built models that *don't* include 'wait and see' decisions, because (i) they haven't learned this concept and (ii) their software hasn't allowed them to create models with recourse decisions. Simulation optimization is very popular, but as described in the technical literature and implemented in software, ***it has no concept of recourse decisions***.

In the next example, Gas Company Recourse, we'll assume that our decision of how much gas to purchase next year *can* be made on a 'wait and see' basis, *after* the uncertainty of the weather has been resolved. Click the **Gas Company Recourse** tab to display the model, which is pictured on the next page.



This model has the same objective (C25), the same decision variables (D14, D15 and D18), and the same constraints (C22 and C23) as in EXAMPLE2. It differs in just two ways: (i) Cell D18 – the amount of gas to purchase next year – appears as a **recourse decision** variable. (ii) Cell C23 is **no longer a chance constraint** – it is a normal constraint, and in fact it's = rather than >= – we expect to satisfy next year's consumer demand *exactly*. The recourse decision variable allows us to do this – in each possible future scenario, once the weather uncertainty is resolved and consumer demand is known, we will purchase just the amount of gas we need to meet demand.

Solving with Robust Optimization

We cannot solve Gas Company Recourse with simulation optimization, since this method has no concept of recourse decisions. But we *can* use robust optimization methods to transform and solve Gas Company Recourse, much as we did with Gas Company Chance. We can proceed in much the same way. If we analyze the structure of the original model (by clicking Analyze – Analyze Transformed Model with the **Solve Uncertain Models** option set to **Simulation Optimization**), we find that it is a stochastic LP:

Model Diagnosis			
Model Type	Stochastic LP		
Variables - Functions - Dependencies			
	Vars	Fcns	Dpns
All	3	3	6
Smooth	3	3	6
Linear	3	3	6
Recourse	1	2	2
Uncertain	1	2	2
Other Model Elements			
Bounds	3		
Integers	0		
Chance Constraints	1		
Sparsity	66.67		

Again, the model has 3 variables, 3 functions, and 1 uncertainty – but now 1 of the 3 variables is a **recourse decision** variable. Note that the recourse variable plays a role in 2 functions – the objective, and the constraint that requires us to meet next year's consumer demand. Our recourse decision variable will have ***many possible values* at the optimal solution** – *one for each realization* of the uncertain demand. With default settings in Analytic Solver Comprehensive (1,000 Monte Carlo trials in a simulation), the Solver will find 1,000 different values for D18.

If we analyze the structure of the robust counterpart model (by clicking Analyze - Analyze Transformed Model with the **Solve Uncertain Models** option set to **Automatic** or **Stochastic Transformation**, and the **Stochastic Transformation** option set to **Robust Counterpart**), the result is:

Model Diagnosis			
Model Type	LP Convex		
Variables - Functions - Dependencies			
	Vars	Fcns	Dpns
All	9	8	20
Smooth	9	8	20
Linear	9	8	20
Recourse	0	0	0
Uncertain	0	0	0
Other Model Elements			
Bounds	7		
Integers	0		
Chance Constraints	0		
Sparsity	27.78		

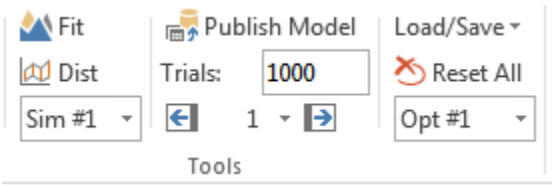
The robust counterpart has 9 variables and 8 functions, but the uncertainty and the recourse decision have been eliminated, yielding a conventional linear programming model. As with Gas Company Chance, solving this robust counterpart model will give us an *approximate* solution to the original problem.

Now click the **Optimize** button, or the green arrow on the Task Pane. In a fraction of a second, the solution appears, with the message "Solver found a solution. All constraints and optimality conditions are satisfied." As shown on the next page, the expected value of the objective is now about $1,365– a

considerable improvement over the minimum cost of about $1,434 in Gas Company Chance.

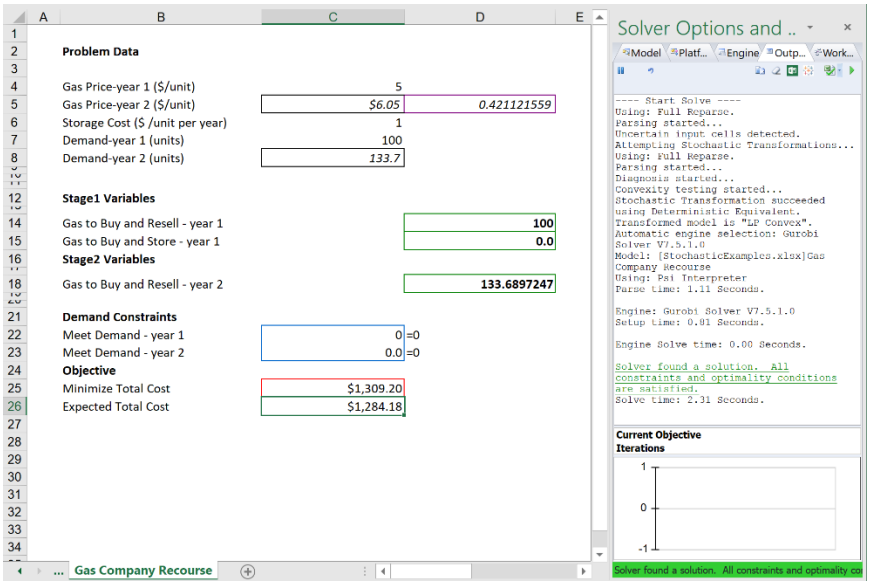
As noted above, our recourse decision variable will have ***many possible values*** **at the optimal solution** – *one for each realization* of the uncertain demand. We can see these different realizations (there are 1,000 different values) by clicking

- the left and right arrows on the Ribbon in **Analytic Solver Desktop**. Starting in Analytic Solver Desktop V2015, it's also possible to enter the number of trials directly into the Trials field.



- the left and right arrows on the Tools tab in the Task Pane in **Anaytic Solver Cloud.**

If you examine the trials, you'll see the pattern: The optimal solution is to not store any gas in Year 1 for use in Year 2, but instead to buy just enough gas to meet the uncertain demand in Year 2. (With higher gas costs or lower storage costs, the optimal solution might change.) Click the Simulation icon to run a simulation and resolve the contents of cell C26.



This solution offers a lower *expected* cost (the average cost over *all future* scenarios) because of the *flexibility* introduced by use of a recourse decision. And we were able to do this because we created the *right kind of model* for the business situation.

The ‘moral of this story’ is that Analytic Solver Comprehensive (Desktop or Cloud) gives you the power to solve such problems, using three different technologies – simulation optimization, stochastic programming, and robust optimization. But it’s *up to you* to take advantage of the concept of recourse decisions – when they can be used – and create the *right kind of model* for your company’s business situation.

Creating Your Own Application

Introduction

When using Analytic Solver you have the ability to not only create, design and solve your optimization, simulation and stochastic optimization models in Microsoft Excel, but also have the ability to embed your model into your own application and solve it on the Web by calling our RASON Server.

RASON (which stands for Restful Analytic Solver Object Notation) is Frontline Systems' modeling language embedded in JSON and a REST API that makes it easy to create, test and deploy analytic models using optimization, simulation and data mining, in web and mobile applications.

Users of Frontline's Excel Solvers will find that it's easy to translate Excel models into RASON models, that your knowledge of Excel formulas and functions is immediately usable, but that RASON models can be more flexibly "bound" to data from a variety of sources.

When you click the newly added Create App icon located on the Analytic Solver ribbon, your existing Excel model will be automatically converted to a mobile application written in JavaScript. Web App Developers will be able to immediately find how exceptionally easy it is to embed RASON models as JSON and solve them using Frontline's RASON server, which exposes a simple REST API that's scalable to handle very large, compute-intensive analytic models. Months of work, that would have previously been required, have been reduced to a single command button click!

The Create App Icon

When you click the Create App icon on the Analytic Solver ribbon, a drop down menu appears with four items:

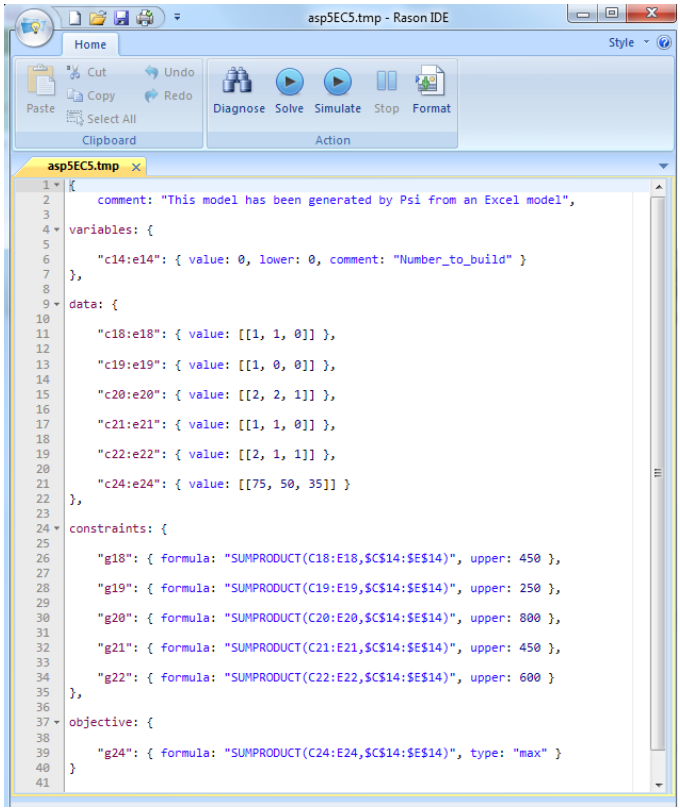
- RASON IDE (Not supported in Analytic Solver Cloud)
- RASON.com
- Web Page
- Power BI
- Tableau

Clicking the first menu item in Analytic Solver Desktop (only) opens the RASON Desk IDE. Clicking the second menu item in either Analytic Solver Desktop or Cloud, automatically opens the RASON Web IDE (located on www.rason.com). Both menu items will open the corresponding IDE containing your existing Excel model converted into the RASON modeling language. From here, you simply need to click the appropriate button to solve the optimization model or run a simulation.

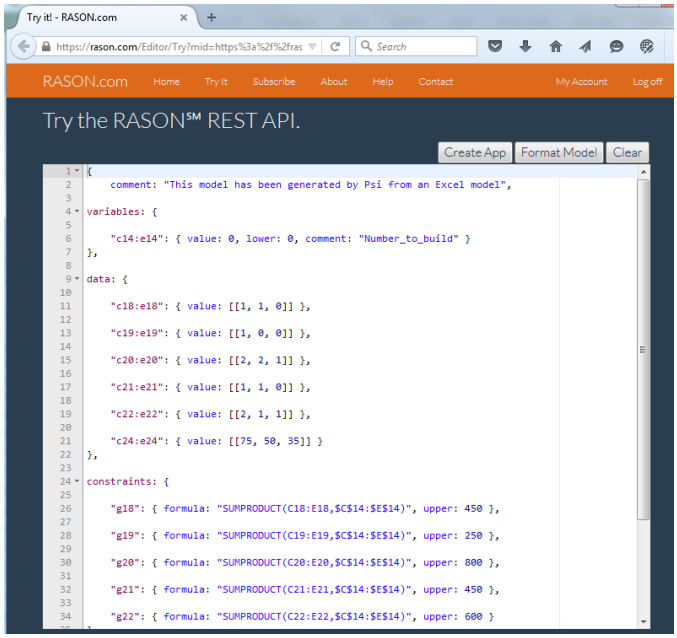
When solving with the RASON IDE in Analytic Solver Desktop, the Solver SDK Platform (installed along with Analytic Solver) will be called to solve the model. When using RASON.com, the RASON Server will be called to solve the model. See the labeled screenshots below. Each contain the Product Mix

model, discussed in the earlier Conventional Optimization chapter, written in the RASON modeling language.

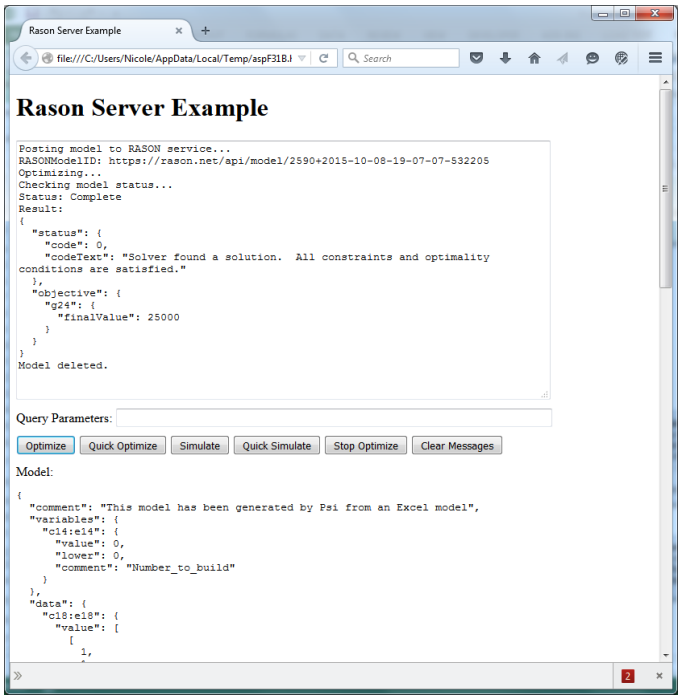
RASON Desk IDE



RASON Web IDE



Clicking the third menu item, Web Page, will result in the creation of a web application written in JavaScript that solves your existing Excel model.



Follow the steps below to convert an optimization and simulation model into a RASON model solved in both the Desk IDE (Analytic Solver Desktop only) and the Web IDE and publish a Web App, *in seconds*.

NOTE: New in V2019, when creating a RASON model through desktop Analytic Solver or AnalyticSolver.com, model elements (objective function, decision variables, constraints, uncertain variables and/or uncertain functions) may now appear on multiple worksheets within the same Excel workbook.

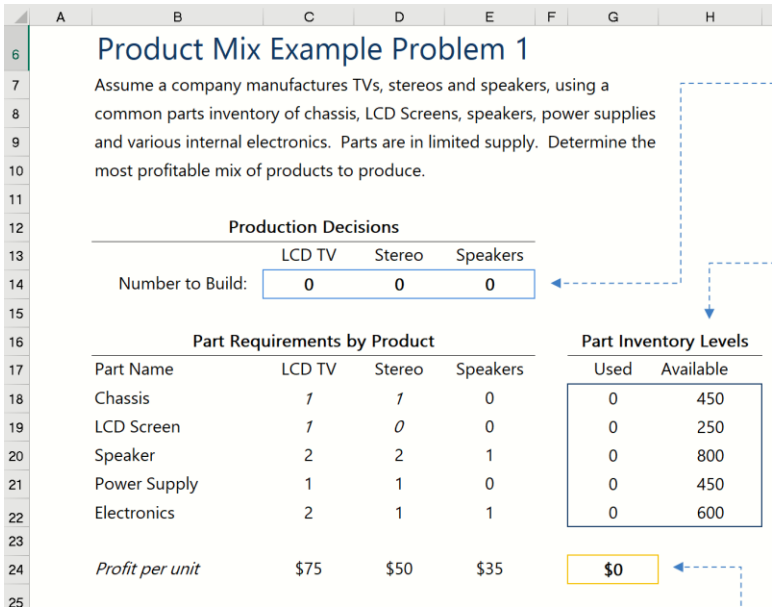
Clicking the fourth option, Power BI, gives you the ability to turn your Excel-based optimization or simulation model into a **Microsoft Power BI Custom Visual**. First, you simply select rows or columns of data to serve as changeable parameters, next, you select **Create App – Power BI**, and thirdly, you save the file created by Analytic Solver. Afterwards, you click the Load Custom Visual icon in Power BI and select the file you just saved. What you get isn't just a chart – it's your *full optimization or simulation model*, ready to accept Power BI data**, run on demand** on the web, and display visual results in Power BI! You simply need to drag and drop appropriate Power BI datasets into the "well" of inputs to match your model parameters. This is possible because Analytic Solver translates your Excel model into **RASON**® then "wraps" a JavaScript-based Custom Visual around the RASON model. For more information on this feature, see the next chapter "Creating Power BI Custom Visuals".

The last option on the Create App menu, Tableau, allows you to turn your Excel-based optimization or simulation model into a **Tableau Dashboard Extension**. You simply select rows or columns of data to serve as changeable parameters, then choose **Create App – Tableau**, and save the file created by Analytic Solver. In Tableau, you'll see the newly-created file under **Extensions** on the left side of the dashboard, where you can drag it onto your dashboard. You'll be prompted to match the parameters your model needs, with data in Tableau. Much like with Power BI, what you get isn't just a chart – it's your *full optimization or simulation model*, ready to accept Tableau data**, run on demand** (using our **RASON** server), and display visual results in Tableau! Note: This feature works (only) with Tableau version 2018.2 or later. For more

information on this feature, see the chapter "Creating Custom Extensions in Tableau".

Solving a Model Using the RASON Desk IDE

In *Analytic Solver Desktop*, open the Product Mix(RASON).xlsx model by clicking Help – Examples on the ribbon, clicking Optimization Examples and then the Product Mix RASON link. A similar version of this model was previously discussed in the Conventional Optimization chapter. Recall this example model determines the optimal mix of products that a company should produce in order to maximize profits.



Product Mix Example Problem 1

Assume a company manufactures TVs, stereos and speakers, using a common parts inventory of chassis, LCD Screens, speakers, power supplies and various internal electronics. Parts are in limited supply. Determine the most profitable mix of products to produce.

Production Decisions

	LCD TV	Stereo	Speakers
Number to Build:	0	0	0

Part Requirements by Product

Part Name	LCD TV	Stereo	Speakers
Chassis	*1*	*1*	0
LCD Screen	*1*	*0*	0
Speaker	2	2	1
Power Supply	1	1	0
Electronics	2	1	1
Profit per unit	$75	$50	$35

Part Inventory Levels

Used	Available
0	450
0	250
0	800
0	450
0	600
$0	

The optimization model is included in the Model tab in the Solver Task Pane. This model written in algebraic form is below.

Maximize: Total Profit = $75x1 + $50x2 + $35x3

Subject To:

Chassis: 1x1 + 1x2 + 0x3 <= 450

LCD Screen: 1x1 + 0x2 + 0x3 <= 250

Speaker: 2x1 + 2x2 + 1x3

Power Supply: 1x1 + 1x2 + 0x3

Electronics: 2x2 + 1x2 + 1x3

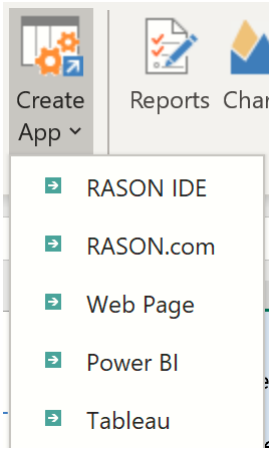
x1, x2, x3 > 0

Click Create App on the ribbon, then select RASON IDE.

NOTE 1: There is no need to solve the model first unless a change has been made to an already existing RASON model. If a change has been made to the workbook after a RASON model has been created, then you MUST either solve or diagnose the Excel model in order for the changes to be reflected in the new RASON model.

NOTE 2: When creating a RASON model through desktop Analytic Solver or AnalyticSolver.com, model elements (objective function and all variables and

constraints) may now exist on multiple worksheets within the same Excel workbook.



Immediately, the RASON Desk IDE is opened and the product mix model is inserted into the model window.

aspB1CC.tmp

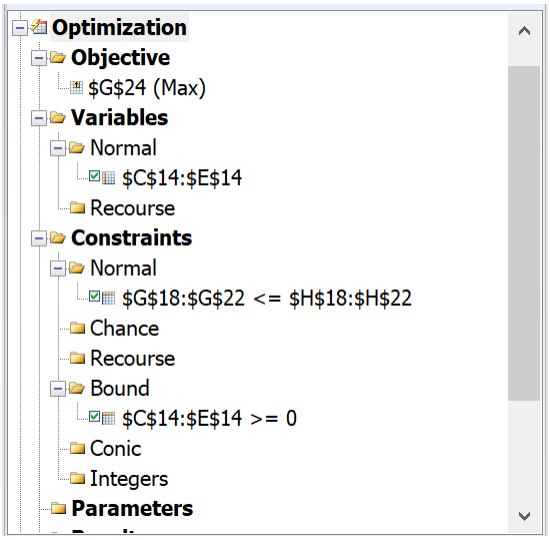
```
{
    comment: "This model has been generated by Psi from an Excel model",

variables: {

    "c14:e14": { value: 0, lower: 0 }
},

data: {

    "c18:e18": { value: [[1, 1, 0]] },

    "c19:e19": { value: [[1, 0, 0]] },

    "c20:e20": { value: [[2, 2, 1]] },

    "c21:e21": { value: [[1, 1, 0]] },

    "c22:e22": { value: [[2, 1, 1]] },

    "c24:e24": { value: [[75, 50, 35]] }
},

constraints: {

    "g18": { formula: "SUMPRODUCT(C18:E18,$C$14:$E$14)", upper: 450 },

    "g19": { formula: "SUMPRODUCT(C19:E19,$C$14:$E$14)", upper: 250 },

    "g20": { formula: "SUMPRODUCT(C20:E20,$C$14:$E$14)", upper: 800 },

    "g21": { formula: "SUMPRODUCT(C21:E21,$C$14:$E$14)", upper: 450 },

    "g22": { formula: "SUMPRODUCT(C22:E22,$C$14:$E$14)", upper: 600 }
},

objective: {

    "g24": { formula: "SUMPRODUCT(C24:E24,$C$14:$E$14)", type: "max" }
}

}
```

A RASON model begins with an opening { and closes with a closing }. Within the two braces, our model is made up of various "sections" – there are a total of

nine: "variables", "uncertain variables", "data", "dataSources", "engineSettings", "formulas", "modelSettings", "objective", "constraints", "indexSets" and "objective". Some optimization models will consist of just 3 sections: *variables* (where the decision variables will be defined), *constraints* (where the constraints will be defined) and *objective* (where the objective will be defined)) where other larger and more complex models might contain several additional segments such as: *engineSettings* (where the engine is chosen and an engine options are specified), `data` (where any arrays used in the calculation of the constraints or objective are defined), *formula* (where any intermediate calculations are performed) and/or *dataSources* (where any data is imported from an outside source such as a CSV file).

Our example is rather simple and only includes four: *variables*, *constraints*, *data*, and *objective*. Let's compare our Excel model with our newly generated RASON model section by section, starting with *variables*.

If we click back to the Excel example, we can see the model in the Model tab in the Solver Task Pane.

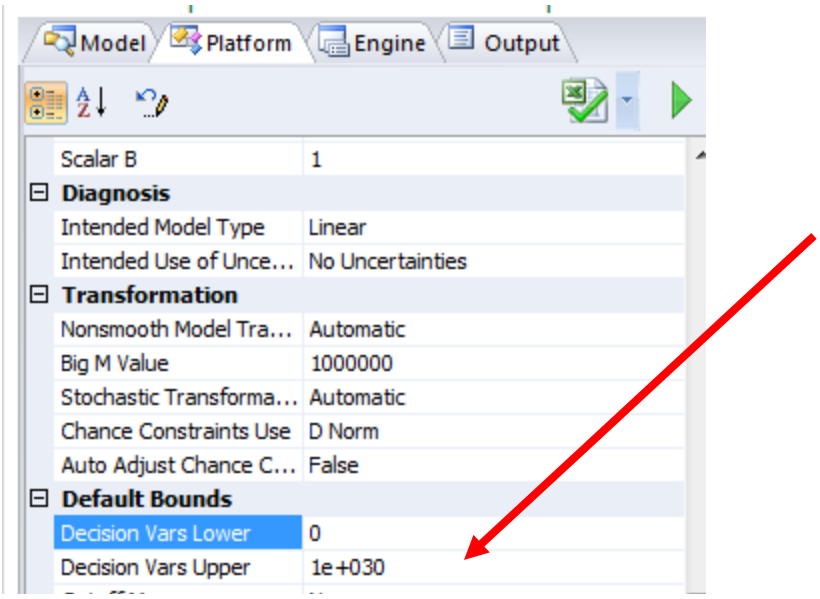


Under Variables, in the Model tab of the Solver Task Pane, we see the cell range: C14:E14. Now click back to your RASON model.

Within the *variables* section, we see the same cell range, "C14:E14". In our RASON model, C14:E14 is a vertical array with three elements: C14, D14, and E14. (To refer to an individual element, use: "C14", "D14", or "E14".) The initial value specified for the *value* property in the RASON model equals the values contained in the Excel cell range C14:E14 at the time the model was converted (0 for all three cells). The *lower* property in the RASON model exists because a constraint specifying the variable lower bounds is present in the Excel model (C14:E14 >= 0). If an upper bound was present, the *upper* property would be inserted into the RASON model too. Upper and lower bounds may be present in the Excel model using explicit constraints, such as we have here, or they may be entered into the Platform tab of the Solver Task Pane for Decision Vars Lower and Upper.

```
variables: {
    "c14:e14": { value: 0, lower: 0 }
}
```

Let's move on to the *data* section.



The data is contained in the Excel model within the cell range: C18:E22 (constraint coefficients) and also C24:E24 (objective function coefficients).

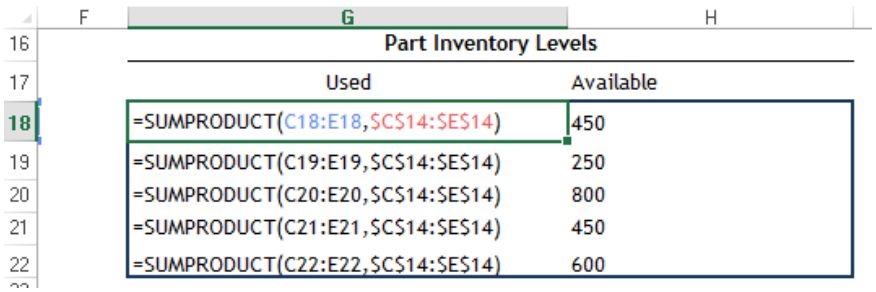
Part Requirements by Product

Part Name	LCD TV	Stereo	Speakers
Chassis	1	1	0
LCD Screen	1	0	0
Speaker	2	2	1
Power Supply	1	1	0
Electronics	2	1	1
Profit per unit	$75	$50	$35

The exact same values have been inserted into 6 vertical arrays containing three elements each: C18:E18, C19:E19, C20:E20, C21:E21, C22:E22, and C24:E24. Again, to refer to individual elements of, say, the c18:e18 array, use: c18, d18, or e18.

```
data: {
    "c18:e18": { value: [[1, 1, 0]] },
    "c19:e19": { value: [[1, 0, 0]] },
    "c20:e20": { value: [[2, 2, 1]] },
    "c21:e21": { value: [[1, 1, 0]] },
    "c22:e22": { value: [[2, 1, 1]] },
    "c24:e24": { value: [[75, 50, 35]] }
},
```

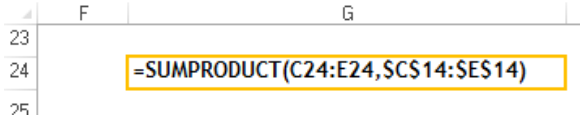
Click back to the Excel model. Under Constraints in the Model tab of the Solver Task pane, we see the entry: G18:G22 <= H18:H22. If we inspect the first cell in the range, G18, we find the formula: =SUMPRODUCT(C18:E18, $C$14:$E$14) while H18=450. The other four cells, G19:G22, hold similar formulas.



In the *constraint* section of the RASON model, we see five arrays, containing one element each, corresponding to the five constraints in our Excel model. The value for each upper bound is taken from cells H18:H22.

```
constraints: {
    "g18": { formula:
"SUMPRODUCT(C18:E18,$C$14:$E$14)", upper: 450 },
    "g19": { formula:
"SUMPRODUCT(C19:E19,$C$14:$E$14)", upper: 250 },
    "g20": { formula:
"SUMPRODUCT(C20:E20,$C$14:$E$14)", upper: 800 },
    "g21": { formula:
"SUMPRODUCT(C21:E21,$C$14:$E$14)", upper: 450 },
    "g22": { formula:
"SUMPRODUCT(C22:E22,$C$14:$E$14)", upper: 600 }
},
```

The objective function being maximized in the Excel model is located in cell G24 and contains the formula, =SUMPRODUCT(C24:E24,$C$14:$E$14).

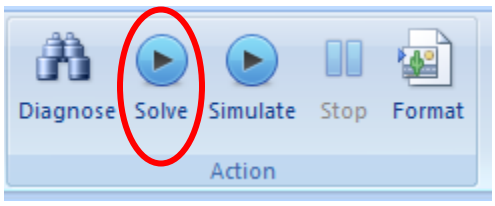


Looking back to the RASON model, we see the same formula for the G24 array. The type property is set to "max" to maximize the objective.

```
objective: {
    "g24": { formula:
"SUMPRODUCT(C24:E24,$C$14:$E$14)", type: "max" }
}
```

At the end of this section, a closing } ends the RASON model.

Click the Solve icon, at the top of the IDE, to solve the optimization model and display the results in the right of the IDE.



The Solver Desk IDE uses the Solver SDK Platform DLL (SolverSDK.dll) to solve the RASON model. The Solver SDK Platform DLL was installed along with the Analytic Solver software, during installation.

```
{
    "status": {
        "code": 0,
        "codeText": "Solver found a solution.  All constraints and optimality conditions are satisfied."
    },
    "objective": {
        "g24": {
            "finalValue": 25000
        }
    }
}
```


The Solver SDK Platform DLL was able to find a solution to the model with an objective equal to $25,000.

Now let's solve a simulation model. Click back to Help – Examples on the ribbon, click Simulation Examples and then the Business Forecast link. Click the Forecast with Uncertainty tab. Recall this example model from the Simulation & Risk Analysis chapter which finds the True Average of a sales forecast.

NOTE: When creating a RASON model through desktop Analytic Solver or AnalyticSolver.com, model elements (objective function, decision variables, constraints, uncertain variables and/or uncertain functions) may now appear on multiple worksheets within the same Excel workbook.

Click Create App – RASON IDE. The RASON Desk IDE opens displaying the code for the converted simulation model.

asp2F3A.tmp

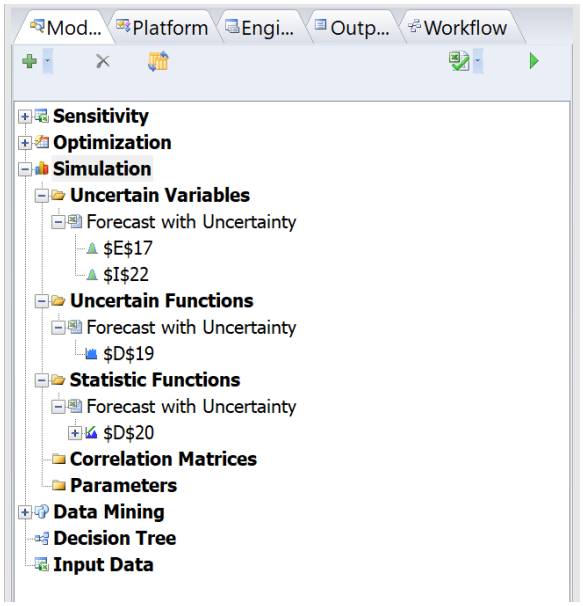
```
{
    comment: "This model has been generated by Psi from an Excel model",


uncertainVariables: {

    "e17": { formula: "PsiTriangular(H20,I20,J20)" },

    "i22": { formula: "PsiIntUniform(1,3)" }
},

data: {

    "h20": { value: 4.5 },

    "i20": { value: 6.5 },

    "j20": { value: 8.5 },

    "h17": { value: 11 },

    "i17": { value: 10 },

    "j17": { value: 8 },

    "h16": { value: 50000 },

    "i16": { value: 75000 },

    "j16": { value: 100000 },

    "d18": { value: 120000 }
},

formulas: {

    "e16": { formula: "IF($I$22=1,H17,IF($I$22=2, I17, IF($I$22 = 3,J17)))" },

    "d15": { formula: "IF($I$22=1,$H$16,IF($I$22=2, $I$16, IF($I$22 = 3,$J$16 )))" },

    "d16": { formula: "E16*D15" },

```

Again, the RASON model opens with an opening {. Most simulation models will be comprised of two components: *uncertainVariables* (where the uncertain variables are defined) and *uncertainFunctions* (where the uncertain functions are defined). However, a simulation model could also contain additional

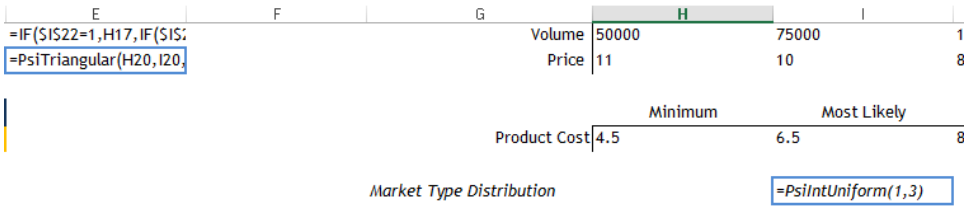
segments such as: *modelSettings* (where options such as the number of simulations maybe be specified), *engineSettings* (where options related to the Engine may be specified), *data* (where constant values used in a constraint or the objective may be defined), and *formula* (where intermediate results may be calculated then used in the calculation of a constraint or the objective).

Our example includes four: *uncertainVariables*, *data*, *formulas* and *uncertainVariables*. Let's compare our Excel model with our newly generated RASON model section by section, starting with *uncertainVariables.*

If we click back to the Excel example, we can see the model in the Model tab in the Solver Task Pane.



Under Uncertain Variables, in the Model tab of the Solver Task Pane, we see two cells, E17 & I22. Each cell contains a PSI Distribution function.



Now click back to your RASON model.

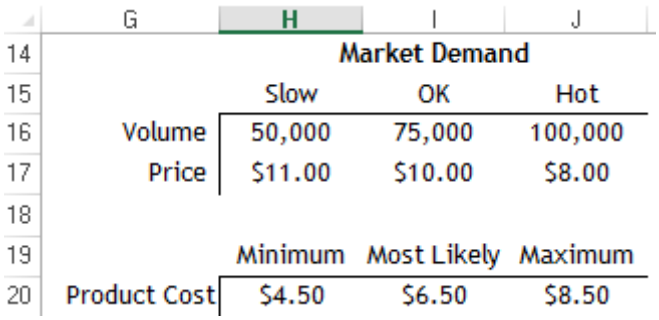
```
uncertainVariables: {
    "e17": { formula: "PsiTriangular(H20,I20,J20)" },
    "i22": { formula: "PsiIntUniform(1,3)" }
},
```

Within the *uncertainVariables* section, we see the same cell ranges, E17 and I22. In our RASON model, e17 and i22 are arrays containing one element each. The formula property contains the PSI Distribution function as contained in the Excel cells.

```
variables: {
    "c14:e14": { value: 0, lower: 0 }
}
```

Let's move on to the *data* section.

The data is contained in the Excel model within the cell ranges: H16:J17 and also H20:J20.

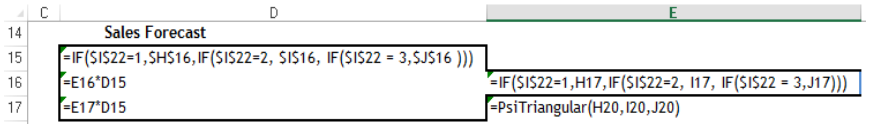


	G	H	I	J
14		Market Demand		
15		Slow	OK	Hot
16	Volume	50,000	75,000	100,000
17	Price	$11.00	$10.00	$8.00
18				
19		Minimum	Most Likely	Maximum
20	Product Cost	$4.50	$6.50	$8.50

The exact same values have been inserted into 10 single element arrays: h20, i20, j20, h17, i17, j17, h16, i16, j16, and d18.

```
data: {
    "h20": { value: 4.5 },
    "i20": { value: 6.5 },
    "j20": { value: 8.5 },
    "h17": { value: 11 },
    "i17": { value: 10 },
    "j17": { value: 8 },
    "h16": { value: 50000 },
    "i16": { value: 75000 },
    "j16": { value: 100000 },
    "d18": { value: 120000 }
},
```

Within the RASON model, intermediate results contained in cells e16, d15, d16, and d17 are calculated in the formulas section.



	C	D	E
14		Sales Forecast	
15		=IF($I$22=1,$H$16,IF($I$22=2, $I$16, IF($I$22 = 3,$J$16)))	
16		=E16*D15	=IF($I$22=1,H17,IF($I$22=2, I17, IF($I$22 = 3,J17)))
17		=E17*D15	=PsiTriangular(H20,I20,J20)

If you compare the cell formulas in Excel to the formula property in RASON, you will find they match.

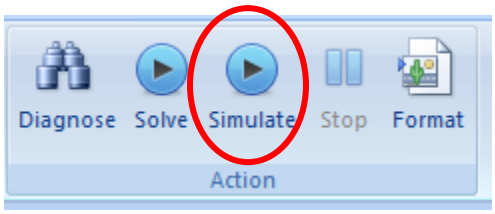
```
formulas: {
    "e16": { formula: "IF($I$22=1,H17,IF($I$22=2,
I17, IF($I$22 = 3,J17)))" },
    "d15": { formula: "IF($I$22=1,$H$16,IF($I$22=2,
$I$16, IF($I$22 = 3,$J$16 )))" },
    "d16": { formula: "E16*D15" },
    "d17": { formula: "E17*D15" }
},
```

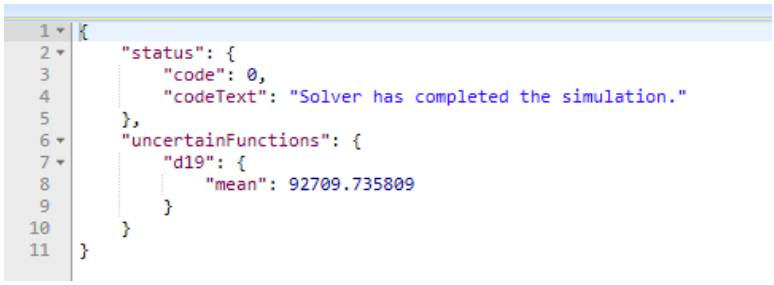
In the last section, *uncertainFunctions*, we find the calculation of D19. In Excel, the formula in cell D20 makes cell D19 an uncertain function using the formula, =PSIMeanD19. In the previous chapter, Examples: Simulation & Risk Analysis, we learned that whenever a PSI Statistic function (such as PsiMean, PsiStdDev, etc.) is applied to a formula containing uncertainty, that cell will become an uncertain function. Therefore, in the RASON model, the definition for the uncertain function d19 contains the statistic property mean:[]. This property will be returned in the solution.

```
uncertainFunctions: {

    "d19": { formula: "D16-D17-D18", mean: [] }
}
```

At the end of this section, a closing } ends the RASON model.

Click the Simulate icon, at the top of the IDE, to run a simulation and display the results in the right of the IDE.





```
{
    "status": {
        "code": 0,
        "codeText": "Solver has completed the simulation."
    },
    "uncertainFunctions": {
        "d19": {
            "mean": 92709.735809
        }
    }
}
```

Solver SDK Platform was able to run a simulation and return the mean of the uncertain function, d19.

Now let's quickly run through one more example using a simulation optimization model. Click back to **Help – Examples** on the ribbon, click Simulation Optimization Examples and then the Yield Management Model 3 link to open YieldManagementModel3.xlsx. In this example, we will maximize the expected revenue of a proposed flight. This model contains 1 integer decision variable (number of tickets sold) and one uncertain variable. The uncertain variable models the uncertainty of the number of no-shows.

NOTE: When creating a RASON model through desktop Analytic Solver or AnalyticSolver.com, model elements (objective function, decision variables, constraints, uncertain variables and/or uncertain functions) may now appear on multiple worksheets within the same Excel workbook.

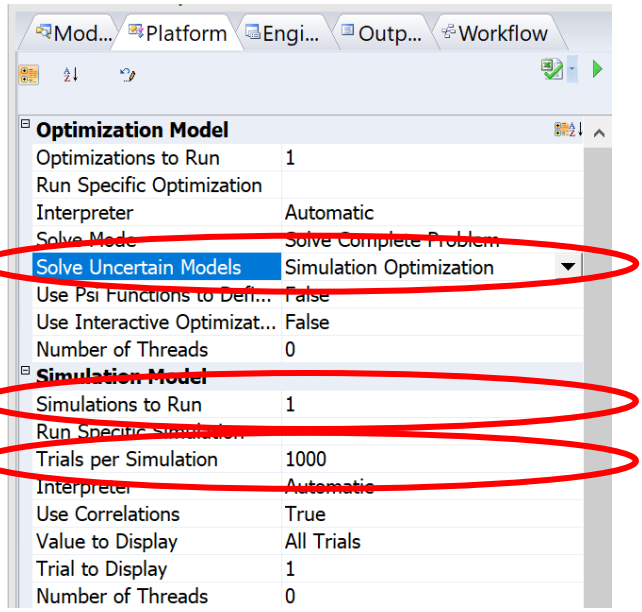
	E	F	G	H
23				
24		Ticket Price	$ 200.00	
25		Flight Capacity	100	
26		Number of no-shows	9	9.02054052
27				
28		Refund to no-shows	50%	
29		Overbooking Compensation	125%	
30				
31		Number of Tickets Sold	117	
32		Number of Customers showing up	108	
33		Number of Overbooked tickets	8	
34				
35		**Total Revenue**	**$ 20,500.00**	
37		**Expected Revenue**	**$ 20,619.65**	
38				

Click Create App – RASON IDE. The RASON Desk IDE opens displaying the code for the converted simulation model.

```
{
    comment: "This model has been generated by Psi from an Excel model in the workbook YieldManagementModel3(SimOpt).xlsx",
modelSettings: { worksheets: ["Yield_Management_3"], activeSheet: "Yield_Management_3", simulationOptimization: true, randomSeed: 123, randomGenerator: 1, samplingMethod: 2 },

variables: {
    "g31": { value: 117, type: "int", lower: 0, upper: 200, finalValue: [] }
},
uncertainVariables: {
    "h26": { formula: "PsiLogNormal(0.1*G31,0.06*G31)" }
},
data: {
    "g24": { value: 200 },
    "g28": { value: 0.5 },
    "g29": { value: 1.25 },
    "g25": { value: 100 }
},
formulas: {
    "g26": { formula: "ROUND(H26,0)" },
    "g32": { formula: "G31-G26" },
    "g33": { formula: "MAX(0,G32-G25)" }
},
uncertainFunctions: {
    "g35": { formula: "(G31*G24)-(G28*G24*G26) - (G29*G24*G33)", mean: [], trials: [], percentiles: [] }
},
objective: {
    "g37_": { formula: "PsiMean(G35)", type: "max", finalValue: [] }
}
}
```

Again, the RASON model opens with an opening {. Simulation optimization models will contain at the very least, the following sections: *variables* (where the decision variables will be defined), uncertainVariables (where the uncertainty will be defined) and objective. Our simulation optimization example includes three more: modelSettings, formulas and data. This simulation model is unconstrained, meaning there are no constraints in the model, only variable bounds. However, most simulation optimization models will have at least one constraint. Let's compare our Excel model with our newly generated RASON model section by section, starting with *modelSettings*.

Click back to the Excel model and then click the Platform tab on the Model Task pane.

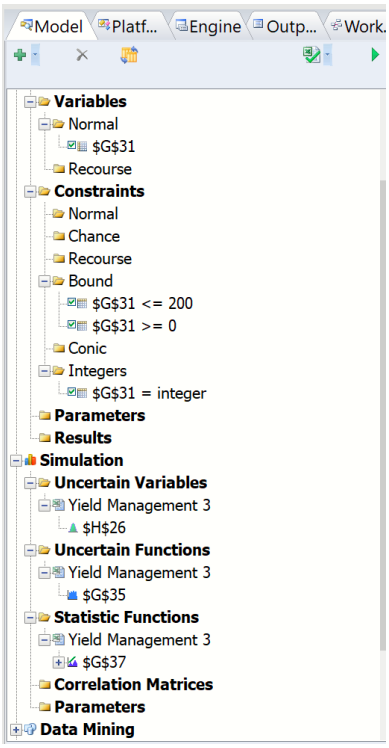


Within this pane, we see that *Solve Uncertain Models* is set to *Simulation Optimization*, *Simulations to Run* equals 1 and *Trials Per Simulation* equals 1000. These settings will cause Solver to solve the model with the Evolutionary Engine and simulation optimization using 1000 trials per simulation.

After the opening {, the first section of the RASON model is *modelSettings*. In this section, options relevant to the solve, such as the number of optimizations or simulations to run, the number of trials to perform in a simulation model, if simulation optimization is to be used, etc., are specified. In this example, the *simulationOptimization* property is set to "true", the Number of Trails to be performed within the simulation is set to 1000 (*numtrials: 1000*) and the random seed is set to 1 (randomSeed: 1). The random seed option is used so that our results will be reproducible. Any option that is set on the Platform tab on the Solver Task Pane will be recorded in this section. See the *Frontline Solvers Reference Guide* for a complete description of each option that may be specified in *modelSettings*.

```
modelSettings : { simulationOptimization: true,
numTrials: 1000, randomSeed: 1 },
```

If we click back to the Excel example, we can see the model in the Model tab in the Solver Task Pane.



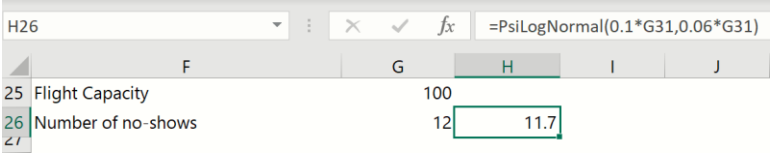
Under Normal Variables, in the Model tab of the Solver Task Pane, we see the Excel range, G30. Lower down, the same Excel range is listed as "integer" under Integers. A little further up under Bound, we see the upper and lower bound for this cell as 200 and 0, respectively. This means that the values in this cell must be an integer greater than or equal to 0 and less than or equal to 200.

In the variables section of the RASON model, you'll see the following line of code.

```
variables: {
    "g31": { value: 117, type: "int", lower: 0,
upper: 200, finalValue: [] }
},
```

In these three lines of code, the single element array *g31* is created and given an initial value of 117 using the value *property*. (This is because cell G31 in the Excel model contained that same value at the time of conversion.) The *type* property indicates that the variable must be an "int" or "integer". The *lower* property holds the lower bound of 0 and the *upper* property holds the upper bound of 200. The finalValue property asks the RASON Server to return the final value of this variable in the results.

Click back to Excel. Under Uncertain Variables, we see the Excel cell address, H25. If you inspect this cell, you will see that it contains the Psi Distribution function PsiLogNormal. This function simulates the number of people who will not show up or miss their flight.

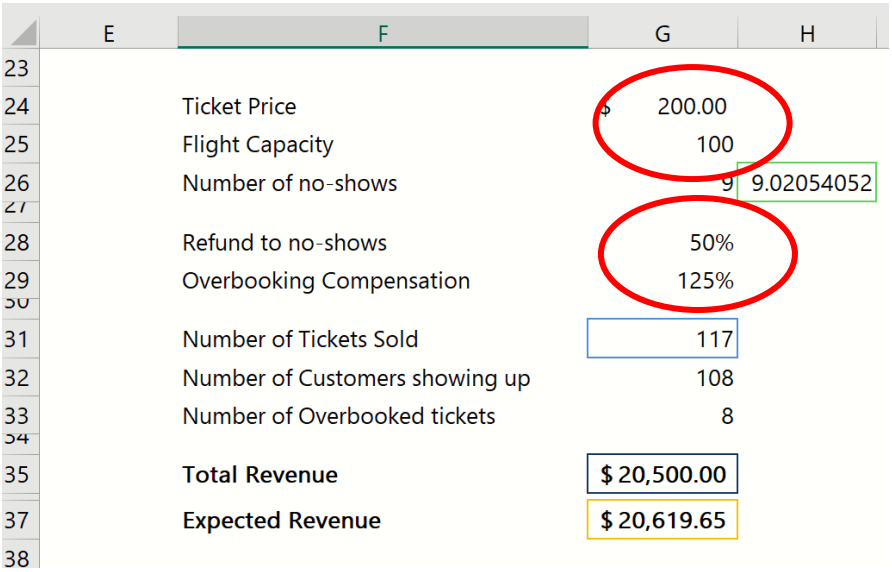


Within the *uncertainVariables* section, the single element array h26 is created with the same formula that is contained in the Excel worksheet cell H25, =PsiLogNormal(0.1 * G31, 0.06*G31).

```
uncertainVariables: {
    "h26": { formula:
"PsiLogNormal(0.1*G31,0.06*G31)" }
},
```

Let's move on to the *data* section where we will define the data used in the model.

In the Excel model, the data is contained in cells: G24 (Ticket Price), G25 (Flight Capacity), G28 (% Refund to No-shows) and G29 (Overbooking Compensation).

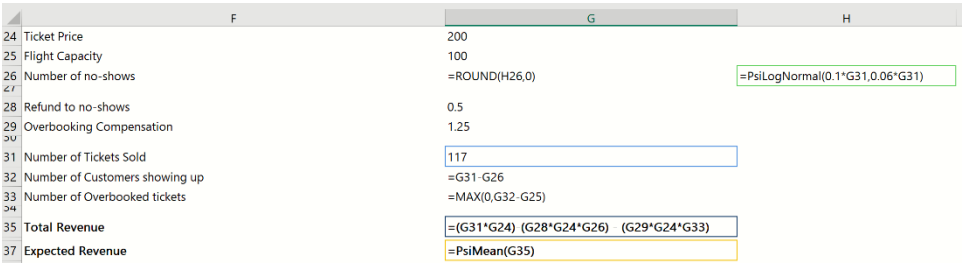


	E	F	G	H
23				
24		Ticket Price	$ 200.00	
25		Flight Capacity	100	
26		Number of no-shows	9	9.02054052
28		Refund to no-shows	50%	
29		Overbooking Compensation	125%	
31		Number of Tickets Sold	117	
32		Number of Customers showing up	108	
33		Number of Overbooked tickets	8	
35		**Total Revenue**	**$ 20,500.00**	
37		**Expected Revenue**	**$ 20,619.65**	
38				

The exact same values have been inserted into 4 single element arrays within the *data* section of the RASON model.

```
data: {
    "g24": { value: 200 },
    "g28": { value: 0.5 },
    "g29": { value: 1.25 },
    "g25": { value: 100 }
},
```

The formulas section, within the RASON model, holds the intermediate formulas contained in the Excel worksheet cells G26, G32, and G33.



	F	G	H
24	Ticket Price	200	
25	Flight Capacity	100	
26	Number of no-shows	=ROUND(H26,0)	=PsiLogNormal(0.1*G31,0.06*G31)
28	Refund to no-shows	0.5	
29	Overbooking Compensation	1.25	
31	Number of Tickets Sold	117	
32	Number of Customers showing up	=G31-G26	
33	Number of Overbooked tickets	=MAX(0,G32-G25)	
35	**Total Revenue**	=(G31*G24) (G28*G24*G26) (G29*G24*G33)	
37	**Expected Revenue**	=PsiMean(G35)	

Notice the formula properties for each of the four single element arrays matches the formula in the matching Excel cell.

```
formulas: {
    "g26": { formula: "ROUND(H26,0)" },
    "g32": { formula: "G31-G26" },
    "g33": { formula: "MAX(0,G32-G25)" }
},
```

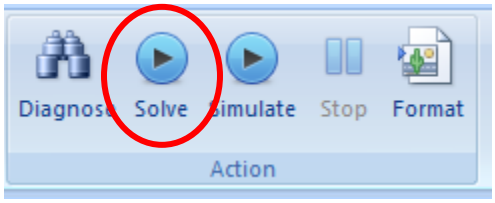
If you click back to the Excel worksheet, the objective is listed at the top of the Model pane. "Max" which appears to the immediate right of the cell address G37, indicates that the model is a maximization. The formula contained in cell G37 = PsiMean(G35). This formula will return the mean value for the uncertain function in cell G35. (See the screenshot above.)

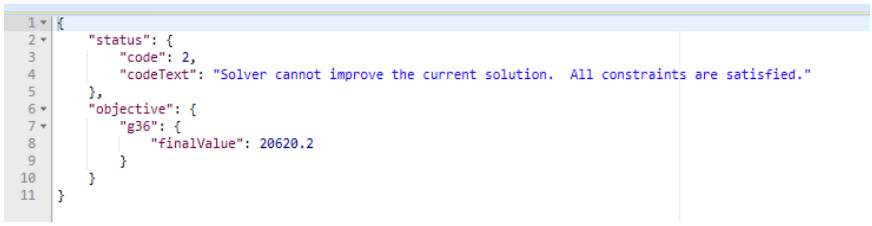
In the RASON model, the single element array g37 holds the objective function definition. As in the Excel model, the objective function will be maximized as indicated by the type property (type: "max").

```
objective: {
    "g37": { formula: "PsiMean(G35)", type: "max" }
}
```

At the end, a closing } ends the RASON model.

Click the Solve icon, at the top of the IDE, to run an optimization simulation and display the results in the right of the IDE.





Solver SDK Platform solves the simulation optimization model and returns the mean of the objective function.

For more information on designing and writing a model in the RASON Modeling Language, please see the *RASON User Guide* and/or *RASON Reference Guide*.

Conversion Exceptions

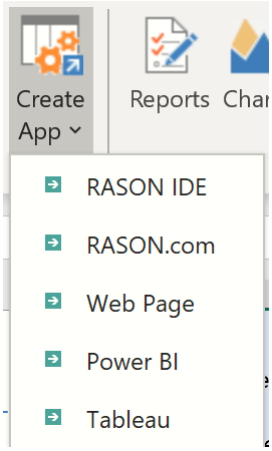
There are several types of models that Frontline Excel Solvers are not able to convert to RASON models. For example, it is not possible to convert NLP/NSP models with conic constraints or Excel models containing errors such as #NUM, #VALUE, etc. For all unsupported features, the conversion generator returns an appropriate message.

Problem Limits

Your Frontline Excel Solver license determines the size and type of model that can be solved with the RASON Desk IDE. If you have a license for Analytic Solver Comprehensive, then the same problem limits will apply when solving a RASON model using the RASON Desk IDE, i.e. linear models with up to 8,000 variables (2,000 integers) and 8,000 constraints; smooth, nonlinear models with up to 1,000 variables and 1,000 constraints; nonsmooth models with up to 1,000 variables and 1,000 constraints and SOCP models with up to 2,000 variables and 8,000 constraints.

Solving a Model Using the RASON Web IDE

Now let's solve the same three models using the RASON Web IDE. Click back to the Product Mix example, then click **Create App – RASON.com.**



NOTE: When creating a RASON model through desktop Analytic Solver or AnalyticSolver.com, model elements (objective function, decision variables, constraints, uncertain variables and/or uncertain functions) may now appear on multiple worksheets within the same Excel workbook.

In a matter of seconds, a browser opens and navigates to the Web IDE on the Try It page at www.RASON.com. The Product Mix model, now written in the RASON modeling language, is displayed in the Model Editor.

Note on RASON Subscriptions

If you have already registered for an account on www.RASON.com, you will be automatically logged in using your existing credentials. If you are a subscriber to a premium plan, you will be subject to the problem limits of the purchased plan.

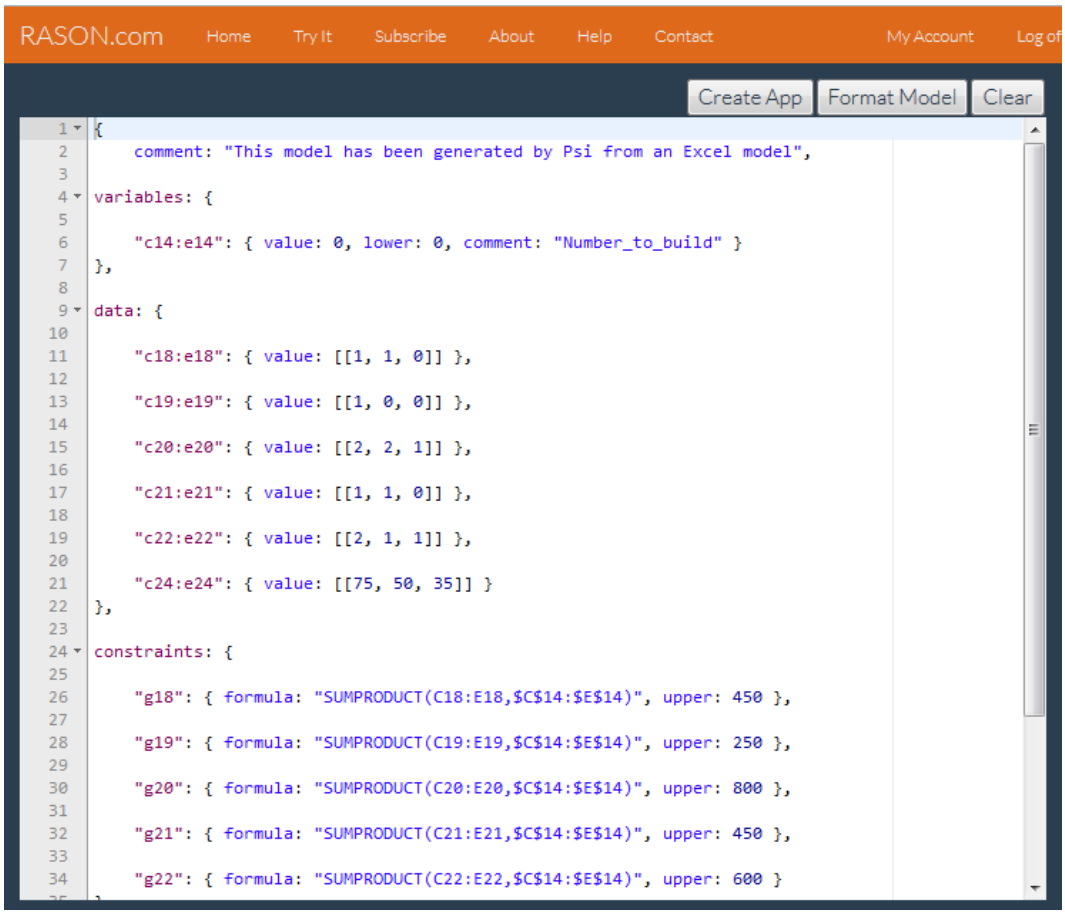
If you have not registered for an account on www.RASON.com, you will be automatically registered for a *free* account and logged in using information obtained from your registration on the Frontline Systems website, www.Solver.com. Your User Name to log in to www.RASON.com will be the same as your User Name for www.solver.com and your default password will be: {your email address} + !A123. You will be subject to the size limits of the free Basic subscription, unless or until you subscribe to a higher level plan.

Currently, there are three subscription plans to choose from, one free Basic plan and two higher level plans (Pro and Platform).

The free basic subscription allows the following problem limits.

- Solve linear models with up to 200 variables
- Solve nonlinear models with up to 100 variables
- Run Monte Carlo simulations with up to 10,000 trials
- Includes 240 minutes (4 hours) of compute time per month

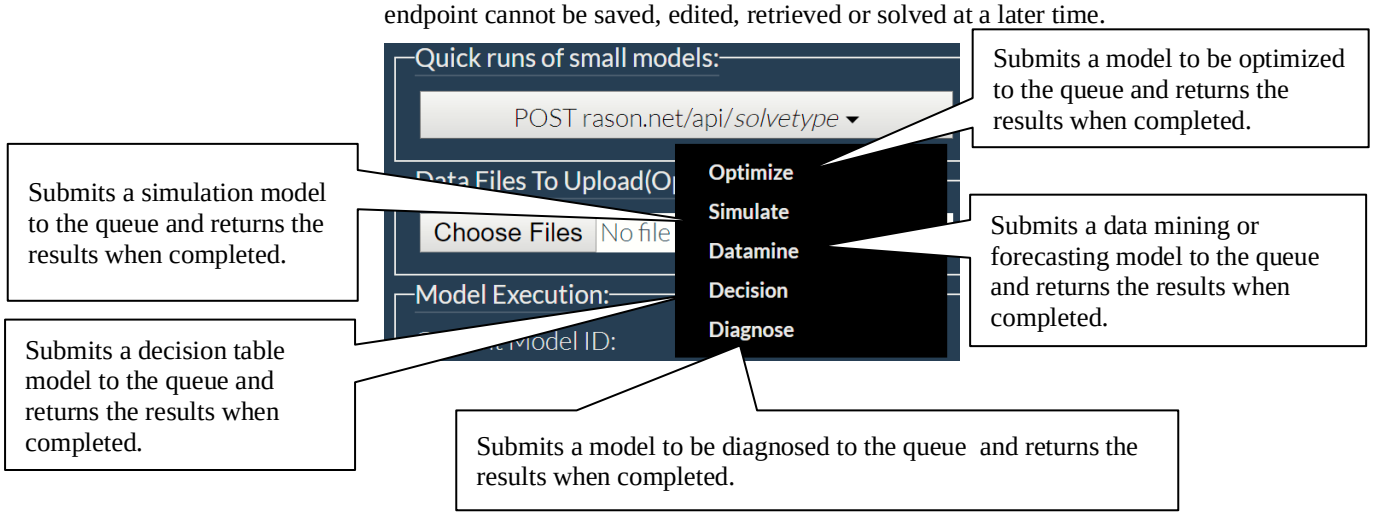
  If you find yourself pushing the limits of the Basic plan, then you can upgrade either to the Platform or Pro plan. (Contact Sales@solver.com for information related to plan pricing.)



Models entered into the Rason Model Editor in the Web IDE may be solved or analyzed using either a 'Quick Solve' REST API endpoint or a standard REST API endpoint. Note: The endpoints displayed on these command buttons are the actual REST API endpoints that will be called when you create your own webpage in the next section. For more information on these endpoints, see the *RASON User Guide*.

The first five REST API calls are the 'Quick Solve' endpoints. 'Quick Solve' endpoints are synchronous and should only be used with models that solve very quickly, i.e. within a few seconds. There is a time limit of 30 seconds on all 'Quick Solve' calls which means that if your model takes longer than 30 seconds

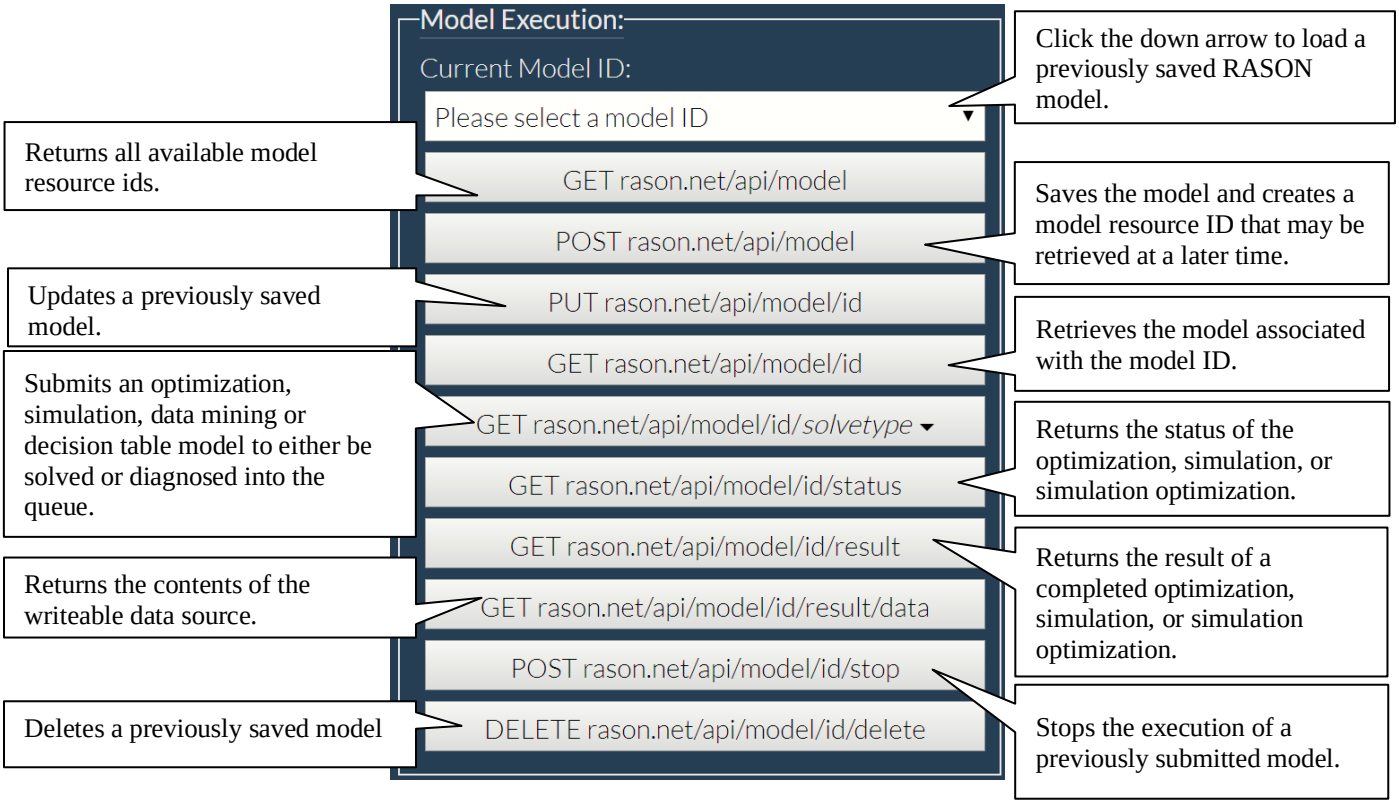
to solve, the RASON Server will return the result: `"status" : { "code" : 10, "codeText" : "Stop chosen when the maximum time limit was reached." }`. In addition, the "model resource ID" for these endpoints are not saved to the RASON server which means that a model optimized, simulated, data mine, calculated or diagnosed with a 'Quick Solve' endpoint cannot be saved, edited, retrieved or solved at a later time.



Select Optimize from the Quick Runs drop down menu to call the RASON endpoint, **POST rason.net/api/optimize**.

The model is submitted to the RASON Server which solves the model and returns the result in the Result window, shown above.

For all but the smallest / most quickly solved models, you'll need to use the second set of REST API calls. You'll first need to make a call to the REST API endpoint *POST rason.net/api/model* which will create a "model resource". Then you'll need to start an optimization via the REST API endpoint *GET rason.net/api/model/id/optimize*. You can check on its progress at any time with the REST API endpoint *GET rason.net/api/model/id/status* and obtain results when finished with the REST API endpoint *GET rason.net/api/model/id/result*.



Click POST rason.net/api/model to call the REST API endpoint *POST rason.net/api/model* to post the model to the RASON Server. In return you will receive a similar result.

```
Model submitted to location:
https://rason.net/api/model/2590+2019-05-15-20-33-31-034142
```

Calling this endpoint creates the Model Resource, 2590+2019-05-15-20-33-31-034142. We can now easily retrieve this model by clicking the down arrow next to "Please select a model ID" and selecting this value from the menu.

Click GET rason.net/api/model/id/optimize to call the REST API endpoint *GET rason.net/api/model/id/optimize* to optimize (or solve) the model . Since we did not specify a specific engine, and we are solving a linear model, the LP/Quadratic engine will be selected automatically.

```
Model has been placed in the queue to be optimized.
```

Call GET rason.net/api/model/id/status to call the REST API endpoint *GET Rason.net/api/model/id/status* to obtain the status of the solve.

```
{"status": "Complete" }
```

Status: Complete means that the optimization has been completed. If the optimization was still in-progress we would have received an incomplete status with intermediate results, for example: `{"status": "Incomplete", "Milliseconds" : -2147483648,"Iterations" : 0, "Subproblems" : 287, "LocalSolutions" : 8, "Objective" : 3849 }`

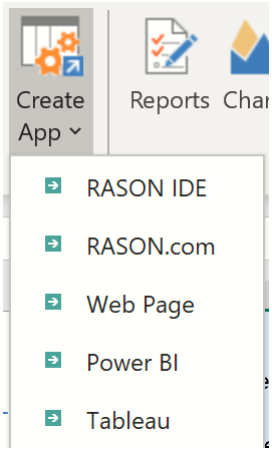
Click GET rason.net/api/model/id/result to call the REST API endpoint *GET rason.net/api/model/id/result* to obtain the result of the optimization.

```
{
"status" : { "code" : 0, "codeText" : "Solver found a
solution. All constraints and optimality conditions
are satisfied." },
"objective" : {
"total" : { "finalValue" : 25000 }
}
}
```

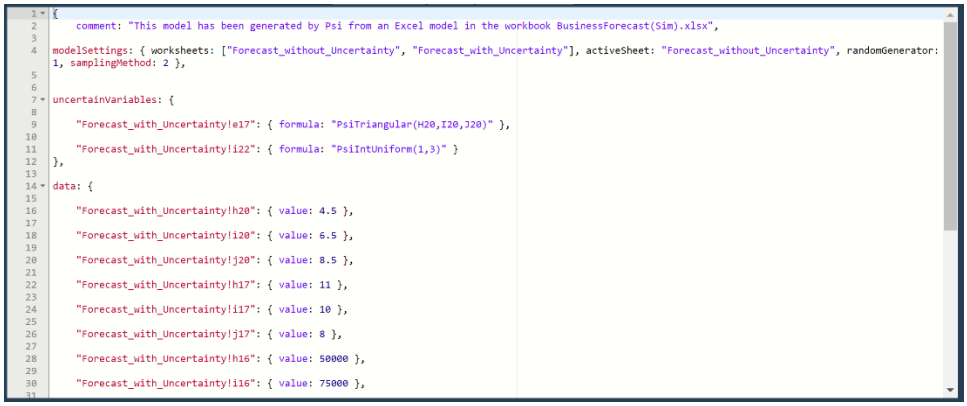
The result "Solver found a solution. All constraints and optimality conditions are satisfied" means that no other solution exists that is better than the solution found. (For more information on this and all possible Solver Result messages, please see the *RASON Reference Guide*.) To maximize profit, we should make 200 TV sets, 200 stereos, and 0 speakers. The final objective value of 25,000 is the maximum profit that we can attain.

Now let's solve the simulation model from the previous section. Click back to Business Forecast example (on the BusinessForecastPsi tab), then click **Create App – RASON.com.**

NOTE: When creating a RASON model through desktop Analytic Solver or AnalyticSolver.com, model elements (objective function, decision variables, constraints, uncertain variables and/or uncertain functions) may now appear on multiple worksheets within the same Excel workbook.

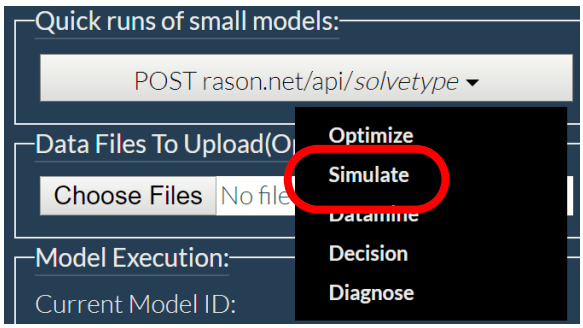


In a matter of seconds, a browser opens and navigates to the Web IDE on the Try It page at www.RASON.com. The Business Forecast model, now written in the RASON modeling language, is displayed in the Model Editor.

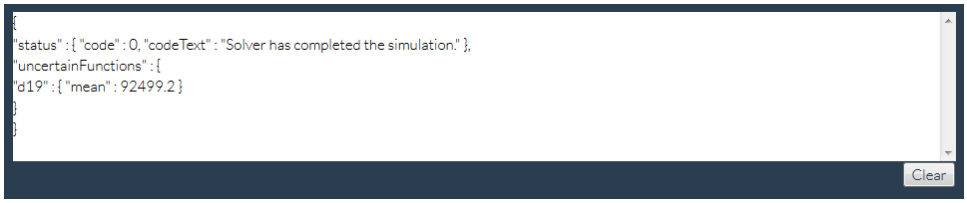


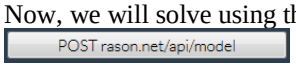
We can solve this model using either the Quick Solve method, by using the Quick Solver endpoint POST rason.net/api/simulate, or by calling the REST API endpoints, POST rason.net/api/model which will create a "model resource". Afterwards, we can run a simulation via the REST API endpoint *GET rason.net/api/model/id/simulate*, check the progress of the simulation at any time with the REST API endpoint *GET rason.net/api/model/id/status* and obtain results when finished with the REST API endpoint *GET rason.net/api/model/id/result.*

First, we will solve via the Quick Solve method. Simply click POST rason.net/aip/simulate under Quick runs of small models.



The model is submitted to the RASON Server and the results are returned in the Output window.



Now, we will solve using the alternative method. Click 

to call the REST API endpoint *POST rason.net/api/model* to post the model to the RASON Server. In return you will receive a similar result in the output window.

```
Model submitted to location:
https://rason.net/api/model/2590+2019-05-26-22-10-22-697698
```

Calling this endpoint creates the Model Resource, 2590+2019-05-26-22-10-22-697698. We can now easily retrieve this model by clicking the down arrow next to "Please select a model ID" and selecting this value from the menu.

Click GET rason.net/api/model/id/simulate to call the REST API endpoint *GET rason.net/api/model/id/simulate* to run a simulation.

```
Model has been placed in the queue to be simulated.
```

Call GET rason.net/api/model/id/status to call the REST API endpoint *GET Rason.net/api/model/id/status* to obtain the status of the simulation.

```
{"status": "Complete" }
```

Status: Complete means that the simulation has been completed. If the optimization was still in progress we would have received an incomplete status with intermediate results, for example: `{"status": "Incomplete", "trials" : 90192 }`

Click GET rason.net/api/model/id/result to call the REST API endpoint *GET rason.net/api/model/id/result* to obtain the results from the simulation.

```
{
"status" : { "code" : 0, "codeText" : "Solver has completed the simulation." },
"uncertainFunctions" : {
"netprofit" : { "mean" : 92619.4 }
}
}
```

The result `"code": 0` means that the simulation completed successfully. Our ***true average*** Net Profit for these 1,000 trials is 92,619.4. Let's ask for the percentile values, as well as the mean, for our uncertain function. It's easy to do. Simply add `percentiles: []` to the end of our `netProfit` uncertain function definition…

```
uncertainFunctions: {
        "d19": {
            formula: "D16-D17-D18",
            mean: [],
            percentiles: []
        }
    }
```

…and update the model by calling PUT rason.net/api/model/id, PUT rason.net/api/model/id

Rather than posting a new model with a new resource ID, this endpoint updates the existing model. Then calls the simulate, status, and result endpoints: *GET rason.net/api/model/id/simulate*, *GET rason.net/api/model/id/status*, and *GET*

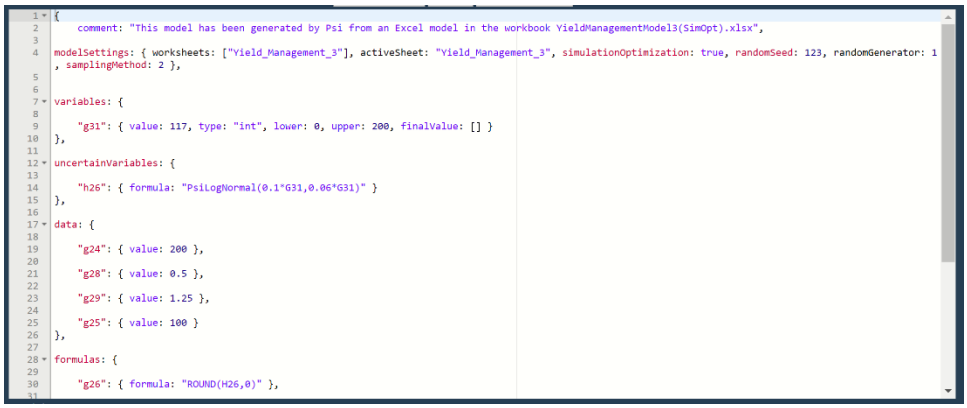
rason.net/api/model/id/result, respectively. The response from the call to *GET rason.net/API/Model/id/result* is below.


```
{
"status" : { "code" : 0, "codeText" : "Solver has
completed the simulation." },
"uncertainFunctions" : {
"d19" : { "mean" : 92466.1, "percentiles" : [-118840,
-100391, -81334.3, -70724.2, -56747.6, -47834.3, -
40197.9, -32682, -24831.7, -18744.9, -11788.1, -
4115.7, 3307.15, 8315.06, 12122.9, 16532.8, 20759.9,
26048.7, 30466.5, 32783.8, 36265.2, 39119.5, 41986.6,
44494.7, 46610.2, 48617.1, 51235.5, 53433.6, 55426.9,
58206.9, 59982.7, 63790.1, 65192.6, 68161.3, 70423.9,
73774.1, 76082.1, 78690.2, 81592.3, 83482.2, 85839.8,
87874.8, 89193.1, 91678.2, 92688.5, 94500.3, 95305.2,
97737.5, 99549.8, 100662, 102015, 103733, 105426,
107313, 109452, 110920, 111992, 113645, 114718,
117848, 119716, 121420, 123089, 124623, 127574,
129610, 130882, 132028, 133942, 136053, 137770,
139250, 141293, 142686, 144987, 147803, 148731,
150397, 154362, 157480, 159889, 162513, 164131,
166126, 169100, 171524, 173488, 176816, 179111,
183990, 187680, 194224, 200666, 205383, 211525,
222330, 233473, 243391, 257954, 284032] }
}
}
```


Using the results from `percentiles: []` we see that we can **lose money** 12% of the time. See the 1st through 12th negative percentile values.

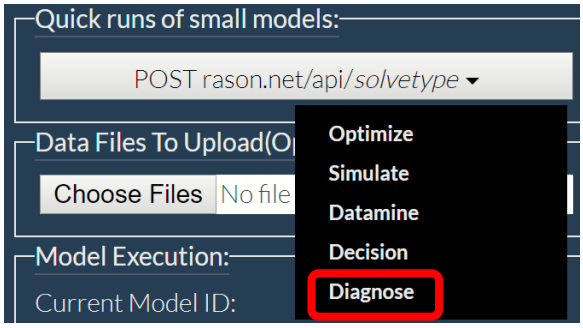
Finally, let's solve our last example, the simulation optimization model, Yield Management 3. Click back to the example, then click **Create App – RASON.com**. A browser opens and displays the model, converted to the RASON Modeling language, in the RASON Web IDE Model window.

NOTE: When creating a RASON model through desktop Analytic Solver or AnalyticSolver.com, model elements (objective function, decision variables, constraints, uncertain variables and/or uncertain functions) may now appear on multiple worksheets within the same Excel workbook.

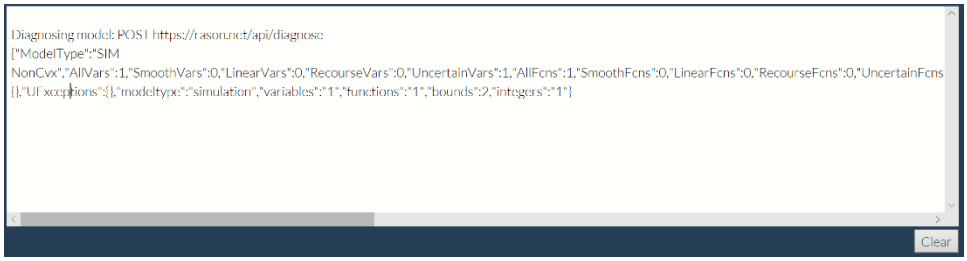


```
{
    comment: "This model has been generated by Psi from an Excel model in the workbook YieldManagementModel3(SimOpt).xlsx",

modelSettings: { worksheets: ["Yield_Management_3"], activeSheet: "Yield_Management_3", simulationOptimization: true, randomSeed: 123, randomGenerator: 1
, samplingMethod: 2 },


variables: {

    "g31": { value: 117, type: "int", lower: 0, upper: 200, finalValue: [] }
},

uncertainVariables: {

    "h26": { formula: "PsiLogNormal(0.1*G31,0.06*G31)" }
},

data: {

    "g24": { value: 200 },

    "g28": { value: 0.5 },

    "g29": { value: 1.25 },

    "g25": { value: 100 }
},

formulas: {

    "g26": { formula: "ROUND(H26,0)" },
```

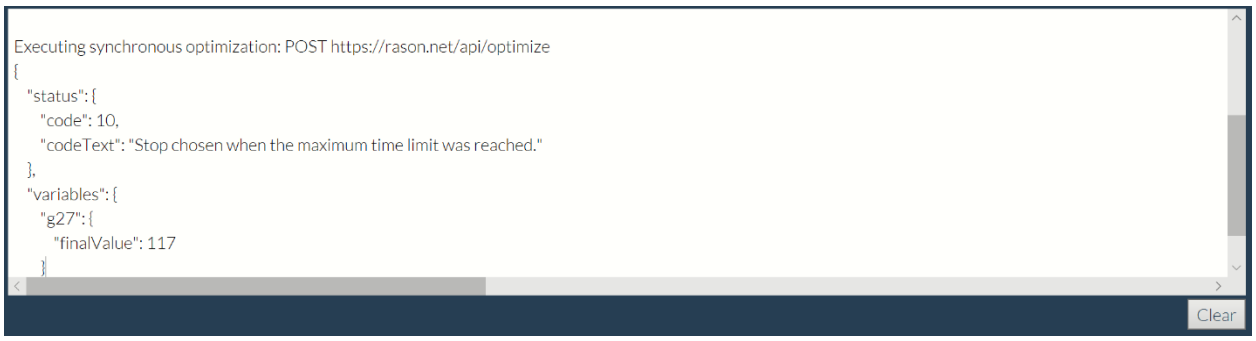
This time, let's diagnose the model first using the Diagnose Quick Solve Endpoint: *POST rason.net/api/diagnose*.



The model is diagnosed as a "simulation" model containing 1 integer variable, 1 function, and 2 variable bounds, an upper and a lower.



Now, let's use the Quick Solve Optimize Endpoint to solve this model. Click the optimize Quick Solver endpoint *POST rason.net/api/optimize*.



The simulation optimization was terminated after the 30 second solving limit elapsed. The result shown in the Output window displays the result code, "Stop chosen when the maximum time limit was reached" along with the intermediate final variable value of 117.

Now let's solve using the RASON Rest API Endpoints. Click POST rason.net/api/model to call the REST API endpoint *POST rason.net/api/model* to post the model to the RASON Server. In return you will receive a similar result in the output window.

```
Model submitted to location:
https://rason.net/api/model/2590+2019-10-14-19-27-12-
984092
```

Calling this endpoint creates the Model Resource, 2590+2019-10-14-19-27-12-984092. We can now easily retrieve this model by clicking the down arrow next to "Please select a model ID" and selecting this value from the menu.

Click GET rason.net/api/model/id/simulate to call the REST API endpoint *GET rason.net/api/model/id/simulate* to start the simulation optimization.

```
Model has been placed in the queue to be optimized.
```

Call GET rason.net/api/model/id/status to call the REST API endpoint *GET Rason.net/api/model/id/status* to obtain the status of the simulation optimization.

```
{"status": "Complete", "Milliseconds" :
31203,"Iterations" : 0, "Subproblems" : 22658,
"LocalSolutions" : 22656, "Objective" : 20620.15 }
```

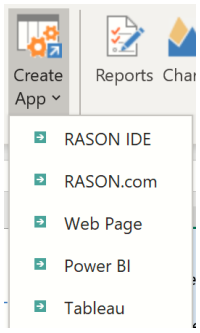
Status: Complete means that the simulation optimization has been completed. If it was still in progress we would have received an incomplete status with intermediate results like we saw with the Quick Solve endpoint.

Click GET rason.net/api/model/id/result to call the REST API endpoint *GET rason.net/api/model/id/result* to obtain the results from the simulation optimization.

```
Getting model results: GET
https://rason.net/api/model/2590+2020-02-26-23-10-38-
393105/result
{ "status": {

      "code": 2,

      "codeText": "Solver cannot improve the current
      solution. All constraints are satisfied."

      },

"variables": {

      "g27": { "finalValue": 117 }

      }

}
```

Creating a Web Page

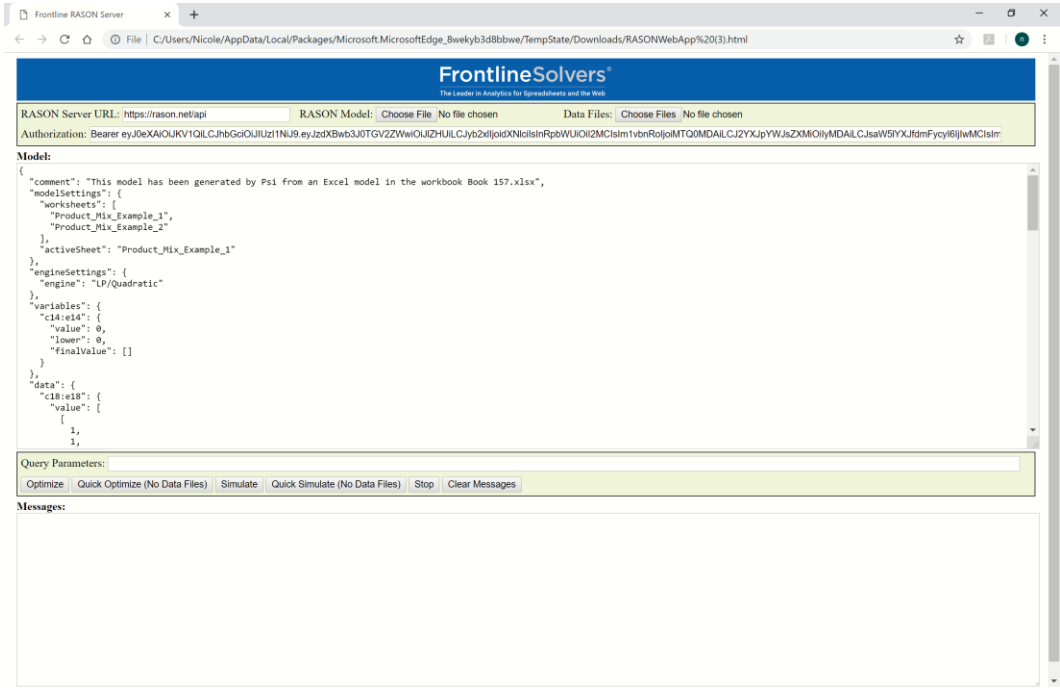
Analytic Solver includes the ability to bypass months of development work by creating a web application that solves the optimization, simulation, and/or simulation optimization model in Excel. Click back to Excel, and the Product Mix example, then click Create App – Web Page.



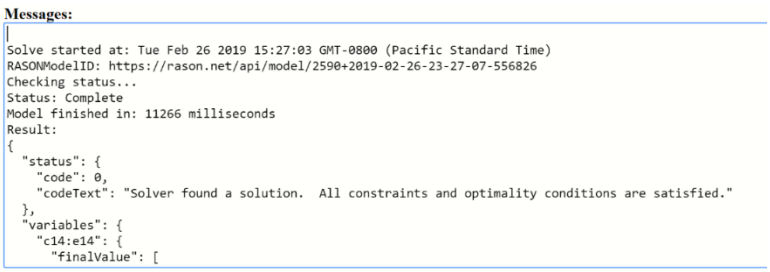
NOTE: When creating a RASON model through desktop Analytic Solver or AnalyticSolver.com, model elements (objective function, decision variables, constraints, uncertain variables and/or uncertain functions) may now appear on multiple worksheets within the same Excel workbook.

Immediately, a browser opens displaying the newly created Web Application.

See *Note on RASON Subscriptions* in the section above for log in and subscription information pertaining to solving models via the RASON Server.



Click O**ptimize**.



Automatically, the model is submitted to the RASON Server using the RASON Rest API Endpoint *POST rason.net/api/model*, an optimization is started with

the Endpoint *GET rason.net/api/model/id/optimize*, the status is checked using the Endpoint *GET rason.net/api/odel/id/status* and the results are obtained via the Endpoint *GET rason.net/api/model/id/result*. All this, at the click of a button.

Clicking the Quick Optimize command button will call the Quick Solve Optimize endpoint. Try it for yourself – the results from the Quick Solve will be appended in the Result window.

Click Stop Optimize to stop an already executing optimization and Clear Messages to clear the output window.

Click back to the Business Forecast example and click Create App – Web Page. A new browser open displaying a new Web Application. This Web App solves the Business Forecast simulation model.

Click Simulate. Automatically, the model is submitted to the RASON Server using the RASON Rest API Endpoint *POST rason.net/api/model*, a simulation is started with the Endpoint *GET rason.net/api/model/id/simulate*, the status is checked using the Endpoint *GET rason.net/api/odel/id/status* and the results are obtained via the Endpoint *GET rason.net/api/model/id/result*. All this, at the click of a button.

```
Simulate started at: Tue Feb 26 2019 15:32:33 GMT-0800 (Pacific Standard Time)
RASONModelID: https://rason.net/api/model/2590+2019-02-26-23-32-35-730216
Checking status...
Status: Incomplete
Status: Complete
Model finished in: 4324 milliseconds
Result:
{
  "status": {
    "code": -10,
    "codeText": "Problem could not be loaded. Duplicated Json assignment PSI could not parse Excel formulas.",
    "message": "Problem could not be loaded. Duplicated Json assignment PSI could not parse Excel formulas.",
    "line": 1
  }
```

Clicking the Quick Simulate command button will call the Quick Solve Simulate endpoint.

To view the code used in the Web Application, right click and select **View Page Source** (if using Mozilla Firefox) or **View Source** (if using Internet Explorer). A browser will open displaying the code for the Web Application. This code gives examples of how to call all RASON REST API Endpoints. Please see the RASON User Guide for a description of each along with complete information about the RASON Rest API.

```
<!DOCTYPE html>
<!-- saved from url=(0014)about:internet -->
<html xmlns="http://www.w3.org/1999/xhtml">
<head>
    <meta charset="utf-8" />
    <meta http-equiv="X-UA-Compatible" content="IE=edge" />
    <script type="text/javascript" src="https://code.jquery.com/jquery-1.9.1.min.js"></script>
    <title>Rason Server Example</title>
    <script type="text/javascript" language="javascript">
        // This script demonstrates how you can solve RASON models in two ways. The first way is the 'Quick Solve' method and is intended
        // to be used with simple models that solve quickly. Solving harder models using the RASON REST API is demonstrated below as well.
        // This approach is intended for more complex models requiring more significant computational effort and time.
        var rasonApp = {
            RASONModelID: false,
            solveStopped: false,
            // URL fragment determining whether or not we are simulating or optimizing the model
            RASONEntry: '/optimize',
            RASONServer: 'https://rason.net/api',
            ////////////////////////////////////////////////////
            // The declarative model we will solve with this app
            RASONModel: {
    comment: "This model has been generated by Psi from an Excel model",


uncertainVariables: {

    "e17": { formula: "PsiTriangular(H20,I20,J20)" },

    "i22": { formula: "PsiIntUniform(1,3)" }
},

data: {

    "h20": { value: 4.5 },

    "i20": { value: 6.5 },

    "j20": { value: 8.5 },

```

Using Decision Tables

Introduction

Decision Tables were introduced to Analytic Solver starting in V2019. A decision table contains a set of rules which specify actions to perform based on specific conditions. Decision tables are a good tool to use when there is a consistent number of rules, or conditions, to be evaluated followed by a specific set of actions to be performed once a rule, or condition, is met. For example, the simple decision table below returns an employee's pay based on the number of hours worked.

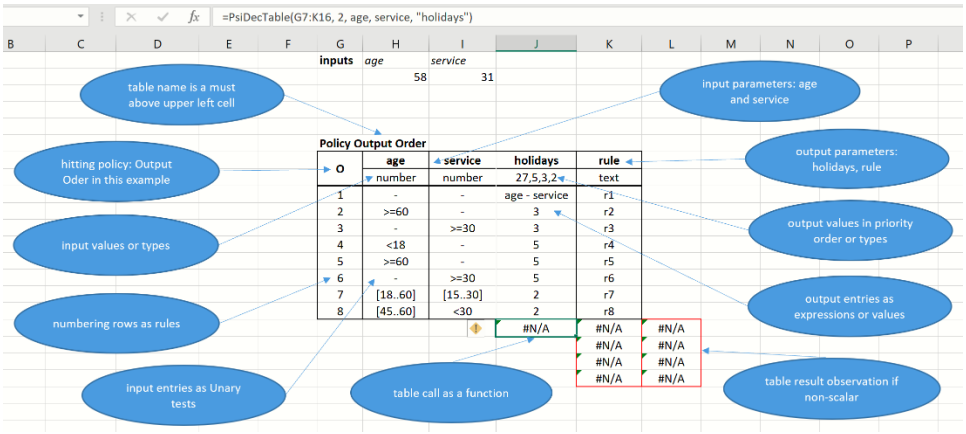
C+	hours	pay
	number	27,5,3,2
1	[1..40]	25*hours
2	>40	45*(hours – 40)

If the employee worked from 1 to 40 hours in a week, the pay is $25 * hour. If any overtime is worked, the employee gets paid $45 an hour for any hour above 40.

In Analytic Solver, a decision table is a specific realization of a custom function. A table has a name, input/output parameters and a body implementing the logic through a structured framework. A decision table is invoked in the same way as a VBA function when computing one or more output parameters for the passed one or more input values. In Analytic Solver, a decision table is invoked using the Psi function, PsiDecTable(). The modeling language inside of Analytic Solver's Decision Table tool is S-FEEL extended to standard conversion functions in FEEL. For more information on Decision Tables, we invite you to reference the following: DMN Method and Style by Bruce Silver (Cody Cassidy Press, September 28, 20180 and DMN Cookbook by Bruce Silver & Edson Tirelli (Cody-Cassidy Press, April 4, 2018).

Decision Table Structure

Open the example model, DT Structure.xlsx by clicking **Help – Examples – Decision Trees/Decision Tables** on the Ribbon. This table returns the number of holidays apportioned to an employee based on his/her age and number of years in service. This file defines the regions of the decision table as illustrated in the screenshot below.



A Decision Table is created using the newly introduced PsiDecTable() function where the cell range of the table is passed as the first argument. See the PsiDecTable() function as it appears in cell J17, =PsiDecTable(G7:K16,2,age,service,"holidays") where:

- G7:K16 - The cell address range of the table is G7:K16.
- 2 – The number of input variables
- age, service – input variables
- "holidays" – output

The steps required to create the decision table above are listed below.

Step 1: Enter a *unique* Name for the table immediately above the upper left corner of the table, to define the table. (This argument creates the decision table object and identifies the table.) *In this example, the table name is specified as "Policy Output Order".* When Excel generates the RASON Code, the name component is used to identify this specific table.

Step 2: Enter a header, consisting of one or two rows, separated to the right and below by a double horizontal line. The first row in the header is mandatory. *Two headers are contained in the table above, age, and service.*

Step 3: Enter a Hit Policy, usually a capital letter or a name, entered in the upper left cell of the table. The Hit policy specifies how the table will be evaluated when multiple rules are applicable and hence, multiple output values are returned. The entered value identifies the supported policies by a capital letter and an operator when applicable. You may enter the 1st letter of the policy or the whole word. The currently supported Hit types and their meanings are:

Unique (U): A unique rule must "hit" evaluating to a unique result. If multiple rules are "hit", an error will be returned.

Any (A): If rules overlap, but point to the same result, that unique result is returned.

Priority(P): If multiple rules are "hit" and multiple results collected, return only one result with the highest priority; the priorities are defined by the order of the output values.

First (F): Only 1 result is returned for this policy. Once a rule is evaluated successfully, or a hit occurs, the search stops.

Rule Order (R) - If multiple rules are hit, return the collection of results as created in the rule order

Output Order (**O**) – *Currently entered value in cell G7.* If multiple rules are hit, return the collection of results in the priority order of the listed output values.

Collect (**C**) – The same as (**R**). However, we may make this policy more specific by adding an operator to it in order to allow aggregation.

Note: If aggregating a date, a scalar is returned. If using an operator, output must not be a string, but only a numerical value.

C+ - sum the matched output values

C< - return the min of matched output values

C> - return the max of matched output values

C# - return the number of matched output values

Step 4: Enter Input Parameters in the 1st header row next to Hit policy and up to the double vertical lines. The input parameter names are listed to the left of the double vertical line. *In this example, age and service are the input parameters.* These input parameters belong to the local scope of this table.

Step 5: Enter Output Parameters in the 1st header row to the right side of the double vertical lines. *In this example, holidays and rule are the output parameters.* After calculation, a table returns a few selected or all output parameter values in the form of a dynamic array. If a table has a single output or a single output has been selected, the result will be a scalar value. These input parameters belong to the local scope of this table

Step 6: (Optional) Enter the Input Values in the 2nd header row, to the left of the double vertical line, beneath the input parameter to which they are releated. Input Values may be a list of values separated by a commas (i.e. 27, 5, 3, 2), a list of unary tests (i.e. <10, >=20, [18..20]), or a data type (i.e. boolean, number, text, data, time, and duration).

Data Types

Boolean: The entered words TRUE and FALSE are interpreted as Boolean reserved words, not strings.

Number: Maybe an integer or fraction. *This is the data type entered in the example above.*

Text: Any string

Date: Any valid date, such as 05-05-1964

Time: Any valid time

Duration: There are two formats for duration, one measuring periods in months and another measuring periods in seconds. For example, P1DT1H2M3S denotes:

- P for "period"
- 1D for 1 day
- T for "time"
- 1H for 1 hour
- 2M for 2 minutes and
- 3S for 3 seconds.

When testing a value against a list of values or unary tests, the OR operator is used. For example, in the first example above, the list of values is evaluated as 27 OR 5 OR 3 OR 2. Likewise, the list of unary tests is evaluated as <10 OR >=20. It's possible to negate a list as well. For example, NOT(27, 5, 3, 2) would result in a selection of a record that does not includes 27 OR 5 OR 3 OR 2. Similarly, NOT(<10, >=20) would equate to neither <10 OR >=20 being selected.

All input entries in the relevant input column should cover the entered domain, otherwise, an error will be generated indicating that the table is not complete. If an input value does not exist, the completeness test is not performed.

Step 7: Enter Output values in the 2nd header row, to the right side of the double vertical line, beneath the output parameter to which they are related. Similar to Input Values, an Output value may be a list of values separated by a commas (i.e. 27, 5, 3, 2), a list of unary tests (i.e. <10, >=20, [18..20]), or a data type (i.e. boolean, number, text, data, time, and duration). Similarly, to an Input values, if a value appears in the table that does not match the output value, an error will be returned.

In this example, the list "27, 5,3,2" is entered beneath "holidays" and "text" is entered beneath "rule". The list beneath "holidays" gives the priority when returning the results. In other words, the results are to be returned largest to smallest. The output value, "text" specifies that the appropriate text contained in cells K9:K16 is to be returned along with the holiday.

Step 8: Enter the Decision Table Rules (or Unary tests) in each row below the double horizontal line. The unary test returns information (true or false) about the rule. Supported unary tests may have one of the following syntax forms: value(Boolean, number, text, date, time, duration), < value, > value, <= value, >= value, [value..value], (value..value], [value..value), (value..value), "-". Note: Currently, rules *may only* be entered as rows.

The first test examines whether the value being tested is equal to the value inside the parenthesis. For example, if the Unary test consists of the single value 'medium', the resulting test would ensure that the variable being tested was equal to 'medium'. The forms, [value..value], (value..value], [value..value) and (value..value), are interval tests. The [ ] operators denote a closed interval while the ( ) operators denote an open interval. The last test, "-" returns TRUE against any value. Note: To return a default value for a table, simply use "-" "-" for the unary tests.

Expressions

Variables and constants can be combines through operations called literal expressions. Literal expressions in S-FEEL are similar to formulas in Excel and in the RASON modeling language.

The following operators are supported in combination with decision table rules: addition (+), subtraction (-), multiplication (*), division (/) and exponentiation (**). Variables and constants can be combined using only these supported operators and parentheses. An example of an expression is: 2 * age – service where two variables, age and service, and a constant, 2, are linked by two arithmetic operations (* and -). Note that an expression is a FEEL expression, NOT an Excel formula. In this example, the expression "age – service" appears in the first rule where "age" and "service" refer to cells H7 and I7. This expression does not refer to any appearances of "age" or "service" outside of the scope of this table. For more information on supported conversion expressions, please see the Expressions heading at the end of this chapter.

Step A: (Optional) Enter the Rule numbers in the first column under the Hit policy starting with "1". Although optional, this component of the table is strongly recommended.

Step B: Enter the Input entries in the input columns

Step C: Enter the Output entries in the output columns.

Decision Tables at Work

The decision table contained within DT Structure.xlsx is shown below. This table returns the number of vacation days allotted to an employee based on his age and number of years in service. Notice cells H1:I2 at the top of the screenshot below containing age and service in the first row and 58 and 31 in the second. Cells H2 and I2 have been given the defined names (Insert – Name – Define) of age and service, respectively. These are the input variables on which the table depends. Each time the values of 58 and 31 are changed and a recalculation is performed (by clicking the green arrow on the task pane), the decision table function (PsiDecTable) will return the appropriate computed result in cell J17.

J17 = PsiDecTable(G7:K16, 2, age, service) where:

- G7:K16 is the location of the decision table on the Excel worksheet,
- 2 is the number of inputs, and
- Age and service are the two input variables. Alternative, we could have specified the cell address (H2 and I2) or the values (58 and 31).

  =PsiDecTable(G7:K16, 2, H2, I2) or =PsiDecTable(G7:K16, 2, 58, 31)

Two additional optional arguments are described below: output and ret_header.

G	H	I	J	K	L
inputs	*age*	*service*			
	58	31			
Policy Output Order					

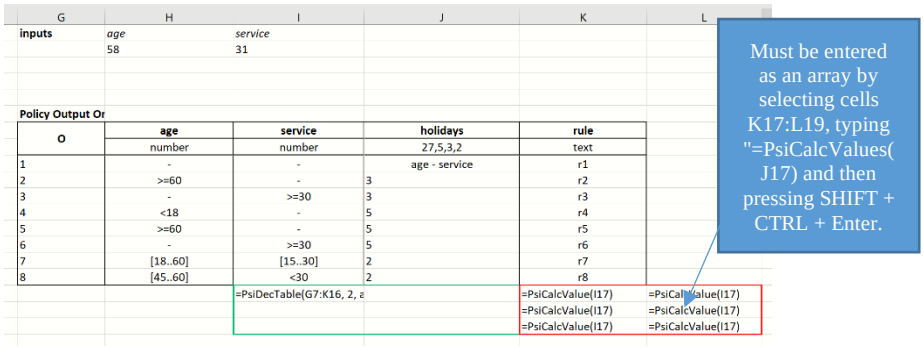
O	age	service	holidays	rule
	number	number	27,5,3,2	text
1	-	-	age - service	r1
2	>=60	-	3	r2
3	-	>=30	3	r3
4	<18	-	5	r4
5	>=60	-	5	r5
6	-	>=30	5	r6
7	[18..60]	[15..30]	2	r7
8	[45..60]	<30	2	r8

		27 r1	27 r1
		5 r6	5 r6
		3 r3	3 r3

The PsiDecTable() signature above includes only 2 input parameters, age and service. If using Excel 2019, the result will "spill" into 3 rows and 2 columns as shown in the screenshot above starting with cell J17. In the first column you see the rule output: 27, 5, and 3. The second column contains the rule numbers, r1,

r6 and r3. Since earlier versions do not support Dynamic Arrays, you'll need to use the PsiCalcValues() function, entered as an array (CTRL + SHIFT + ENTER) in cells K17:L19, to view the results.

Note: It's important when using Dynamic arrays in Excel V2019 that you enter the array in a cell location where there are enough blank cells to contain the array. This example contains two output values: holidays and rule. Therefore, we automatically know that the dynamic array will contain two columns, one containing the number of holidays and one containing the rule label. The first column will start in the cell containing the PsiDecTable() function. However, you will not know in advance how many rows will be used. This is also true when entering PsiCalcValues as an array in earlier versions of Excel.



During recalculation, each rule is evaluated. Both unary tests must be satisfied in order for a "hit" to occur and the results to be added to the result collection.

1. The first rule, under age, uses the unary tests age: "-" and service: "-", which, as you will recall, returns TRUE against any value. Therefore, the first "hit" occurs with R1, as age – service or 58 – 31 = 27.
2. The next rule tests whether age is >= 60 which is not successful as 58 is not greater than or equal to 60.
3. The next rule (rule 3) returns TRUE for age ("-") and TRUE for service (>= 30). Therefore, the next "hit" is for R3 which returns "3" (from column J).
4. The fourth rule returns FALSE for age <= 18.
5. The fifth rule returns FALSE for age >= 60.
6. The sixth rule returns TRUE for "-" for age and service >= 30. Therefore a hit occurs and the result for r6, "5", is added to the result collection.
7. The 7th rule returns FALSE for both the age interval [18..60] and the service interval [15..30].
8. The 8th rule returns TRUE for the age interval [45..60] but FALSE for service <30.

Three rules, r1, r3, and r6 are added to the result collection. The results for these three rules are 27, 3, and 5, respectively. After the reslts are updated, the HIT policy is checked. In this example, the hit policy is "O" or "Output Order" which specifies that if multiple rules are hit, the collection is retuned in the priority order of the listed output values which can be found beneath "holidays" or 27, 5, 3, 2. Therefore, our results are returned as 27 (r1), 5 (r6) and 3 (r3) or largest to smallest.

Open the example DT Hit Policy Examples.xlsx to see how the different Hit policies work.

Note: During parse-time, each PsiDecTable() function is uniquely identified by it's cell address. A "completeness test" ensures that all input/output entries per column cover the domain of the input/output values in the same column, as long as the output values are not expressions against the output values. If so, these expressions are evaluated at run-time. Type verification is performed for those columns in which a data type is specified rather than an input/output value.

Optional Arguments

PsiDecTable() supports two optional arguments: output and ret_header.

To return the result for a given output only, we must pass an additional argument to the PsiDecTable() function. For example, to only receive the number of holidays, rather than both holidays and the rule label, add "holidays" as the last arguent to our existing formula in cell J17. In this instance, only one column will be returned containing the values: 27, 5, 3.

J17=PsiDecTable(G7:K16, 2, age, service, "holidays") where

- G7:K16 is the location of the decision table on the Excel worksheet,
- 2 is the number of inputs,
- age and service are the two input variables and
- "holidays" (optional) to ensure that the returned results only include the specified output.

You can pass as many output arguments as needed.

It's also possible to use a 2nd optional argument, ret_header, this time a Boolean argument, as the last argument to PsiDecTable(). When TRUE is passed for this argument, a header containing the names of the output(s) is included in the result. In this instance, one column will be returned containing the values: "holidays", 27, 4, 3.

J17=PsiDecTable(G7:K16, 2, age, service, "holidays", TRUE) where

- G7:K16 is the location of the decision table on the Excel worksheet,
- 2 is the number of inputs,
- age and service are the two input variables,
- "holidays" (optional) to ensure that the returned results only include the specified output and
- TRUE to add a header to the result.

This is the complete signature for the PsiDecTable() function.

Additional Examples

This section presents a special class of tables, in which the specific Date, Time, and Duration data types are utilized.

Decision Table Containing Dates

Open the first tab within the workbook DT Date & Time Examples.xlsx. This table returns the credit risk rating of an individual based on their age and

medical history. The PsiDecTable function appears in cell G19 = PsiDecTable(B13:E19, 2, bd, mh) where

- B13:E19 is the location of the decision table,
- 2 is the number of input variables and
- bd (cell G14 containing "1964-05-05") and mh (cell H14 containing "good") are the input variables.

	B	C	D	E	F	G	H	I
12	Risk Rating							
13	U	birthDate	medHistory	riskRating		born		med history
14		date	text	text		"1964-05-05"		good
15	1	>"1970 05 05"	good	medium				
16	2	>'1970-05-05'	bad	high				
17	3	['1935-05-05'..'1970-05-05']	-	medium				
18	4	<'1935 05 05'	good	low				
19	5	<'1935-05-05'	bad	medium		medium		

Notice that the string values in columns D (medHistory) and E (riskRating) in the table are entered without quotes. This is because Analytic Solver always assumes any output as an expression requiring parsing. If a single word or "token" is detected, the Psi Interpreter first checks if it is a local scope variable name. If not, the word-token is assumed to be a string. In the first example table the expression *age – service* existed in the "holidays" column. Since age and service are variables connected through the operator '-', the Psi Interpreter assumed the entry as an expression to be evaluated. If instead, we wanted to enter that expression as a string value, then we would need to surround the expression with quotation marks.

The situation with dates is however, different. While in Excel we may enter a date without " ", when a Date is part of a Decision table, we must surround the date with single ' ' or double " ". S-FEEL defines a single format for the **Date** type **'yyyy-mm-dd'**. Optionally a date may begin with the letter D, for example "D1964-05-05". Other date type formats in Excel are not valid in S-FEEL. When we pass a date as an input parameter to a Decision table, the date must be a string formatted as S-FEEL Date. If we enter an Excel date in that cell, it will be automatically converted into the date representing number and the Decision table will still recognize it as date. However, we strongly recommend using the S-FEEL format outside of Decision tables for readability of the model.

In this example,the unique rule which matches the input birthdate "1964-05-05" is rule #3, because "1964-05-05" is in the date interval ['1935-05-05'..'1970-05-05'].

Decision Table Containing Time

The Psi Interpreter will convert any time entries in a decision table into the Time format, "hh:mm:ss". Optionally, we could enter the times using the format beginning with the letter **T** such as in "**T**18:29:30". Usually this time format denotes local time. If we want to specify the UTC time, we can simply add **z** at the end of the format, for example "**T**18:29:30z". However, it's important to note that the z time format is just a readable format. The Psi Interpreter cannot effectively convert local and zulu times, because the location of the local time is not specified in the supported format.

	B	C	D	E	F	G
10	Toll Tax					
11	U	operTime	traffic	toll		now
12		time	text	number		"18:50:05"
13	1	>'19:00:00'	low	5		
14	2	['15:00:00'..'19:00:00']	high	7		
15	3	['09:00:00'..'15:00:00')	medium	6		
16	4	['06:00:00'..'09:00:00')	high	7	toll	7
17	5	<'06:00:00'	low	5	traffic	high

Click the 2nd tab in the workbook to open the example shown above which returns the traffic prediction (low, medium, or high) for a toll station based on the time of day.

To avoid the downward spill of the result for the two outputs, we use the optional output argument in both PsiDecTable() functions in cells G16 and G17.

G16 = PsiDecTable(B14:E20, 1, byNow, "toll")

G17 = PsiDecTable(B14:E20, 1, byNow, "traffic")

Decision Table Containing Duration

Finally, let's take a look into an example using the data type, duration. Click the third tab in the workbook to open the decision table, shown below, which computes the output parking fee according to the input parking time. The table is invoked through the Excel formula in cell F16 = PsiDecTable(B11:D16, 1, period).

	B	C	D	E	F
10	Parking Fee				
11	U	dtDuration	parkingFee		
12		duration	number		period
13	1	<'PT20M'	0		PT25M
14	2	['PT20M'..'PT1H')	2 *ceiling(duration(dtDuration)/duration('PT20M'))		
15	3	['PT1H'..'PT4H')	6 *ceiling(duration(dtDuration)/duration('PT1H'))		
16	4	>='PT4H'	30*ceiling(duration(dtDuration)/duration('P1D'))		4

There are two types of formats for Duration:

- **P1Y2M** - measures duration in months
- **P1DT1H20M10S** – measures duration in seconds

The individual components in these formats are optional. For example, if we have 0 hours to represent, we may skip the hour component. For example, we can represent a 20 minutes duration using either: PT0H20M0S or PT20M.

While we can skip a duration component in the format, the order of components in a format must be followed. For example, we cannot first enter minutes and then hours; PT20M1H is not a currently supported syntax.

Hit Policies

This section presents a collection of tables to illustrate each of the 7 Hit policies currently supported by Analytic Solver: Any, Collect, First, Rule Order, Output Order, Priority Order and Unique. Open the example workbook, DT Hit Policy Examples.xlsx. This workbook contains 7 tabs, one tab for each example.

Hit Policy: Any

The decision table appearing on the Any tab returns the loan compliance for an individual given their credit rating, current card balance, and current student loan balance.

The PsiDecTable() function is located in cell F19. This function returns "compliant" or "not compliant" given a credit rating of "B", a credit card balance of $12,000, and a student loan balance of $75,000. The Hit policy Any will return only one result even if multiple rules overlap.

F19 = PsiDecTable(B13:F18, 3, "B", 12000, 75000)

	B	C	D	E	F
12	Policy Any				
13	A	creditRating	creditCardBalance	studentLoanBalance	loanCompliance
14					
15	1	A	<10000	<50000	compliant
16	2	Not(A)	-	-	not compl
17	3	-	>=10000	-	not compl
18	4	-	-	>=50000	not compl
19					not compl

In this table, all rules except for rule 1 are evaluated successfully for a "hit". However, the result collection only includes 1 "not compl" entry.

Hit Policy: Collect

Click the Collect tab to display the 2nd Hit Policy example. This decision table returns the total number of holidays allotted to an employee based on their age and number of years in service. In the previous example, the Hit Policy was equal to Unique which resulted in all successfully hit rules returning their unique result. In this example, the Collect policy is used with the "+" operator. This operator returns the sum of the collection of results in rule order when multiple rules are applicable. The Collect Policy allows 4 operators, + (sum), < (return the minimum of matched output values), > (return the maximum of matched output values) and # (return the number of matched output values).

	B	C	D	E
13	Policy Collect			
14	C#	age	service	holidays
15		number	number	number
16	1	-	-	22
17	2	>=60	-	3
18	3	-	>=30	3
19	4	<18	-	5
20	5	>=60	-	5
21	6	-	>=30	5
22	7	[18..60]	[15..30]	2
23	8	[45..60]	<30	2
24				3

In this example, the PsiDecTable() function appears in cell E24 = PsiDecTable(B14:E23, 2, 58, 31). As in the previous example, three rules, 1, 3 and 6, are included in the results returning the values, 22, 3 and 5, respecitvely. However, since this Hit policy sums the results, the answer 30 is returned.

Let's see what happens when we change the Hit Policy to C<. Simply select cell C+ and enter C<, then click the green arrow on the Model tab of the Solver Task Pane to recalculate the table. When the Hit Policy is equal to C<, PsiDecTable() returns the minimum result value, 3.

	B	C	D	E
13	**Policy Collect**			
14	**C<**	**age**	**service**	**holidays**
15		number	number	number
16	1	-	-	22
17	2	>=60	-	3
18	3	-	>=30	3
19	4	<18	-	5
20	5	>=60	-	5
21	6	-	>=30	5
22	7	[18..60]	[15..30]	2
23	8	[45..60]	<30	2
24				3

Let's repeat these steps for "C"> to find the maximum result value of 22,

	B	C	D	E
13	**Policy Collect**			
14	**C>**	**age**	**service**	**holidays**
15		number	number	number
16	1	-	-	22
17	2	>=60	-	3
18	3	-	>=30	3
19	4	<18	-	5
20	5	>=60	-	5
21	6	-	>=30	5
22	7	[18..60]	[15..30]	2
23	8	[45..60]	<30	2
24				22

and "C#" to find the number of returned results, 3.

	B	C	D	E
13	**Policy Collect**			
14	**C#**	**age**	**service**	**holidays**
15		number	number	number
16	1	-	-	22
17	2	>=60	-	3
18	3	-	>=30	3
19	4	<18	-	5
20	5	>=60	-	5
21	6	-	>=30	5
22	7	[18..60]	[15..30]	2
23	8	[45..60]	<30	2
24				3

Hit Policy: First

Click the First tab to display the next Hit Policy example. In this example, a percentage discount is returned based on where an order originated, on the web or by phone, the location of the order, inside or outside the US, and customer type, wholesaler or retail according to the First Hit Policy. When this policy is in use, only the first entry in the result collection is returned.

The PsiDecTable() function appears in cell F19.

F19=PsiDecTable(B13:F18, 3, "web", "non_US", "retailer")

	B	C	D	E	F
12	Policy First				
13	F	order	location	customer	discount
14					
15	1	web	US	wholesaler	10
16	2	phone	-	-	2
17	3	-	non_US	-	0
18	4	-	-	retailer	5
19					0

Two rules are "hit", rule 3 and rule 4. However, since we are using the First Hit Policy, only the result for rule 3 is returned, 0.

Hit Policy: Rule Order

Click the next tab to display the Rule Order Hit Policy example. This table returns the amount of money available to a student based on their grade point average and number of times they took the ACT. Funds may be provided via a scholarship, loan, or work study program. The "Rule Order" Hit policy returns the collection of results in priority order of the listed output values. The PsiDecTable() function is located in cell F19 = PsiDecTable(B13:G18, 3, 3.6, 4, TRUE). Given an honors student with a gpa = 3.6 and an act_count = 4, this student would be eligible to receive a scholarship covering 20% of tuition (rule 1) and a student loan covering 30% of tuition (rule 2).

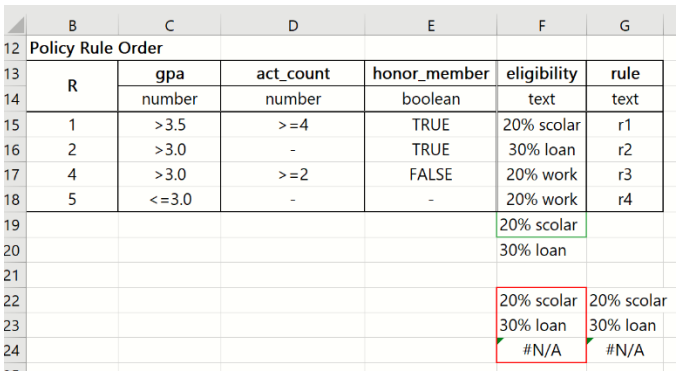
	B	C	D	E	F	G
12	Policy Rule Order					
13	R	gpa	act_count	honor_member	eligibility	rule
14		number	number	boolean	text	text
15	1	>3.5	>=4	TRUE	20% scolar	r1
16	2	>3.0	-	TRUE	30% loan	r2
17	4	>3.0	>=2	FALSE	20% work	r3
18	5	<=3.0	-	-	20% work	r4
19					20% scolar	*r1*
20					30% loan	r2
21						
22					20% scolar	r1
23					30% loan	r2
24					#N/A	#N/A

Rules 3 and 4 are not applicable because the student is an honor student (honor_member = TRUE) and the student's GPA is greater than 3.0.

Adding the last two optional arguments, returns the header "eligibility", and only the eligibility text.

F19 = PsiDecTable(B13:G18, 3, 3.6, 4, TRUE).

Cells F22:G24 contain PsiCalcValue(F19). Use these values to return the contents of the result collection when using a version of Excel that does not support Dynamic Arrays. Note that if this function is entered into more than the number of cells required, #N/A is returned.

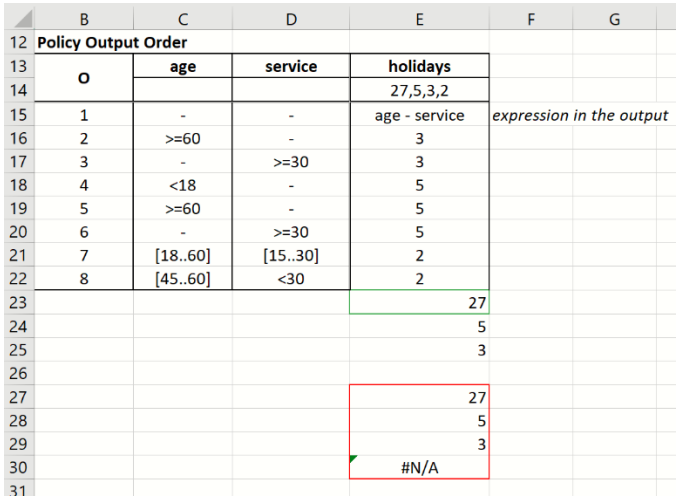


	B	C	D	E	F	G
12	Policy Rule Order					
13	R	gpa	act_count	honor_member	eligibility	rule
14		number	number	boolean	text	text
15	1	>3.5	>=4	TRUE	20% scolar	r1
16	2	>3.0	-	TRUE	30% loan	r2
17	4	>3.0	>=2	FALSE	20% work	r3
18	5	<=3.0	-	-	20% work	r4
19					20% scolar	
20					30% loan	
21						
22					20% scolar	20% scolar
23					30% loan	30% loan
24					#N/A	#N/A

Notice that when only one column is returned, the PsiCalcValue array simply repeats the results in cells G22:G23.

Hit Policy: Output Order

Click the next tab to display the Output Order Hit Policy example. This example returns to our original example where the number of holidays allotted to an employee is returned based on the employee's age and number of years of service. The output is returned in the order as given in the Output values header (cell D3). The PsiDecTable() function is located in cell E23 = PsiDecTable(B13:E22, 2, 58, 31). According to the rules of the table, a 58 year old employee with 31 years of service is allotted 27 + 3 + 5 vacation days via rules 1, 3, and 6, respectively. However, since the Hit Policy specifies that the results must be returned priority order, the result collection is listed as 27, 5, and 3.



	B	C	D	E	F	G
12	**Policy Output Order**					
13	**O**	**age**	**service**	**holidays**		
14				27,5,3,2		
15	1	-	-	age - service	*expression in the output*	
16	2	>=60	-	3		
17	3	-	>=30	3		
18	4	<18	-	5		
19	5	>=60	-	5		
20	6	-	>=30	5		
21	7	[18..60]	[15..30]	2		
22	8	[45..60]	<30	2		
23				27		
24				5		
25				3		
26						
27				27		
28				5		
29				3		
30				#N/A		
31						

Hit Policy: Priority

Click the next tab to display the last Hit Policy example. According to the Priority Hit Policy, if multiple rules are "hit" and multiple results are collected, only one result will be returned. The priority of the returned result is defined by the order of the output values in the header.

This example returns a risk of disease rating of low, medium, or high based on a person's age and medical history. The PsiDecTable() function in cell E18 (=PsiDecTable(B12:E17, 2, 61, "bad")) returns "medium" for a 61 year old person with a "bad" medical history. Note that according to our criteria, two rules are returned as successful, rule 2 (age > 60 and medicalHistory = "bad")

and rule 3 (age = "-" and medHistory = "medium"). Why isn't "high" returned? Because the priority list in cell B13 (low, medium, high) specifies that "medium" should have higher priority than "high".

	B	C	D	E
12	Policy Priority Order			
13	P	age	medHistory	riskRating
14				low,medium,high
15	1	>=25	good	medium
16	2	>60	bad	high
17	3	-	bad	medium
18	4	<25	good	low
19				medium

Hit Policy: Unique

Click the last tab to display the last Hit Policy example. According to the Unique Hit Policy, only one rule may "hit". If multiple rules are "hit" and multiple results are collected, an error will be returned.

	B	C	D	E	F
10	Policy Unique				
11	U	age	medHistory	riskRating	rule
12					
13	1	>60,<25	good	medium	r1
14	2	>60	bad	high	r2
15	3	[25..60]	-	medium	r3
16	4	<25	good	low	r4
17	5	<25	bad	medium	r5
18				medium	r3
19					
20				medium	r3

E18 = PsiDecTable(B11:F17, 2, 54, "good")

This table also returns a risk rating for an individual based on their age and medical history (medHistory). In this example, given an age or 54 and a "good" medical history, a "medium" risk rating is returned by rule 3.

Merging Decision Table Results

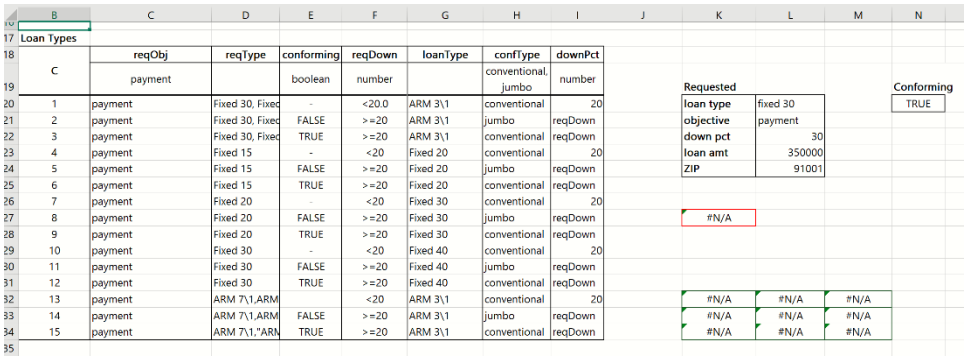
The DT Loan Recommend Example illustrates how to use the PsiJoin() function to merge the results of one decision table with a 2nd table.

The decision table, in cells B18:I34, returns a loan or loans meeting various criteria. Cell K27 includes the PsiDecTable() formula. Two types of loans meet the 4 loan requirements (reqObj = payment, reqType = fixed 30, conforming = TRU and reqDown = 30): a conventional Arm 3\1 and a conventional Fixed 40. (See the results in cells J32:L34).

K27=PsiDecTable(B18:I34, 4, reqObj, reqType, conforming, reqDown, TRUE)

The PsiCalcValue() functions located in cells Loan Types!K32:M34 are used to persist the results from PsiDecTable().

Notice that the optional "header" argument has been passed to PsiDecTable() in cell K27. This was done in preparation for the use of the PsiJoin() function to merge the results (cells K32:M34) with the table on the Bank Rates tab.



	B	C	D	E	F	G	H	I	J	K	L	M	N
17	Loan Types												
18		reqObj	reqType	conforming	reqDown	loanType	confType	downPct					
19	C	payment		boolean	number		conventional, jumbo	number		Requested			Conforming
20	1	payment	Fixed 30, Fixed	-	<20.0	ARM 3\1	conventional	20		loan type	fixed 30		TRUE
21	2	payment	Fixed 30, Fixed	FALSE	>=20	ARM 3\1	jumbo	reqDown		objective	payment		
22	3	payment	Fixed 30, Fixed	TRUE	>=20	ARM 3\1	conventional	reqDown		down pct	30		
23	4	payment	Fixed 15	-	<20	Fixed 20	conventional	20		loan amt	350000		
24	5	payment	Fixed 15	FALSE	>=20	Fixed 20	jumbo	reqDown		ZIP	91001		
25	6	payment	Fixed 15	TRUE	>=20	Fixed 20	conventional	reqDown					
26	7	payment	Fixed 20	-	<20	Fixed 30	conventional	20					
27	8	payment	Fixed 20	FALSE	>=20	Fixed 30	jumbo	reqDown		#N/A			
28	9	payment	Fixed 20	TRUE	>=20	Fixed 30	conventional	reqDown					
29	10	payment	Fixed 30	-	<20	Fixed 40	conventional	20					
30	11	payment	Fixed 30	FALSE	>=20	Fixed 40	jumbo	reqDown					
31	12	payment	Fixed 30	TRUE	>=20	Fixed 40	conventional	reqDown					
32	13	payment	ARM 7\1,ARM		<20	ARM 3\1	conventional	20		#N/A	#N/A	#N/A	
33	14	payment	ARM 7\1,ARM	FALSE	>=20	ARM 3\1	jumbo	reqDown		#N/A	#N/A	#N/A	
34	15	payment	ARM 7\1,"ARM	TRUE	>=20	ARM 3\1	conventional	reqDown		#N/A	#N/A	#N/A	
35													

Click the Bank Rates tab to view the 2nd table in cells A2:I8. This table lists six banks offering loans in the area. Notice that no bank is offering the Fixed 40 loan.

The PsiJoin function has been entered as an array in cells A12:L15.

A12:L15{= PsiJoin('Loan Types'!J32:L34, A2:I8, "loanType = loanType, confType = confType, downPct >= 'minDown %'")}

This function joins results from the decision table function in Loan Types!J27 with the second table on the Bank Rates tab.

PsiJoin() takes three arguments, Table1, Table2, and Clause. The Table1 argument passes the first table, in this example, the table in Loan Types!A18:H34. The Table2 argument passes the second table, in this example, the table in Bank Rates!A2:I8. The third argument, Clause, passes the conditions for joining the table. In this example, the results and the table are joined via three columns: loanType, confType, and downPct. This argument must be surround by quotes.

Note that in this example, two conditions used to join the results from PsiDecTable() and the Bank Rates table are the same, i.e. loanType = loanType and confType = confType. This is not a requirement; table headers can be different.

The third condtion, downPct >= 'minDown %' requires that the downPct in the Loan Types decision table must be greater than the "minDown %" in the Bank Rates table. In other words, the down payment percentage in the Loan Types table must be greater than the minimum percentage down in the Bank Rates table in order for the loan to be selected and displayed by PsiJoin().

Note: Recall that the PsiDecTable() function in cell Loan Types!J27 included the optional "header" argument. If the results had not included this argument, it would not have been possible to use the PsiJoin() function complete the merge.

All three columns are common to both the PsiDecTable() results and the Bank Rates table. Three banks offer a conventional ARM 3\1 loan: Mount Diablo, AimLoan, and America One. The first three columns (A12:L15) are the three columns passed to the Clause argument: loanType, confType, and downPct. Columns D through L contain the remaining information for each offered loan: Lender, loanType, confType, minDown%, Term, APR %, Rate %, Points, and feesAmt.

	A	B	C	D	E	F	G	H	I	J	K	L
1	**Bank Rates**											
2	**Lender**	**loanType**	**confType**	**minDown %**	**Term**	**APR %**	**Rate %**	**Points**	**feesAmt**			
3	Mount Diablo Lending	ARM 3\1	conventional	20	360	3.002	3	0				
4	AimLoan	ARM 3\1	conventional	20	360	3.103	2.875	0	1995			
5	America One	ARM 3\1	conventional	20	360	3.13	2.875	1	899			
6	Mount Diablo Lending	Fixed 30	conventional	20	360	3.629	3.625	0				
7	AimLoan	Fixed 30	conventional	20	360	3.682	3.625	0	1068			
8	America One	Fixed 30	conventional	20	360	3.79	3.75	0	799			
9	Than											
10												
11	**Excel Solution**											
12	loanType	confType	downPct	Lender	loanType	confType	minDown %	Term	APR %	Rate %	Points	feesAmt
13	ARM 3\1	conventional	30	Mount Diablo L	ARM 3\1	convention	20	360	3.002	3	0	0
14	ARM 3\1	conventional	30	AimLoan	ARM 3\1	convention	20	360	3.103	2.875	0	1995
15	ARM 3\1	conventional	30	America One	ARM 3\1	convention	20	360	3.13	2.875	1	899

Using Cascading Decision Tables

Open the DT Loan Strategy Model to learn how to use cascading decision tables where the output of one decision table is the input to another.

This Input worksheet contains the input parameters to the Loan Strategy model contained on the Loan Strategy and Post Bureau worksheets. Input parameters are all constant values.

	B	C	D	E	F	G
11	Customer				Loan	
12						
13	age	40			type	standard
14						
15	exist	FALSE			rate	5
16						
17	marital status	s			term	30
18						
19	employment status	selfemployed			amount	100000
20						
21	credit score	610				
22						
23	bankrupt	FALSE				
24						
25	monthly income	2500				
26						
27	monthly expenses	1000				

Click the Loan Strategy worksheet. This worksheet contains six cascading decision tables. The first table appears in cells A2:E14. This table returns a partial "risk of default" score based on a loan applicant's age, marital and employment status. Higher scores are given to older, employed, married applicants. Cell E15 contains the PsiDecTable() function.

	A	B	C	D	E
1	App R	sk Score			
2	C+	**cust age**	**marital status**	**employment status**	**partial score**
3		[18..120]	s, m	unemployed,employed,self employed,student	
4	1	[18..21]	-	-	32
5	2	(21..25]	-	-	35
6	3	(25..35]	-	-	40
7	4	(35..49]	-	-	43
8	5	>49	-	-	48
9	6	-	s	-	25
10	7	-	m	-	45
11	8	-	-	unemployed	15
12	9	-	-	student	18
13	10	-	-	employed	45
14	11	-	-	selfemployed	36
15					104

E15=PsiDecTable(A2:E14, 3, custAge, maritalSt, employSt)

The input parameters from the Input worksheet are: custAge="40", maritalSt = "s", employSt = "selfemployed". The applicable rules for these input parameters are: 4, 6, and 11 resulting in partial scores of 43, 25, and 36, respectively. Since the Hit Policy is "C+" the result collection is added together, 43 + 25, + 36 = 104.

The next decision table is located in cells G5:J14, the Bureau Risk Cat table. This table returns a risk category of high, medium, or low based on their customer status (existing or not) and their application risk score. Non-existing customers are allowed a higher risk score. Cell J15 contains the PsiDecTable() function

	G	H	I	J
4	**Bureau Risk Cat**			
5	**U**	**cust exist**	**app risk score**	**bureau risk cat**
6				
7	1	FALSE	<100	high
8	2	FALSE	[100..120]	medium
9	3	FALSE	[120..130]	low
10	4	FALSE	>130	veryLow
11	5	TRUE	<80	decline
12	6	TRUE	[80..90]	high
13	7	TRUE	[90..110]	medium
14	8	TRUE	>110	low
15				medium

J15 =PsiDecTable(G5:J14, 2, custExist, tblAppRiskScore) where custExist = False and tblAppRiskScore() refers to the value in cell E15, or 104. Based on these conditions, one rule is "hit", rule 2. This rule returns "medium" for the bureau risk category. Since the hit policy is equal to U (Unique) only one result is returned, even if multiple results are returned.

The next decision table, Bureau Call Type, is located in cells L11:N14. This table returns the bureau call type based on the bureau risk category found in the previous decision table, Bureau Risk Cat. Cell N15 contains the PsiDecTable() function.

	K	L	M	N
9				
10		**Bureau Call Type**		
11		**U**	**bureau risk cat**	**bureau call type**
12		1	high, medium	full
13		2	low	mini
14		3	veryLow, decline	none
15				full

N15=PsiDecTable(L11:N14, 1, tblBureauRiskCat) where tblBureauRiskCat is equal to the result of the PsiDecTable() function in cell J15, or "medium". Only 1 rule is "hit", rule 1, which returns "full".

The nextdecision table, Eligibility, is located in cells A20:E25. This table returns the applicant's eligibility based on three criteria: the bureau risk category, from cell J15, bureau afford, calculated in cell C36, and customer age, located in cell Input!C13. Since the Hit Policy is equal to P (Priority), the result collection will be returned in the order listed according to the list in cell E21. The PsiDecTable() function is located in cell E26.

	A	B	C	D	E
19	**Eligibility**				
20	**P**	**bureau risk cat**	**bureau afford**	**cust age**	**eligibility**
21					ineligible, eligible
22	1	decline	-	-	ineligible
23	2	-	FALSE	-	ineligible
24	3	-	-	<18	ineligible
25	4	-	-	-	eligible
26					eligible

E26 = PsiDecTable(A20:E25, 3, tblBureauRiskCat, bureauAfford, custAge)

Intermediate Formulas

Cell C36 calculates the bureau afford statistic, =IF(disposIncome * tblCreditContFactor > monthInstall, TRUE, FALSE)

where disposIncome is calculated in cell C34, tblCreditContFactor is calculated in cell N26 (more on this later) and monthInstall is calculated in cell C32.

Cell 34 calculates an applicant's disposable income using the formula, =monthIncome - (monthRepay + monthExpenses) where monthIncome = 2500, monthRepay is calculated in cell C30 and monthExpenses = 1000.

Cell C30 calculates the monthly loan replayment amount using the formula, -PMT(loanRate%/12, loanTerm*12, loanAmnt) where loanRate is 5%, loanTerm = 30 and loanAmnt = 100,000.

Finally, cell C28 calculates the monthly fee using the IF statement, = IF(loanType = "standard", 20, IF(loanType = "special", 25, 0)), where loanType = standard.

Using the final input values of tblBureauRiskCat = medium, bureauAfford = True, and custAge = 40, the last rule, rule 4, is the only rule "hit", returning "eligible".

The next decision table is located in cells G22:J25. This table returns the loan strategy based on the applicant's eligibility and bureau call type. The PsiDecTable() function is located in cell J26.

	G	H	I	J
21	**Strategy**			
22	**U**	**eligibility**	**bureau call type**	**strategy**
23	1	ineligible	-	decline
24	2	eligible	full, mini	bureau
25	3	eligible	none	through
26				bureau

J26=PsiDecTable(G22:J25, 2, tblEligibility, tblBureauCallType) where tblEligibility is calculated in cell E26 and tblBureauCallType is calculated in cell N15. Both of these inputs are outputs of earlier decision tables. Based on the results calculated by the previous decision tables, this PsiDecTable() function results in a "bureau" strategy.

Finally, the last decision table, Credit Cont Factor, is contained in cells L22:N25. The PsiDecTable() function is located in cell N26.

	K	L	M	N
21		**Credit Cont Factor**		
22		**U**	**bureau risk cat**	**credit cont factor**
23		1	high, decline	0.6
24		2	medium	0.7
25		3	low, veryLow	0.8
26				0.7

N26 =PsiDecTable(L22:N25, 1, tblBureauRiskCat) where tblBureauRiskCat is calculated in cell J15. Again, this input is an output from an earlier discussed decision table.

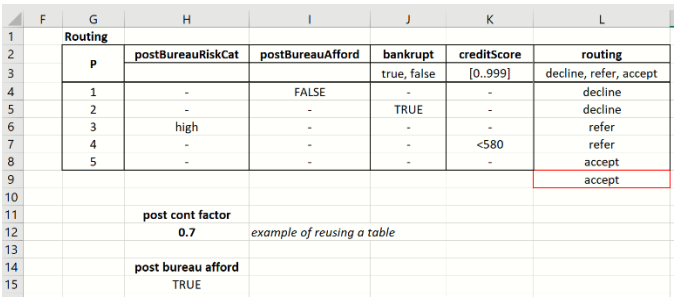
If the result of the PsiDecTable function in cell J26 would have been either "decline" or "through", then our work would be finished. We would either decline or accept the applicant, respectively. However, since "bureau" was returned, more analysis is required and on we must go. Click the Post Bureau worksheet to proceed.

The first decision table on the Post Bureau tab is the Post Bureau Risk Cat table. This table returns a Post Bureau Risk Category based on if the applicant is an existing customer, his/her application Risk Score and credit score. The PsiDecTable() function can be found in cell E17.

	A	B	C	D	E
1	**Post Bureau Risk Cat**				
2	**U**	**custExist**	**appRiskScore**	**creditScore**	**postBureauRiskCat**
3					
4	1	FALSE	<120	<590	high
5	2	FALSE	<120	[590..610]	medium
6	3	FALSE	<120	>610	low
7	4	FALSE	[120..130]	<600	high
8	5	FALSE	[120..130]	[600..625]	medium
9	6	FALSE	[120..130]	>625	low
10	7	FALSE	>130	-	veryLow
11	8	TRUE	<=100	<580	high
12	9	TRUE	<=100	[580..600]	medium
13	10	TRUE	<=100	>600	low
14	11	TRUE	>100	<590	high
15	12	TRUE	>100	[590..615]	medium
16	13	TRUE	>100	>615	low
17					medium
18					

E17 = PsiDecTable(A2:E16, 3, custExist, tblAppRiskScore, creditScore) where custExist is False, tblAppRiskScore (104) is calculated in cell E15 and creditScore = 610. Given these input values, 1 rule is "hit", rule 2.

Finally, we come to the Routing table in cells G2:L8. This table returns a final strategy based on two decision table results (postBureauRiskCat and postBureauAfford) and two input parameters, bankrupt and creditScore. The PsiDecTable() function in cell L9 = PsiDecTable(G2:L8, 4, tblPostBureauRiskCat, postBureauAfford, bankrupt, creditScore) where tblPostBureauRiskCat = medium, postBureauAfford = True (calculated in cell H15), bankrupt = FALSE (never bankrupt) and creditScore = 610.



Routing					
P	postBureauRiskCat	postBureauAfford	bankrupt	creditScore	routing
			true, false	[0..999]	decline, refer, accept
1	-	FALSE	-	-	decline
2	-	-	TRUE	-	decline
3	high	-	-	-	refer
4	-	-	-	<580	refer
5	-	-	-	-	accept
					accept

post cont factor	
0.7	*example of reusing a table*

post bureau afford
TRUE

The input parameter postBureauAfford is calculated in cell H15 according to the formula, =IF(disposIncome * postCreditContFactor > monthInstall, TRUE, FALSE). Since the product of disposIncome and postCreditContFactor (963.18 * .7) is greater than the monthly installment (556.82), the IF function returns TRUE.

The input parameter postCreditContFactor is calculated in cell H12 = PsiDecTable('Loan Strategy'!L22:N25, 1, tblPostBureauRiskCat). Note that this PsiDecTable() function refers to the App Risk Score decision table in cells Loan Strategy!L22:N25. Analytic Solver supports multiple PsiDecTable() functions that refer to the same table, as long as the input variables are different. Multiple PsiDecTable() functions with identical input variables are not supported and will result in an error. Two PsiDecTable() functions return to the App Risk Score decision table.

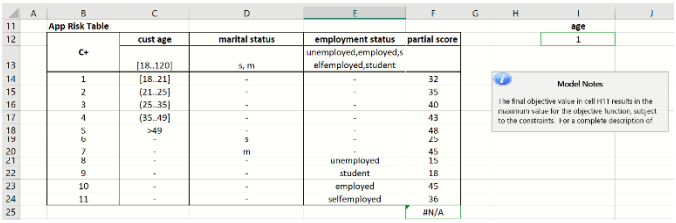
With these criteria, the last rule, rule 5, is hit, accept the loan application.

Using Decision Tables in Optimization and Simulation

It's also possible to build an optimization and simulation model using a decision table as input. See the Data Mining User Guide for an example on how to use a decision tree in conjunction with a data mining model saved in PMML format.

Optimization

Open DT Opt & Sim Examples.xlsx and click the Optimization tab. The decision table appearing in cells B12:F24 returns the collective score, due to the Hit Policy of "Collect +", of a set of partial scores based on a customer's age, marital status, and employment status. The PsiDecTable() function appearing in cell F25 = PsiDecTable(B12:F24, 3, I12, maritalSt, employSt) where I12 currently refers to the age "1", "maritalSt" refers to cell Input!B15 ("s" for single) and "employSt" refers to cell Input!B17 ("selfemployed").



App Risk Table					age
C+	cust age	marital status	employment status	partial score	1
	[18..120]	s, m	unemployed,employed,selfemployed,student		
1	[18..21]	-	-	32	
2	[21..25]	-	-	35	
3	[25..35]	-	-	40	
4	[35..49]	-	-	43	
5	>49	-	-	48	
6	-	s	-	25	
7	-	m	-	45	
8	-	-	unemployed	15	
9	-	-	student	18	
10	-	-	employed	45	
11	-	-	selfemployed	36	
				#N/A	

Model Notes

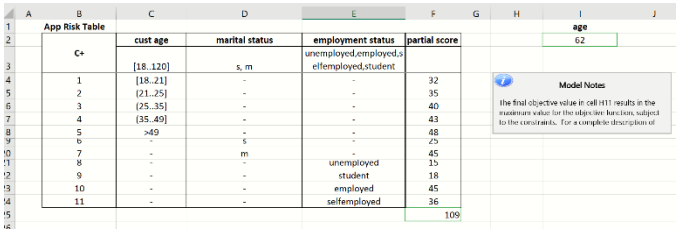
The final objective value in cell H11 results in the maximum value for the objective function, subject to the constraints. For a complete description of

The Model tab on the Solver Task Pane shows the optimization model which is maximizing the PsiDecTable() function in cell F25 by varying cell I12 subject to the variable bounds of 18 and 65. Click Optimize – Analyze Original Model. Analytic Solver will report the model type as "NSP" meaning "nonsmooth problem". The model is nonsmooth due to the use of the decision table. As a

result, you will need to either select the Evolutionary Engine to solve the model or set Automatically Select Engine on the Engine tab. Then click the green arrow on the Model tab to solve the optimization model.

Almost immediately, the Evolutionary Engine stops with the result, "Solver has converged to the current solution. All constraints are satisfied." This result means that the Solver has been unable to find a new, better member of the population whose "fitness" represents a relative (percentage) improvement over the current best member's fitness. For more information on this result, see the "Solver Result Messages" chapter within the Frontline Solvers Reference Guide.

The final variable age results in the largest collective score according to the decision table rules, based on the initial starting point. (For more information on optimizing with the Evolutionary Engine, see the Frontline Solvers Reference Guide.)



App Risk Table

	cust age	marital status	employment status	partial score
C+	[18..120]	s, m	unemployed,employed,selfemployed,student	
1	[18..21]	-	-	32
2	(21..25]	-	-	35
3	(25..35]	-	-	40
4	(35..49]	-	-	43
5	>49	-	-	48
6	-	s	-	25
7	-	m	-	45
8	-	-	unemployed	15
9	-	-	student	18
10	-	-	employed	45
11	-	-	selfemployed	36
				109

age: 62

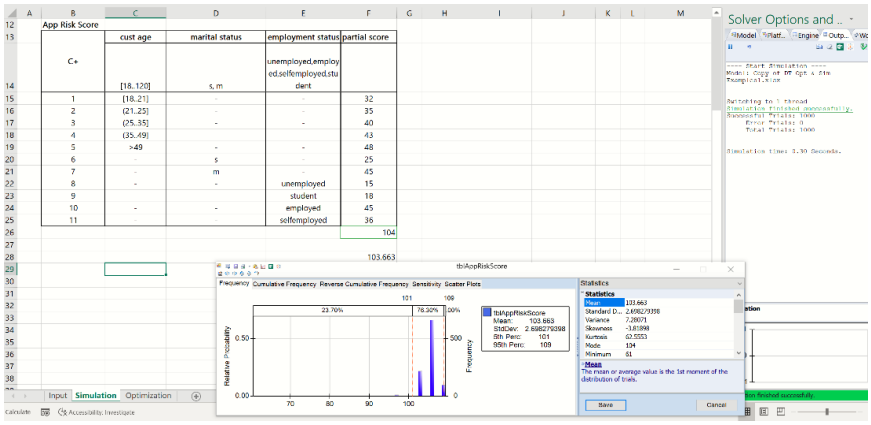
Model Notes

the final objective value in cell H11 results in the maximum value for the objective function, subject to the constraints. For a complete description of

Simulation

Click the Simulation tab to open the simulation example. This example uses the same decision table as in the optimization example. However, in this example, the PsiDecTable() function in cell E26 = PsiDecTable(A13:F25, 3, custAge, maritalSt, employSt), where "custAge" refers to Input!C11 which holds a PsiNormal() function. This function will pull 1000 values from the PsiNormal() distribution, with a mean of 40 and a standard deviation of 7, during the simulation. The PsiMean() function in cell E28 will summarize the 1000 trial values into one mean value. In addition, the PsiMean function will also denote cell E26, the cell containing the PsiDecTable() function, as an output cell. For simulations, Analytic Solver tracks the values of all uncertain functions (simulation outputs, referenced in PsiOutput() or PSI Statistics function calls).

Click the green arrow on the Model tab to run a simulation. Immediately, the simulation finishes and the uncertain function dialog opens displaying a discrete distribution where we can see that over 70% of the time, the values for the collective sum of the partial scores is over 101 when the age parameter follows a normal distribution with mean 40 and standard deviation 7. For more information on simulation with Analytic Solver, see the Examples: Simulation chapter that appears previously in this guide.



Using Decision Tables with Data Mining

This DT Loan Strategy + Predictive.xlsx example expands on the DT Loan Strategy Model by adding an element to the APP Risk Score table on the Loan tab. The formula in cell Loan!E15 returns the minimum of 2 outputs. The first output is produced from a linear regression model scoring new data contained in cells Input!F26:I27. The second output is from the decision table.

Input Parameters

This Input worksheet contains the input parameters to the Loan Strategy model contained on the Loan Strategy and Post Bureau worksheets. Input parameters are all constant values.

Customer				**Loan**			
age	40			**type**	standard		
exist	FALSE			**rate**	5		
marital status	s			**term**	30		
employment status	selfemployed			**amount**	100000		
credit score	610						
bankrupt	FALSE			**New Applicant**			
monthly income	2500			*X1*	*X2*	*X3*	*X4*
				7	26	6	60
monthly expenses	1000						

Loan Strategy

Click the Loan Strategy worksheet. Like in the DT Loan Strategy Model.xlsx workbook, this worksheet contains six cascading decision tables. The first table appears in cells A2:E14. This table returns a partial "risk of default" score based on a loan applicant's age, marital and employment status. Higher scores are given to older, employed, married applicants. Cell E15 contains the PsiDecTable() function.

	A	B	C	D	E
1	App Risk Score				
2	C+	cust age	marital status	employment status	partial score
3		[18..120]	s, m	unemployed,employed,self employed,student	
4	1	[18..21]	-	-	32
5	2	(21..25]	-	-	35
6	3	(25..35]	-	-	40
7	4	(35..49]	-	-	43
8	5	>49	-	-	48
9	6	-	s	-	25
10	7	-	m	-	45
11	8	-	-	unemployed	15
12	9	-	-	student	18
13	10	-	-	employed	45
14	11	-	-	selfemployed	36
15					20.56795175

In this workbook, however, the formula in cell E15, has an added component. In this example, the Excel MIN function is used to return the minimum of a predicted value obtained from a linear regression model made to score on an applicant's data (see cells Input!F26:I28) and the decision table result given the applicant's name, marital status, and employment status.

=MIN(PsiPredict(Predictive_PMML_Model!B12:B44,Input!E15:H16),PsiDecTable(A2:E14, 3, custAge, maritalSt, employSt))

The input parameters for the first term in the MIN function (PsiPredict(Predictive_PMML_Model!B12:B44,Input!E15:H16) are the linear regression model saved in PMML format on the Predict_PMML_Model tab in cells B12:B44 and the new data saved on the Input tab in cells E15:H16. The result from PsiPredict() is 20. 57 For a complete explanation of the PsiPredict function, see the Data Mining User Guide.

The input parameters from the Input worksheet are: custAge="40", maritalSt = "s", employSt = "selfemployed". The applicable rules for these input parameters are: 4, 6, and 11 resulting in partial scores of 43, 25, and 36, respectively. Since the Hit Policy is "C+" the result collection is added together, 43 + 25, + 36 = 104. As shown in the DT Loan Strategy Model, the output from the App Risk Score table is 104.

The minimum value returned is of course 20.57, or the output from the PsiPredict() function.

The remaining decision tables are calculated as in the DT Loan Strategy Model.

- The next decision table is located in cells G5:J14, the Bureau Risk Cat table. This table returns a risk category of high, medium, or low based on their customer status (existing or not) and their application risk score. Non-existing customers are allowed a higher risk score. Cell J15 contains the PsiDecTable() function

	F	G	H	I	J
4		**Bureau Risk Cat**			
5		**U**	**cust exist**	**app risk score**	**bureau risk cat**
6					
7		1	FALSE	<100	high
8		2	FALSE	[100..120]	medium
9		3	FALSE	[120..130]	low
10		4	FALSE	>130	veryLow
11		5	TRUE	<80	decline
12		6	TRUE	[80..90]	high
13		7	TRUE	[90..110]	medium
14		8	TRUE	>110	low
15					high

J15 =PsiDecTable(G5:J14, 2, custExist, tblAppRiskScore) where custExist = False and tblAppRiskScore() refers to the value in cell E15, or 20.57. Based on these conditions, one rule is "hit", rule 2. This rule returns "high" for the bureau risk category. Since the hit policy is equal to U (Unique) only one result is returned, even if multiple results are returned.

The next decision table, Bureau Call Type, is located in cells L11:N14. This table returns the bureau call type based on the bureau risk category found in the previous decision table, Bureau Risk Cat. Cell N15 contains the PsiDecTable() function.

	K	L	M	N
9				
10		**Bureau Call Type**		
11		**U**	**bureau risk cat**	**bureau call type**
12		1	high, medium	full
13		2	low	mini
14		3	veryLow, decline	none
15				full

N15=PsiDecTable(L11:N14, 1, tblBureauRiskCat) where tblBureauRiskCat is equal to the result of the PsiDecTable() function in cell J15, or "medium". Only 1 rule is "hit", rule 1, which returns "full" This means that a full evaluation by the bureau must be performed.

The next decision table, Eligibility, is located in cells A20:E25. This table returns the applicant's eligibility based on three criteria: the bureau risk category, from cell J15, bureau afford, calculated in cell C36, and customer age, located in cell Input!C13. Since the Hit Policy is equal to P (Priority), the result collection will be returned in the order listed according to the list in cell E21. The PsiDecTable() function is located in cell E26.

	A	B	C	D	E
19	**Eligibility**				
20	**P**	**bureau risk cat**	**bureau afford**	**cust age**	**eligibility**
21					ineligible, eligible
22	1	decline	-	-	ineligible
23	2	-	FALSE	-	ineligible
24	3	-	-	<18	ineligible
25	4	-	-	-	eligible
26					eligible

E26 = PsiDecTable(A20:E25, 3, tblBureauRiskCat, bureauAfford, custAge)

Intermediate Formulas

Cell C36 calculates the bureau afford statistic, =IF(disposIncome * tblCreditContFactor > monthInstall, TRUE, FALSE)

where disposIncome is calculated in cell C34, tblCreditContFactor is calculated in cell N26 (more on this later) and monthInstall is calculated in cell C32.

Cell 34 calculates an applicant's disposable income using the formula, =monthIncome - (monthRepay + monthExpenses) where monthIncome = 2500, monthRepay is calculated in cell C30 and monthExpenses = 1000.

Cell C30 calculates the monthly loan replayment amount using the formula, -PMT(loanRate%/12, loanTerm*12, loanAmnt) where loanRate is 5%, loanTerm = 30 and loanAmnt = 100,000.

Finally, cell C28 calculates the monthly fee using the IF statement, = IF(loanType = "standard", 20, IF(loanType = "special", 25, 0)), where loanType = standard.

Using the final input values of tblBureauRiskCat = high, bureauAfford = True, and custAge = 40, the last rule, rule 4, is the only rule "hit", returning "eligible".

The next decision table is located in cells G22:J25. This table returns the loan strategy based on the applicant's eligibility and bureau call type. The PsiDecTable() function is located in cell J26.

	G	H	I	J
21	**Strategy**			
22	**U**	**eligibility**	**bureau call type**	**strategy**
23	1	ineligible	-	decline
24	2	eligible	full, mini	bureau
25	3	eligible	none	through
26				bureau

J26=PsiDecTable(G22:J25, 2, tblEligibility, tblBureauCallType) where tblEligibility is calculated in cell E26 and tblBureauCallType is calculated in cell N15. Both of these inputs are outputs of earlier decision tables. Based on the results calculated by the previous decision tables, this PsiDecTable() function results in a "bureau" strategy.

Finally, the last decision table, Credit Cont Factor, is contained in cells L22:N25. The PsiDecTable() function is located in cell N26.

	K	L	M	N
21		**Credit Cont Factor**		
22		**U**	**bureau risk cat**	**credit cont factor**
23		1	high, decline	0.6
24		2	medium	0.7
25		3	low, veryLow	0.8
26				0.6
27				

N26 =PsiDecTable(L22:N25, 1, tblBureauRiskCat) where tblBureauRiskCat is calculated in cell J15. Again, this input is an output from an earlier discussed decision table.

If the result of the PsiDecTable function in cell J26 would have been either "decline" or "through", then our work would be finished. We would either decline or accept the applicant, respectively. However, since "bureau" was returned, more analysis is required.

More Information on Decision Tables

Supported **conversion** functions are listed below.

- **date**(string *date*) returns a date serial number, the same as Excel DATEVALUE
- **date**(number *y*, number *m*, number *d*)
- **time**(string *time*) returns a time serial number, the same as Excel TIMEVALUE
- **time**(number *h*, number *m*, number *s*[, number *offset*]) the optional *offset* is duration in seconds, which can be used to model UTC
- **duration**(string *dur*) returns duration in months or seconds depending on format
- **yearsAndMonthsDuration**(string *from_date*, string *to_date*) return difference between two dates as a duration in months
- **number**(string num, string group_sep, string dec_sep) returns a number from a string
- **string**(float *num*) returns a float number as a string
- Supported **numeric** functions are:
- **ceiling**(number *num*) rounds up a number
- **decimal**(number *num*, number *decimals*) rounds a number to the given number of decimals
- **floor**(number *num*) rounds down a number
- Supported **string** functions:
- **substring**(string *str*, number *pos*, number num_*chars*)
- **stringLength**(string *str*)
- **upperCase**(string *str*)
- **lowerCase**(string *str*)
- **substringBefore**(string *str*, string *match*)
- **substringAfter**(string *str*, string *match*)
- **contains**(string *str*, string *match*)
- **startsWith**(string *str*, string *match*)
- **endsWith**(string *str*, string *match*)
- Supported **list** functions are:
- **min**(number n1, number n2,…) returns the minimum number
- **max**(number n1, number n2,…)

- **sum**(number n1, number n2,…)
- **mean**(number n1, number n2,…)
- **and**(bool b1, bool b2,…)
- **or**(bool b1, bool b2,…)

Creating Power BI Custom Visuals

Starting with V2017-R2, Analytic Solver can turn your Excel-based optimization or simulation model into a **Microsoft Power BI Custom Visual**. Where others must learn JavaScript (or TypeScript) programming and a whole set of Web development tools to even begin to create a Custom Visual in Power BI, after reading this section, Analytic Solver users will be able to create one right away.

To summarize, users simply select rows or columns of data to serve as changeable parameters, then choose **Create App – Power BI**, and save the file created by Analytic Solver. Afterwards, users click the Load Custom Visual icon in Power BI and select the file just saved. What is produced isn't just a chart – it's a *full optimization or simulation model*, ready to accept Power BI data**, run on demand** on the web, and display visual results in Power BI. Users simply need to drag and drop appropriate datasets into the "well" of inputs in Power BI to match the model parameters.

Analytic Solver translates the Excel model into **RASON**® (RESTful Analytic Solver Object Notation, embedded in JSON), then "wraps" a JavaScript-based Custom Visual around the RASON model. See the previous chapter "Creating Your Own Application" for more information on RASON.

Installing Power BI

Power BI is Microsoft's desktop or cloud-based interactive data visualization business intelligence tool. In past versions of Analytic Solver, users have only been able to upload their model parameters (model data) to Power BI after solving an optimization or simulation model. Starting with V2017-R2, Analytic Solver can turn your Excel based optimization or simulation model into a Microsoft Power BI Custom Visual, *that is your full optimization or simulation model*, ready to accept power BI data, run on demand on the web, and display visual results in Power BI.

Note: Click this link to download Power BI for desktop.

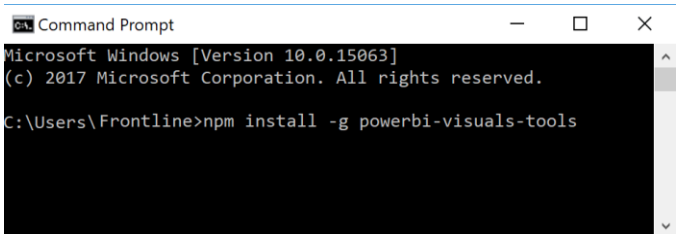
In order to use this new feature in Analytic Solver, you must first open desktop Power BI or the free cloud based version of Power BI. (Power BI is part of the office 365 suite.) For more information on this business tool, see the following website: https://powerbi.microsoft.com/en-us/documentation/powerbi-custom-visuals-getting-started-with-developer-tools/

It is important to note, that in order to create a custom visual in Power BI, you will first need to install Power BI's Developer Tools which is comprised of NodeJS and the Power BI tools. Follow the steps below to install both required items.

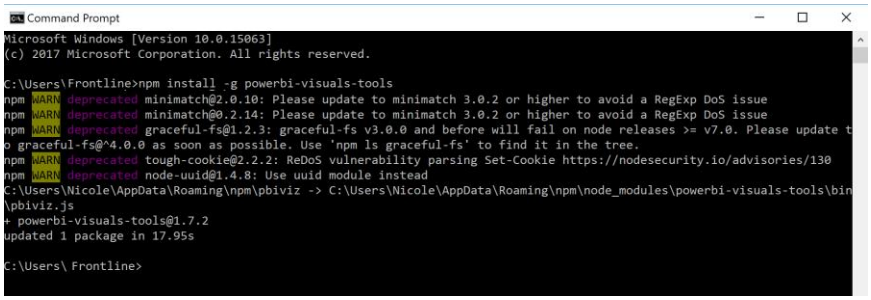
1. Click here to download NodeJS.
2. Click the Download v6.11.2 LTS button to download NodeJS for 64-bit Windows.

3. Once the NodeJS installer is downloaded, run the installer and follow the directions on the installer dialogs to install NodeJS onto your machine.
4. Install the command line tools by opening a command prompt and typing: "npm install -g powerbi-visuals-tools" as shown in the screenshot below.

   Note: If using V2017-R2, type: "npm install -g powerbi-visuals-tools@1.5".



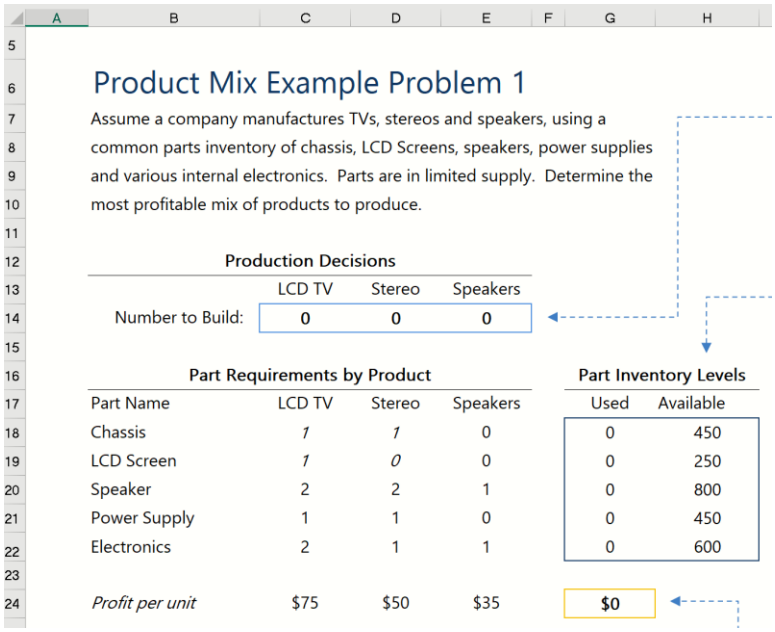
After clicking Enter, you'll see the following results in the command prompt window.



Creating a Custom Visual from an Optimization Model

Now that the Developer Tools are installed, we can move on to a small optimization example. In this section, we will create a custom visual using the Product Mix example model.

Open the Product Mix.xlsx model that was previously discussed in the Conventional Optimization chapter by clicking Help – Examples on the ribbon, clicking Optimization Examples and then the Product Mix link. Recall this example model determines the optimal mix of products that a company should produce in order to maximize profits.



Product Mix Example Problem 1

Assume a company manufactures TVs, stereos and speakers, using a common parts inventory of chassis, LCD Screens, speakers, power supplies and various internal electronics. Parts are in limited supply. Determine the most profitable mix of products to produce.

Production Decisions

	LCD TV	Stereo	Speakers
Number to Build:	0	0	0

Part Requirements by Product

Part Name	LCD TV	Stereo	Speakers
Chassis	1	1	0
LCD Screen	1	0	0
Speaker	2	2	1
Power Supply	1	1	0
Electronics	2	1	1
Profit per unit	$75	$50	$35

Part Inventory Levels

Used	Available
0	450
0	250
0	800
0	450
0	600
$0	

The optimization model is included in the Model tab in the Solver Task Pane. This model written in algebraic form is below.

Maximize: Total Profit = $75x1 + $50x2 + $35x3

Subject To:

Chassis: 1x1 + 1x2 + 0x3 <= 450

LCD Screen: 1x1 + 0x2 + 0x3 <= 250

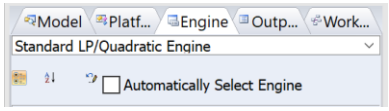
Speaker: 2x1 + 2x2 + 1x3 <= 800

Power Supply: 1x1 + 1x2 + 0x3 <= 450

Electronics: 2x2 + 1x2 + 1x3 <= 600

x1, x2, x3 > 0

The engine selected to solve this model is the Standard LP/Quadratic Engine as shown on the Engine tab in the Solver Task Pane.



Click Create App on the ribbon, then select Power BI.

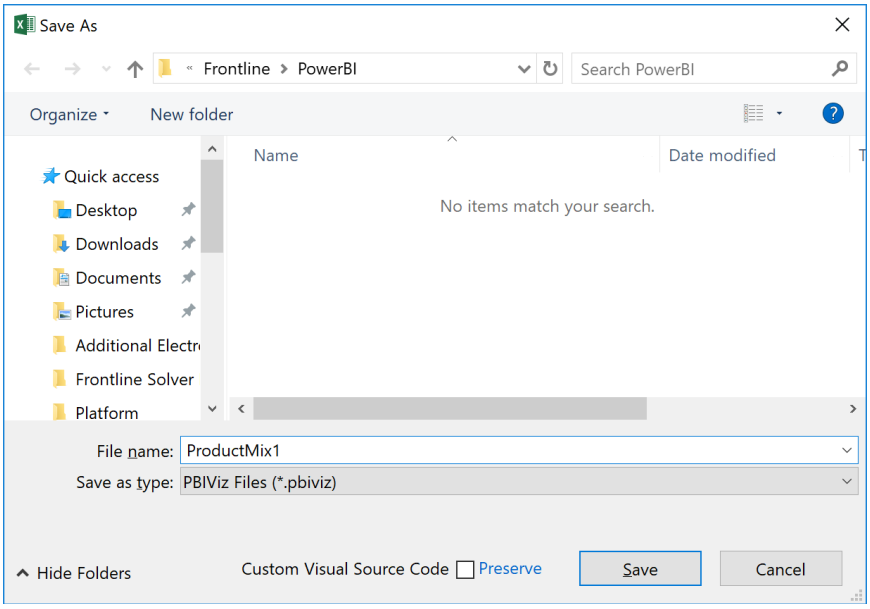
NOTE 1: There is no need to solve the model first unless a change has been made to an already existing RASON model. If a change has been made to the workbook after a RASON model has been created, then you MUST either solve or diagnose the Excel model in order for the changes to be reflected in the new RASON model.

NOTE 2: When creating a Power BI custom visual through desktop Analytic Solver, model elements (objective function and all variables and constraints) may now appear across multiple worksheets within the same Excel workbook.

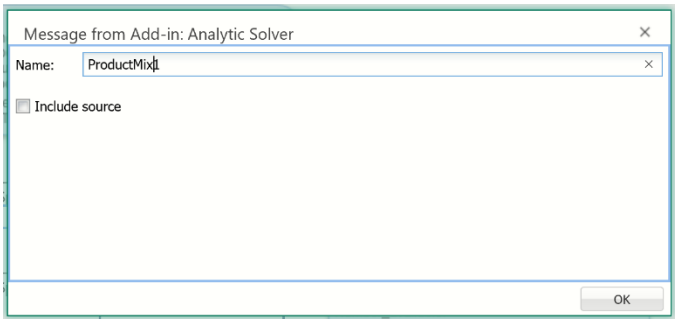
Immediately, the Save As dialog appears. Enter a file name in the location of your choice and then click Save.

- The screenshot below displays a file name of "ProductMix1" being saved into the Power BI folder, in Analytic Solver Desktop.

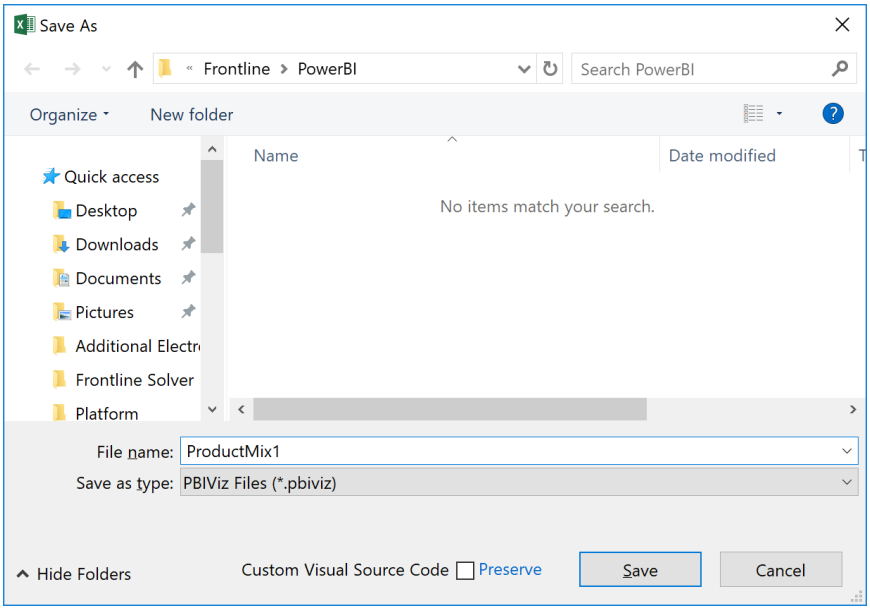
  Analytic Solver Desktop



- In Analytic Solver Cloud, you'll first receive a dialog where you'll name the file to be exported.

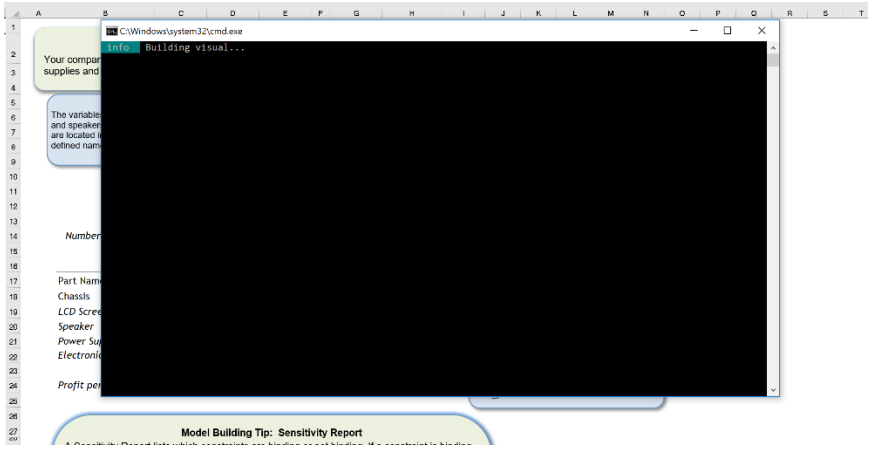


After you click OK and the file downloads, you'll be asked if you'd like to open or save the file. Choose "Save As" to open the Save As dialog and browse to where you'd like to save the Power BI export.

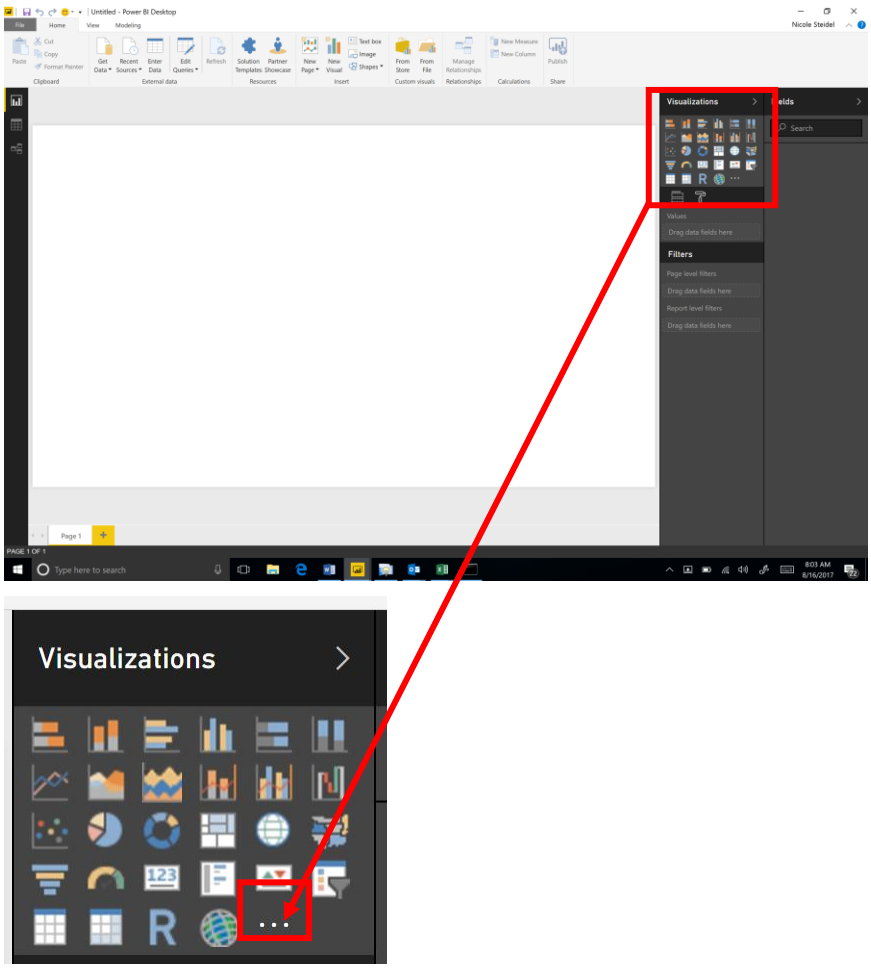


Note the Custom Visual Source Code checkbox at the bottom of the dialog. This feature will be explained a little later in this chapter.

Save ProductMix1.pbiviz. Two command prompt windows will appear on your screen. After several moments, both will disappear. It is during this time that your Excel model is being translated into the **RASON**® modeling language, and your Power BI custom visual is created.

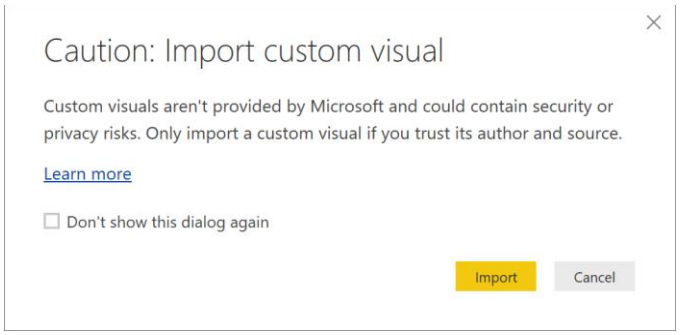


Open either desktop or cloud-based Power BI. The screenshot below depicts the opening screen of desktop Power BI. Click the icon containing three horizontal dots that appears at the bottom of Visualizations (in the top right-hand corner).

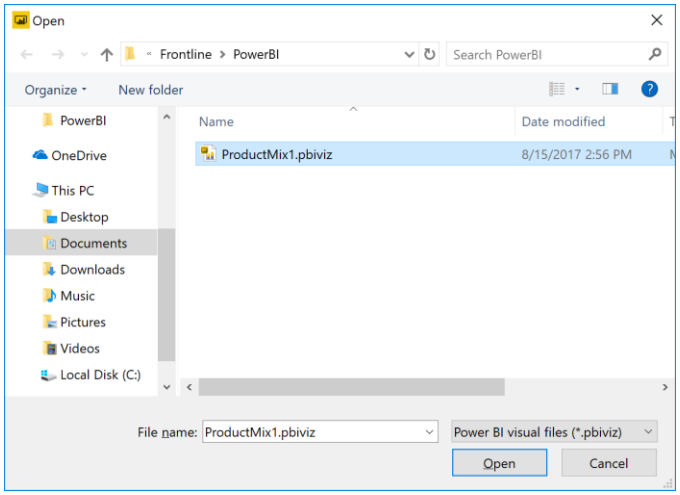


Then select *Import from file* from the menu.

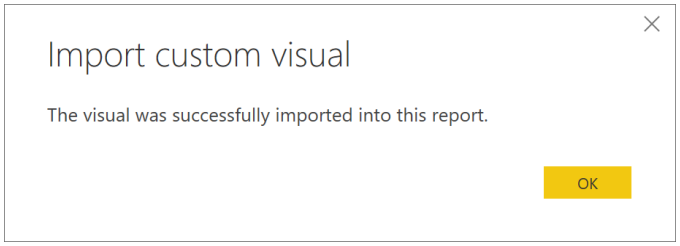
Click **Import** on the *Import custom visual* dialog that appears. (You can select *Don't show this dialog again* if you'd rather not see this dialog each time you import a custom visual.)



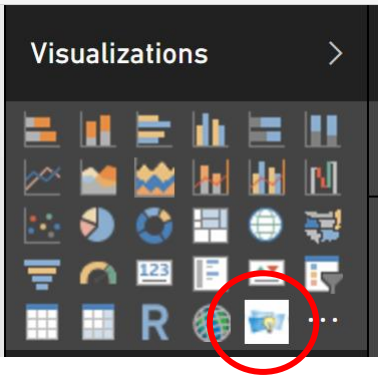
Navigate to the location of the saved ProductMix1.pbiviz file.



Then click Open. If the import was successful, you will see a message indicating as such. Click OK to clear this dialog.



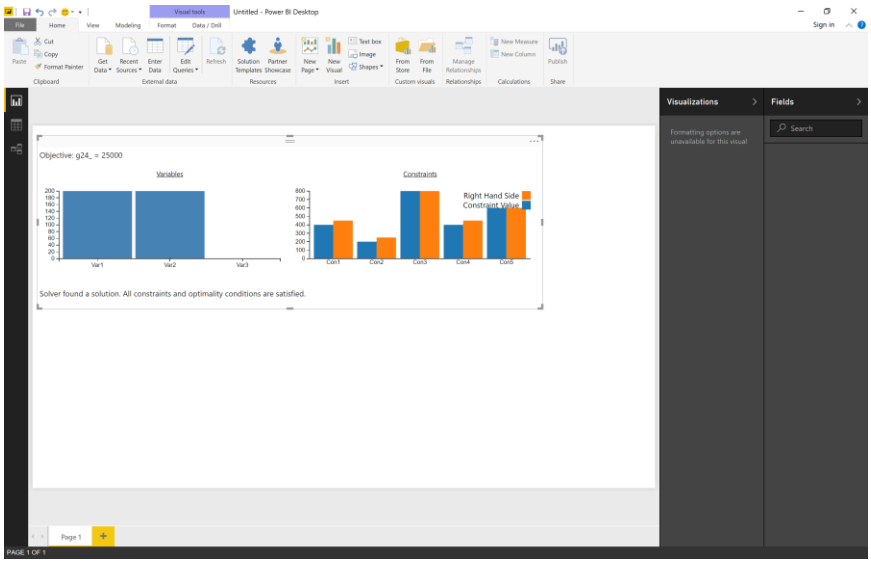
A new icon, bearing the Frontline Solvers logo is added under Visualizations.



Click this icon to open Frontline Solvers' custom visual. At first you'll see two gears moving to indicate that the RASON model has been submitted to Frontline

Solvers' RASON server for solving. If the model is an optimization or stochastic optimization model, the RASON server will use the engine selected in the Excel model to solve the model. Recall that the LP/Quadratic engine was selected in the Product Mix example model, above. (If the model is a simulation model, Frontline Systems' Risk Solver engine will be used.)

After the model is solved, values for the objective function, variables and constraints, or uncertain variables and uncertain functions, are imported back into Power BI and the results are displayed in the Power BI window. After enlarging the custom visual, your screen should appear similar to the screenshot below.



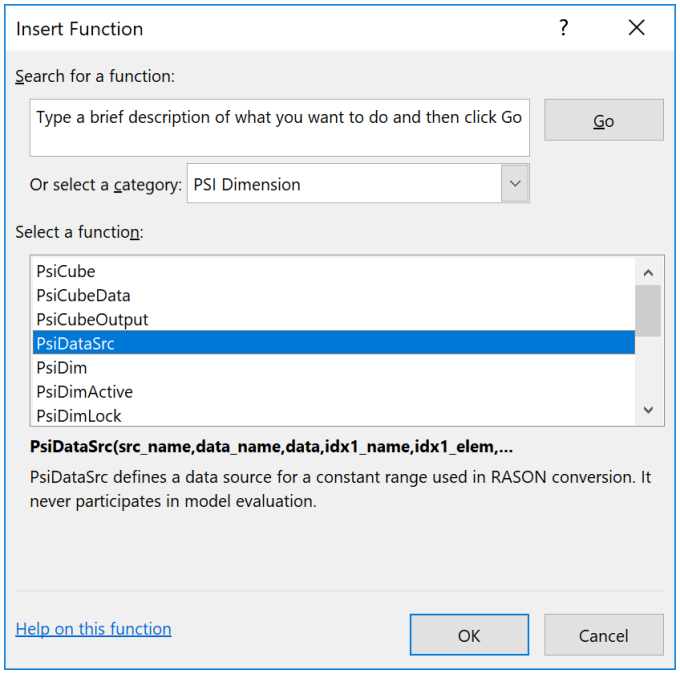
At the bottom of the custom visual, we find Solver's result message: Solver found a solution. All constraints and optimality conditions are satisfied. Recall that since we are solving a linear model, this message indicates that Solver has found the globally optimal solution: There is no other solution satisfying the constraints that has a better value for the objective. For more information on this Solver result, please see the chapter "Solver Results Messages" within the *Frontline Solvers Reference Guide*.

In the first chart, we see that final variable values are: Var1 (LCD TV) equal to 200, Var2 (Stereo) equal to 200 and Var3 (Speakers) equal to 0. These variable values result in an objective function value equal to $25,000. In the chart to the right, we see the final constraint values are: Con1 (number of Chassis used) = 400, Con2 (number of LCD Screens used) = 200, Con3 (number of Speakers used) = 800, Con4 (number of Power Supplies used) = 400, and Con5 (number of Electronics used) = 600.

Solving this model in Power BI could be useful and the chart is certainly informative. However, what if we wanted to change the inventory? What if Purchasing was able to obtain a discount on Speakers and our inventory increased from 800 to 1,000? In order to solve the new model with the updated inventory parameters, we would have to go back to the Excel model, update the chassis inventory, save the model, create a new .pbiviz file, Import the new .pbiviz file into Power BI and then finally open the new custom visual. That's a lot of effort to change just one model parameter!

Thankfully, there is an easier way. By using the Psi function, PsiDataSrc(), we are able to specify the parameters in the Excel model that could change in the future, for example, the amount of inventory on hand for each part, the profit point for each product or the number of parts that makeup each product.

Click back to the Excel model and select a blank cell, say J6. In Analytic Solver Desktop, click Formulas – Insert Function to open the Insert Function dialog, then select Psi Dimension for Category. Afterwards, highlight the function PsiDataSrc, and click OK.



In Analytic Solver Desktop or AnalyticSolver.com, you can simply type the formula directly into the cell.

The Function Arguments dialog opens displaying 5 arguments: Src_name, Data_name, Data, Idx1_name, and Idx1_elem. We will use this dialog to create a PsiDataSrc() in cell J6 that will allow us the ability to change the inventory values and resolve the Product Mix example model not in Excel, but in Power BI.

PsiDataSrc() Arguments

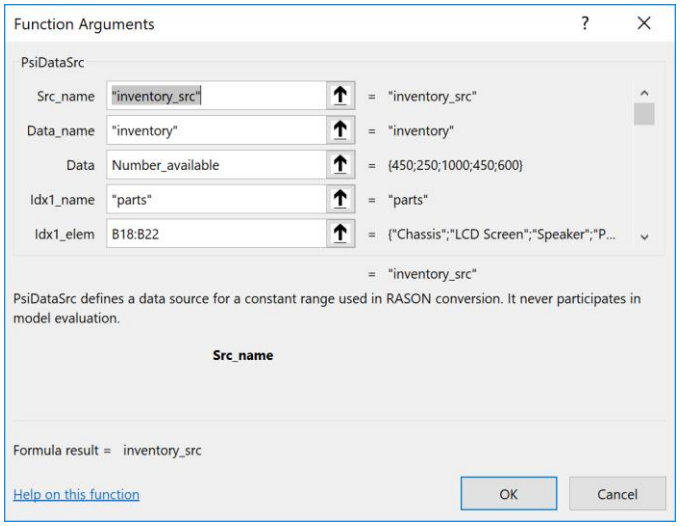
Src_name – This argument names the text file, created by the custom visual, which is submitted, along with the RASON model, to the RASON server. For this example, type: inventory_src.

Data_name – This is the name given to the "data well" that will appear in Power BI. This "data well" will hold the actual data. For this example, type: inventory.

Data – Enter the Excel range where the data is located on the spreadsheet for this argument. For this example, use your mouse to click the upward pointing arrow to the right of the Data argument and select cells H18:H22. You can also simply type this range into the edit box. Notice that if you select cells H18:H22 in the spreadsheet when entering the range into the Data argument, the selection automatically changes to "Number_available" in the Function Arguments dialog. This is because cells H18:H22 have been assigned to the Excel defined name, Number_available.

Idx1_name – Enter the name of the (1st) index set for the data specified in the Data argument. In this example, our Index set is simply the inventory available for each Part. Therefore, enter "parts" for this argument.

Idx1_elem – Enter the Excel range containing the data (or elements) for the first index set. For this example, either type or select cells: B18:B22



Since this index set is 1-dimensional, nothing further is needed and we can click OK to enter the PsiDataSrc() function into cell J6.

In Analytic Solver Cloud or AnalyticSolver.com, you can type the formula directly into cell J26.

```
=PsiDataSrc("inventory_src", "inventory",
Number_available, "parts", B18:B22)
```

Afterwards, cell J26 will display the value given to the Src_name argument, inventory_src. Save the Excel model and then click Create App – Power BI to save a new file using a new name such as ProductMix2.pbiviz.

In order to provide our new data to Power BI, we must create a data file. This data file, containing the new inventory levels by part, will be imported into Power BI. This data file can be of any format supported by Power BI such as a CSV file, a text file, a database, etc. In this example, we will use an Excel workbook to hold the data. For more information on what types of files Power

BI supports, please see the Power BI documentation at:
https://powerbi.microsoft.com/en-us/documentation/powerbi-landing-page/

Open a blank worksheet and create a table with two columns. List the parts by name in the first column using the column heading "Part" and the inventory levels in the second column using the column heading "Inventory", as shown in the screenshot below. Make sure to pass the new inventory value of 1,000 Speakers.

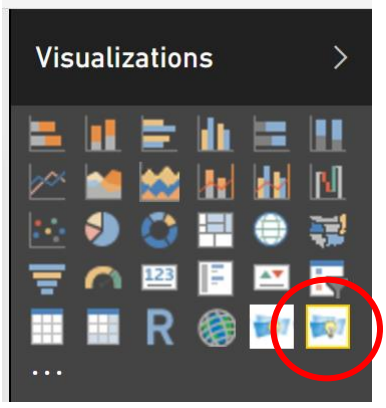
	A	B
1	Parts	Inventory
2	Chassis	600
3	*LCD Screen*	250
4	*Speaker*	1,000
5	*Power Supply*	450
6	*Electronics*	600
7		

*Note: Column headings **must be identical** to the names of the Index Sets passed to the PsiDataSrc function. Make sure there are no spaces before or after column headings or row elements.*

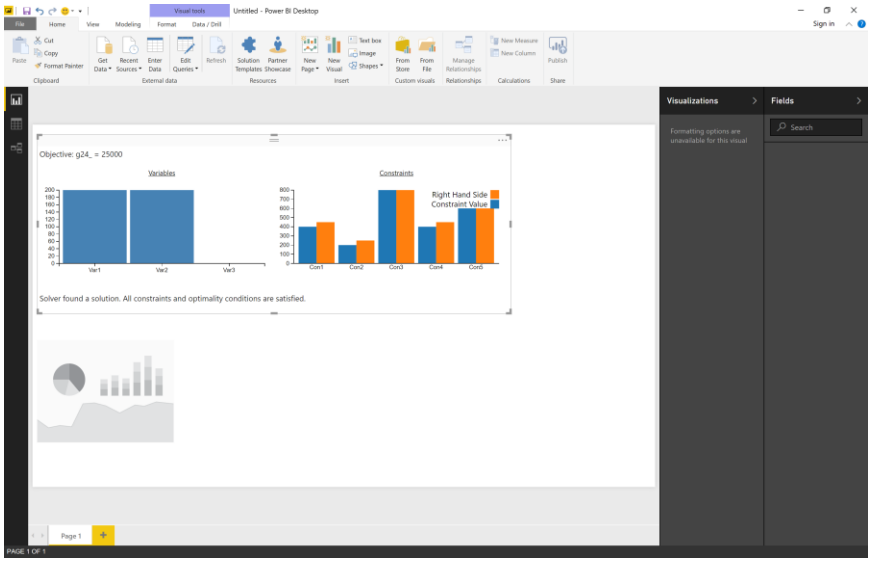
```
=PsiDataSrc("inventory_src","inventory",Number_available,"parts",B18:B22)
```

Recall that we labeled the IndexSet as "Parts" (4th argument of PsiDataSrc) and Data_name as Inventory (2nd argument of PsiDataSrc) so the title for column A must be Parts and the title for column B must be Inventory. Now save the workbook to a desired location.

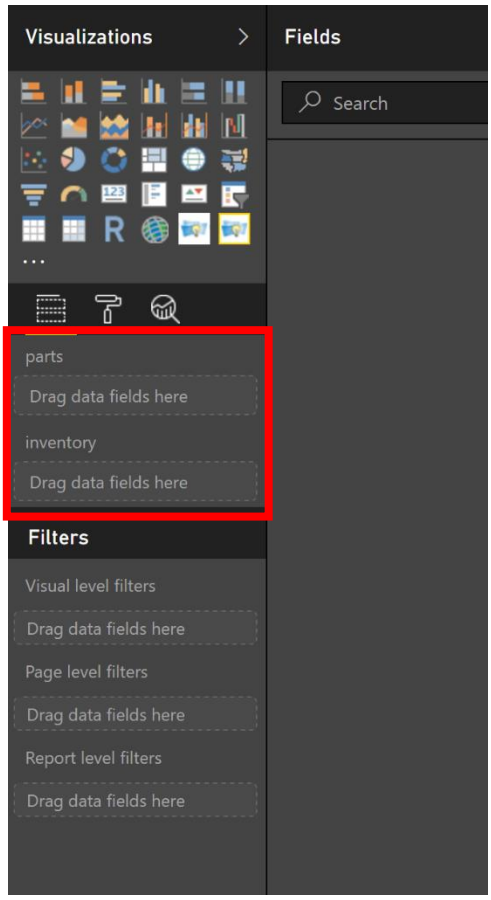
Open either desktop or cloud-based Power BI, click the icon containing three horizontal dots at the bottom of Visualizations, then select *Import from file* from the menu. Navigate to the location of the saved ProductMix2.pbiviz file. Select the file, then click Open. If the import was successful, you will see a message indicating as such. Click OK to clear this dialog. A new second icon, bearing the Frontline Solvers logo is added under Visualizations.



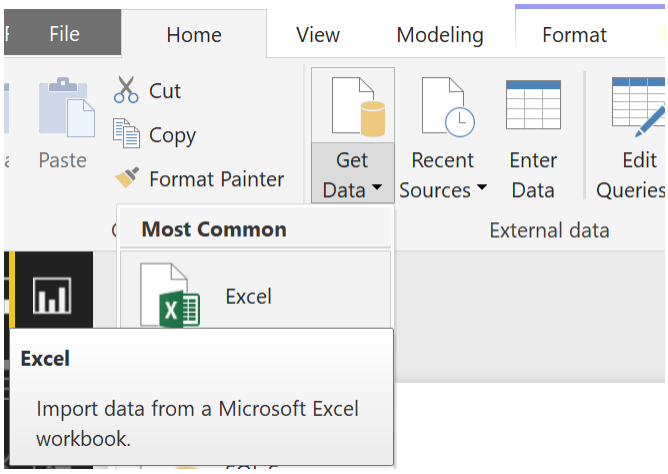
Click this icon to open Frontline Solvers' custom visual. Your Power BI screen should appear similar to the screenshot below.



Click the newly added custom visual, the black and white chart. At this point you should see newly added items such as "Part" and "Inventory" under Visualizations in the task pane on the right. Recall that these are the same names that we passed to the PsiDataSrc() function within the Excel example model, ProductMixOpt.xlsx.

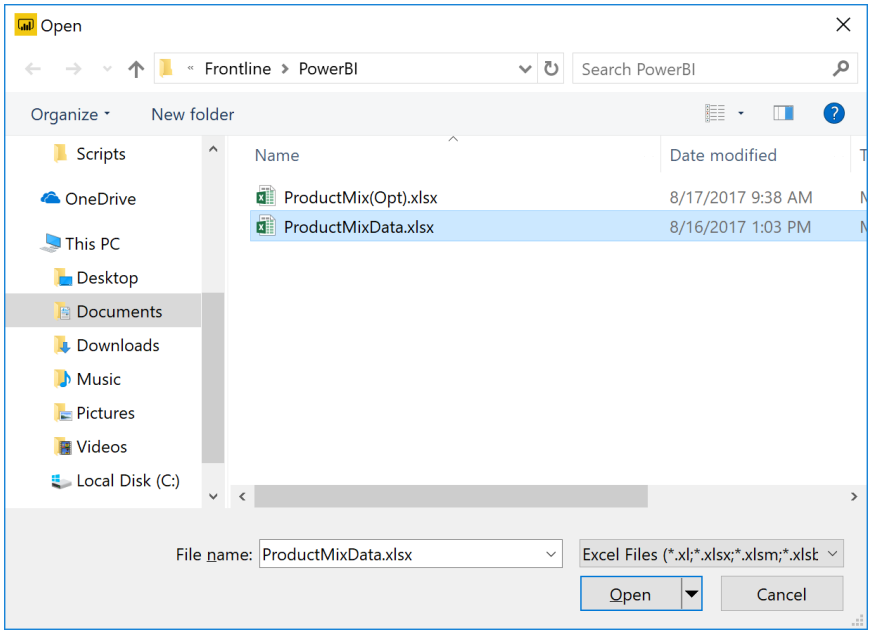


Now we are ready to upload our data file that contains the data for the part inventory. Within Power BI, click Get Data – Excel.

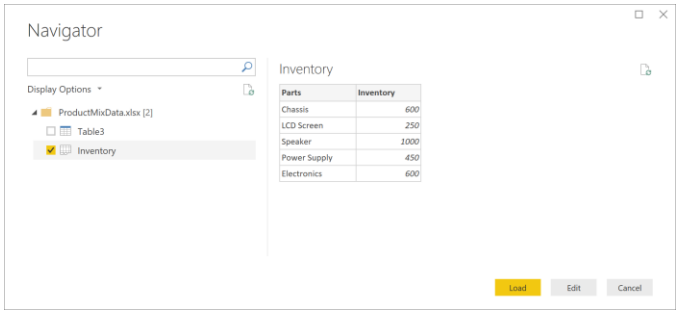


Navigate to the location of your data file, select the appropriate file, and then click Open.

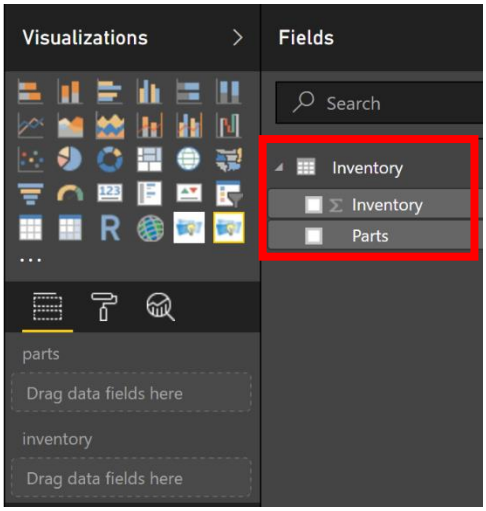
sele



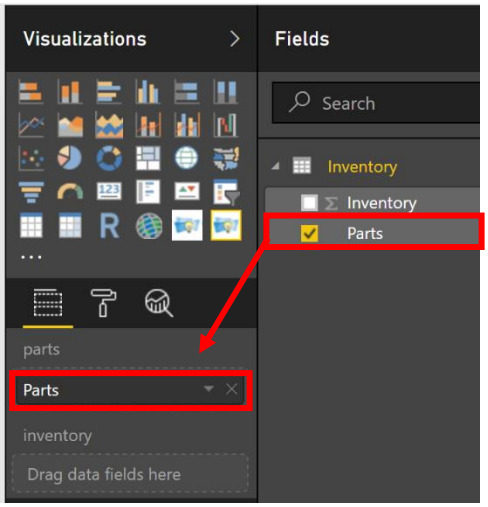
Select the Data table on the Navigator window, then click Load.



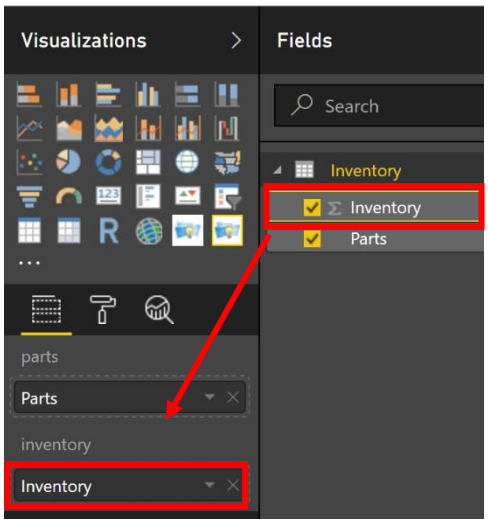
Two fields are added under Inventory in the Fields section of the Task Pane: Inventory and Part.



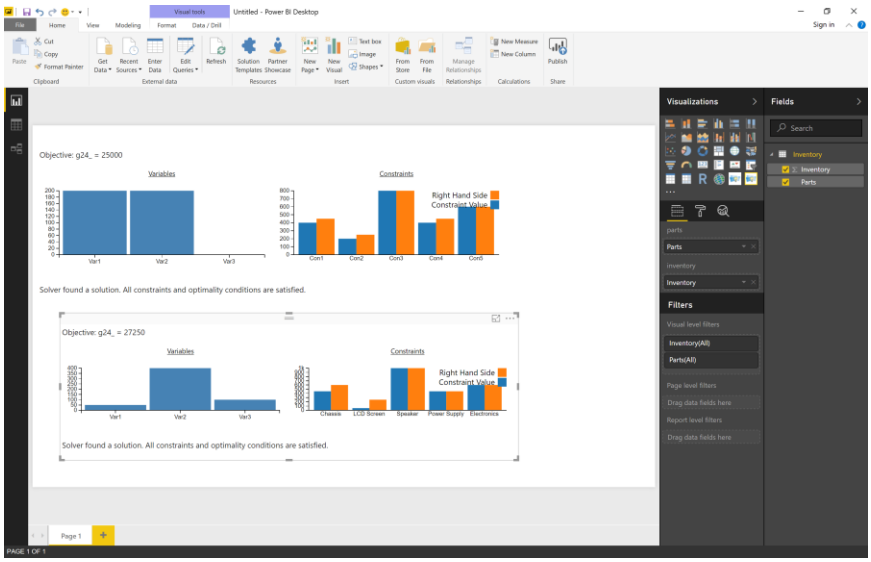
Click Part Under Fields and move to Part under Visualizations where the words "Drag data fields here" is located.



Now drag Inventory on the right to Inventory on the left.



Immediately, you should see the two gears start to turn while the model is sent to the RASON server, solved, and the final values are returned. After enlarging the custom visual, your screen should appear similar to the screenshot below.



At the bottom of the custom visual, we find Solver's result message: Solver found a solution. All constraints and optimality conditions are satisfied. In the Variables chart, we see that final variable values are: Var1 (LCD TV) equal to 50, Var2 (Stereo) equal to 400 and Var3 (Speakers) equal to 100. These variable values result in an objective function value equal to 27,250. The payoff of increasing the available speakers from 800 to 1,000 is an added profit of $2,250 ($27,250 - $25,000).

In the chart to the right, we see the final constraint values are: Con1 (number of Chassis used) = 450, Con2 (number of LCD Screens used) = 50, Con3 (number of Speakers used) = 1,000, Con4 (number of Power Supplies used) = 450, and Con5 (number of Electronics used) = 600.

Now let's go back to the Excel Model and see what happens when we change other parameters such as adding 2 more speakers to a Stereo and increasing the Stereo's selling price to $100.

First, we will use a 2nd PsiDataSrc() function to denote that new data (an increased selling price for Stereos) will be available in Power BI. Click back to the ProductMix(Opt) example model, select cell J7 and then click Formulas – Insert Formulas, select Psi Dimension for Category, select PsiDataSrc, then click OK.

Enter the following for the arguments appearing on the Function Arguments dialog.

Src_name – Enter "profit_src" to name the text file, created by the custom visual, which will be submitted, along with the RASON model, to the RASON server.

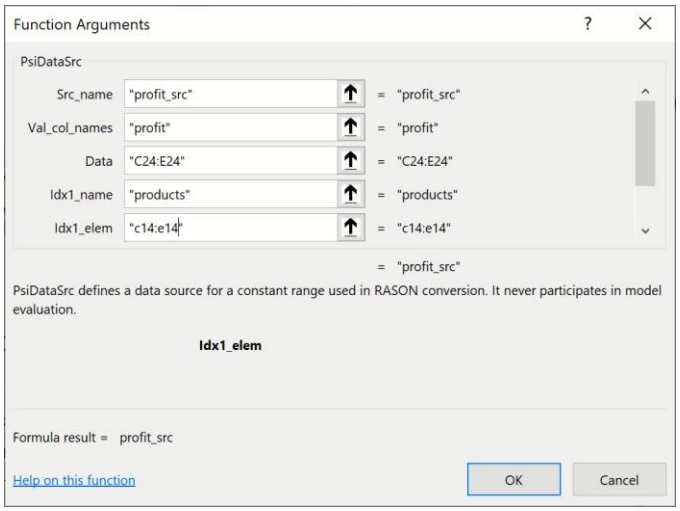
Data_name – Enter "Profit" for the data well name.

Data – Enter the Excel range, C24:E24.

Idx1_name – Enter "Products" which is the name of the 1st index set for the data specified in the Data argument. In this example, our Index set is simply the selling price for each product.

Idx1_elem – Enter the Excel range containing the data for the first index set, C14:E14.

Since this index set is 1-dimensional, nothing further is needed and we can click OK to enter the PsiDataSrc() function into cell J27. Afterwards, cell J27 will display the value given to the Src_name argument, profit_src.



In Analytic Solver Cloud or AnalyticSolver.com, you can type the formula directly into cell J27.

```
=PsiDataSrc("profit_src", "profit", C24:E24,
"Products", C13:E13)
```

Finally, we will use a 3rd PsiDataSrc() function to denote that new data (an increase in the number of speakers to be included in the building of a stereo) will be available in Power BI. This time, we will simply enter the formula directly into cell J28.

First type "=PsiDataSrc(", then enter the arguments below.

Src_name – Enter "reqparts_src" to name the text file which will be submitted, along with the RASON model, to the RASON server.

Data_name – Enter "requiredparts" for the data well name.

Data – Enter the Excel range, C18:E22.

Idx1_name – Enter "parts" which is the name of the 1st index set for the data specified in the Data argument. In this example, there are two index sets. When data is 2-dimensional, we must enter the index set that describes the rows first.

Idx1_elem – Enter the Excel range containing the data for the first index set, B18:B22.

Idx2_name – Enter "products" which is the name of the 2nd index set for the data specified in the Data argument.

Idx2_elem – Enter the Excel range containing the data for the second index set, C13:E13.

Now we can type ")" to close the function, then press Enter to enter the PsiDataSrc() function into cell J8. Afterwards, cell J8 will display the value given to the Src_name argument, reqparts_src.

Your PsiDataSrc function should be similar to the screenshot below.

```
=PsiDataSrc("reqparts_src", "requiredparts", C18:E22, "parts", B18:B22, "products", C13:E13)
```

At this point, cell J26 displays "inventory_src", cell J27 displays "profit_src" and cell J28 displays "reqparts_src". Save the Excel model and then click Create App – Power BI to save a new file using a new name such as ProductMix3.pbiviz.

Now we are ready to add a new data table to the ProductMixData.xlsx file.

Open the ProductMixData.xlsx workbook.

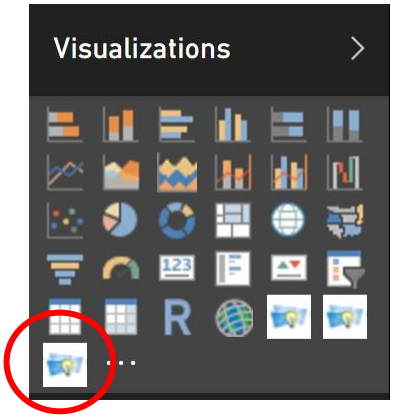
Important Note: **All data for a custom visual MUST be contained within the same Excel table or from within multiple tables with the same number of rows and columns.** As a result, we must create a new table in Excel and enter all data into this new table, including the information from the Inventory worksheet.

In a new Excel sheet, create a table (Insert – Table) with 16 rows and 5 columns, then list the products in the first column using the column heading "products", the parts by name using the column heading "parts" in the 2nd column, the parts required per product (requiredparts) in the 3rd column, the selling price or "profit" per product in the 4th column, and the part inventory for each product in the last column. Make sure to pass the new selling price for Stereos ($100) and the increased number of speakers per stereo (4).

	A	B	C	D	E
1	products	parts	requiredparts	profit	inventory
2	LCD TV	Chassis	1	75	450
3	LCD TV	LCD Screen	1	75	250
4	LCD TV	Speaker	2	75	1,000
5	LCD TV	Power Supply	1	75	450
6	LCD TV	Electronics	2	75	600
7	Stereo	Chassis	1	100	450
8	Stereo	LCD Screen	0	100	250
9	Stereo	Speaker	4	100	1,000
10	Stereo	Power Supply	1	100	450
11	Stereo	Electronics	1	100	600
12	Speakers	Chassis	0	35	450
13	Speakers	LCD Screen	0	35	250
14	Speakers	Speaker	1	35	1,000
15	Speakers	Power Supply	0	35	450
16	Speakers	Electronics	1	35	600

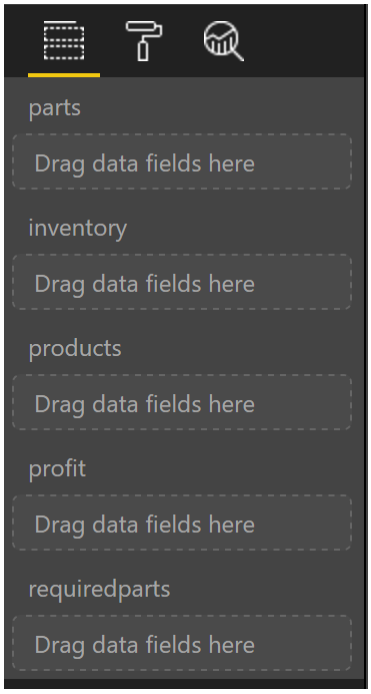
Notice that in order to list all of the required parts for each product, we must list each part and selling price for each part. In addition, each column heading matches the index sets used in the PsiDataSrc() functions. Rename the worksheet "AllData" then save the workbook. *If there are any leading or trailing spaces for the column headings or elements, Power BI will stop with an error.*

Open either desktop or cloud-based Power BI, click the icon containing three horizontal dots at the bottom of Visualizations, then select Import from file from the menu. Navigate to the location of the saved ProductMix3.pbiviz file. Select the file, then click Open. If the import was successful, you will see a message indicating as such. Click OK to clear this dialog. A new third icon, bearing the Frontline Solvers logo is added under Visualizations.

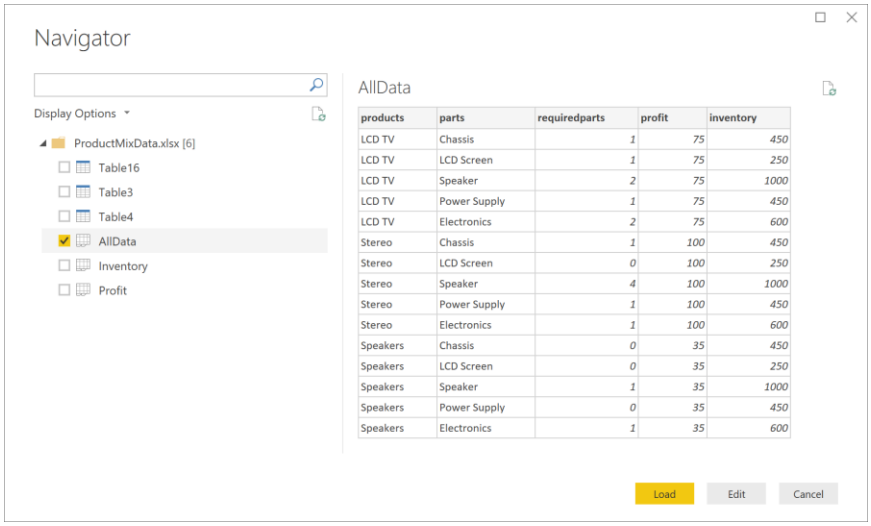


Click this icon to open Frontline Solvers' custom visual.

If you look to the right of the screen, you will see new data wells appearing under Visualizations. Recall that the "parts" and "inventory" data wells were created by the PsiDatasrc() function in the ProductMix(Opt) example model cell J6, inventory_src. Data wells "products" and "profit" were created by the PsiDatasrc() function in cell J7, profit_src. The PsiDataSrc() function in cell j28, requiredparts_src, created the data well "requiredparts".

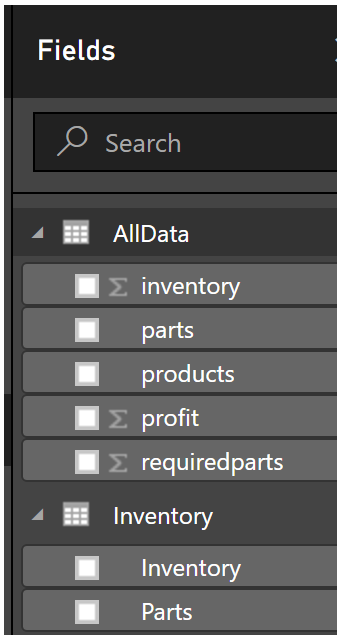


Now it is time to upload our data. Click to Power BI, then click Get Data – Excel and open the ProductMixData.xlsx file.



Select AllData on the left, then click Load on the right.

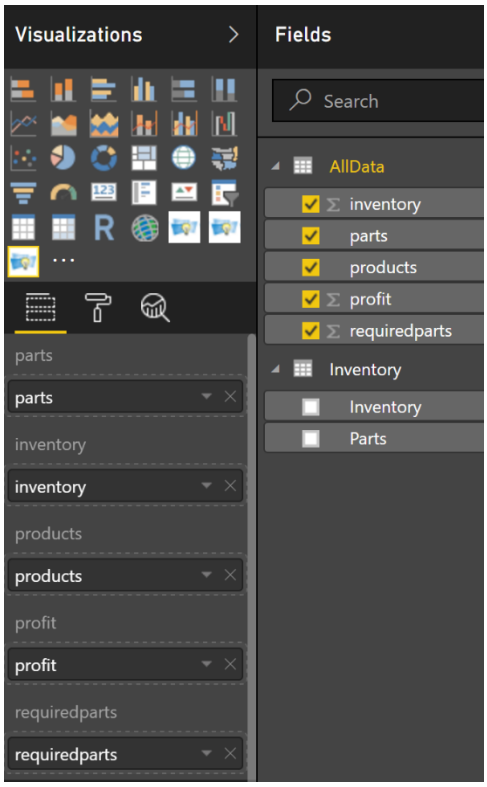
The table headings from the AllData worksheet are uploaded to the Fields task pane in Power BI.



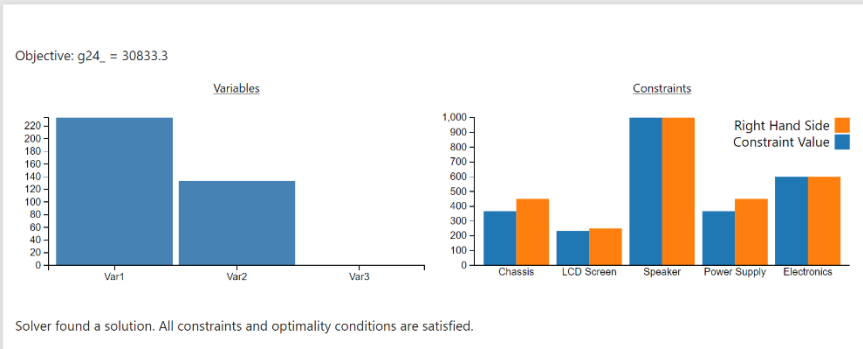
Drag the fields into the data wells according to the following table.

Field	Data Well
inventory	Inventory
parts	Parts
products	Products
profit	Profit
requiredparts	Requiredparts

Afterwards, your task pane should match the following screenshot.



Immediately, the RASON model is submitted to the RASON Server, the model is solved and the final variable values are imported back into Power BI.



Troop Rotation Optimization Example

In this example, we will create a Power BI Custom Visual using a slightly more complex example. In this section, we will create a custom visual using the Troop Rotation example model by clicking Help – Examples on the Analytic Solver ribbon, then click Optimization Models and scroll down to Troop Rotation. Click this hyperlink to open the example model. This example model determines how army troops should be moved to minimize costs.

Moving Cost per Soldier

	Base 1	Base 2	Base 3	Base 4
Camp 1	34	26	29	31
Camp 2	42	33	28	35
Camp 3	36	29	32	38

Number of Troops Moved

	Base 1	Base 2	Base 3	Base 4	Total	Available
Camp 1	0	0	0	0	0	500
Camp 2	0	0	0	0	0	400
Camp 3	0	0	0	0	0	400
Total	0	0	0	0		
Required	200	250	350	300		
Cost	$0	$0	$0	$0	$0	

The optimization model is included in the Model tab in the Solver Task Pane. This model written in algebraic form is below.

Maximize: Total Cost = 34 * x1 + 42 * x5 + 36 * x9 + 26 * x2 + 33 * x6 + 29 * x10 + 29 * x3 + 28 * x7 + 32 * x11 + 31 * x4 + 35 * x8 + 38 * x12

Subject To:

Number of troops from Camps 1, 2 and 3 moved to Bases 1, 2, 3 and 4 must not exceed the number of troops available

Camp1: x1 + x2 + x3 + x4 <= 500

Camp2: x5 + x6 + x7 + x8 <= 400

Camp3: x9 + x10 + x11 + x12 <= 400

Number of troops assigned per base must not be less than the amount required.

Base 1: x1 + x5 + x9 >= 200

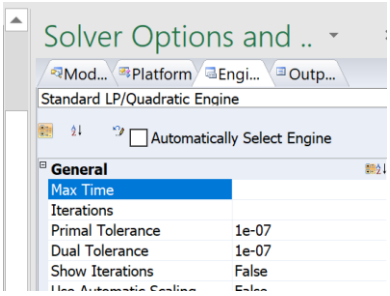
Base 2: x2 + x6 + x10 >= 250

Base 3: x3 + x7 + x11 >= 350

Base 4: x4 + x8 + x12 >= 300

x1, x2, x3, x4, x5, x6, x7, x8, x9, x10, x11, x12 > 0

The engine selected to solve this model is the Standard LP/Quadratic Engine as shown on the Engine tab in the Solver Task Pane.



Next, we will enter four PsiDataSrc() functions into cells P27, P28, P29, and P30.

In P27, we will expose the moving costs per soldier according to base and camp in cells C13:F15. To open the Function Arguments dialog, click Formulas – Insert Function, select Psi Dimension for Category, select PsiDataSrc, then click OK.

Src_name = Enter "cost_src" for this argument. This names the text file that will be submitted to the RASON server, along with the RASON model.

Data_name – Enter "MovingCost" for this argument. This will be the name of the data well associated with the data passed in the next argument.

Data – Enter C13:F15 which is the actual cells containing the moving price per soldier.

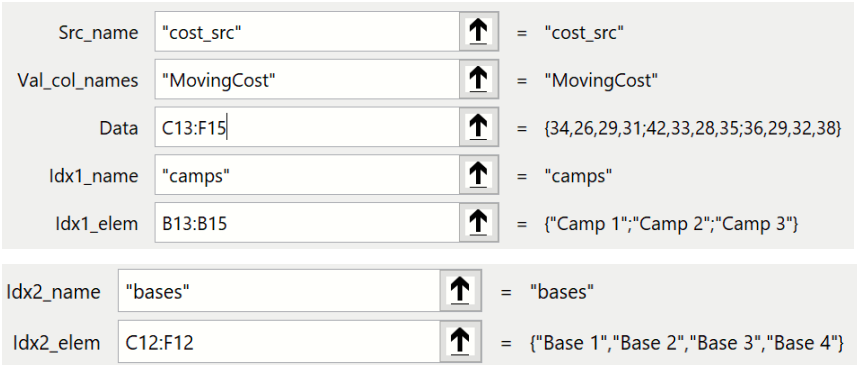
Idx1_name – Enter "camps" which is the name of the 1st index set, the row-wise index set. Remember, you must pass the row-wise index set before the column-wise index set.

Idx1_elem – Enter the elements of the "camps" index set. These appear in cells B13:B15.

Idx2_name – Enter "bases" which is the name of the 2nd index set, the column wise index set.

Idx2_elem – Enter the elements of the "bases" index set. These appear in cells C12:F12.

The Function Arguments dialog should now appear as shown in the screenshots below.



Click OK to save this function to cell P27.

In Analytic Solver Cloud or AnalyticSolver.com, you can type the formula directly into cell P7.

```
=PsiDataSrc("cost_src", "MovingCost", C13:F15,
"camps", B13:B15, "bases", C12:F12)
```

Click cell P28 and open the Function Arguments dialog to enter the next PsiDataSrc() function.

In P28, we will expose the variables that indicate the number of troops moved by camp and base in cells C14:F16. To open the Function Arguments dialog, click Formulas – Insert Function, select Psi Dimension for Category, select PsiDataSrc, then click OK.

Src_name = Enter "vars_src" for this argument.

Data_name – Enter "TroopsMoved" for this argument. This will be the name of the Data Well in Power BI that is associated with this data.

Data – Enter C19:F21 which is the actual cells containing the moving price per soldier. Note: The data range C19:F21 will automatically convert to "Troops_moved" which is the defined name for this Excel range.

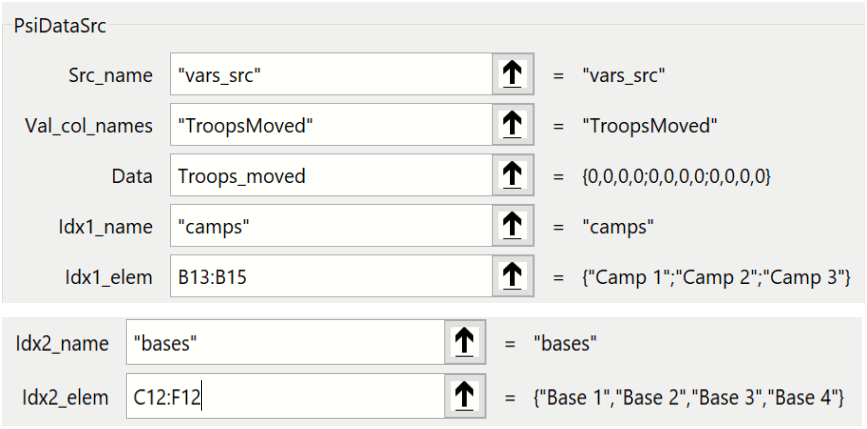
Idx1_name – Enter "camps" which is the name of the 1st index set, the row-wise index set.

Idx1_elem – Enter the elements of the "camps" index set. These appear in cells B13:B15.

Idx2_name – Enter "bases" which is the name of the 2nd index set, the column-wise index set.

Idx2_elem – Enter the elements of the "bases" index set. These appear in cells C12:F12.

The Function Arguments dialog should now appear as shown in the screenshots below.



Click OK to save this function to cell P28.

In Analytic Solver Cloud or AnalyticSolver.com, you can type the formula directly into cell P28.

```
=PsiDataSrc("vars_src", "TroopsMoved", Troops_moved,
"camps", B13:B15, "bases", C12:F12)
```

Let's enter the last two PsiDataSrc() functions by typing the formulas directly into the Excel cells, starting with the function in cell P29 that will expose the number of troops available for movement.

In cell P29, enter: "=PsiDataSrc("

First the first argument, Src_name, enter "available_src".

For the second argument, Data_name, enter: available. The Data Well associated with this data will be given this name.

For the Data argument, the third argument, enter: Troops_available. This is the defined name for cells H19:H21. Alternatively, we could have typed this Excel range.

Type "camps" for the 4th argument, Idx1_name, which is the name given to the row-wise index set.

Enter the range for this index set, B13:B15, for Idx1_elem.

Your PsiDataSrc() function should match the one in the screenshot shown below.

```
=PsiDataSrc("available_src", "available", Troops_available, "camps", B13:B15)
```

Click Enter to enter the PsiDataSrc() function into cell P29.

Finally, the last PsiDataSrc() function in cell P30 should be entered as:

=PsiDataSrc("required_src","required",Troops_required,"bases",C12:F12)

Where:

Data_src = “required_src”

Data_name = “required” This is the name that will appear for the Data Well associated with this data in Power BI.

Data = Troops_required This is the data associated with Data_name.

Idx1_name = “bases” This is the name of the index set that is associated with the data passed to the Data argument.

Idx1_elem – c12:f12 This is the Excel range where the elements for Idx1_name are located on the worksheet.

Now we are ready to create the custom visual.

Click Create App on the ribbon, then select Power BI. Since this is the first time we are creating a custom visual from this model, there is no need to solve the model first. If however, we make a change to the Troop Rotation model, then we would need to either diagnose or solve the model first to ensure that the changes are captured in the new custom visual.

Save the .pbiviz file as TroopRotation1.pbiviz in a location of your choice.

Next, we will create the data file. Open a new Excel workbook. Recall, that when supplying data to Power BI, all data must be contained in tables containing the exact same number of rows and columns. If you are unable to pass your data using Excel tables with the exact same number of rows and columns, then you must pass all data in one table.

In this example, since we would not be able to pass the data in multiple tables with the same number of rows, we will pass all data in one Excel table.

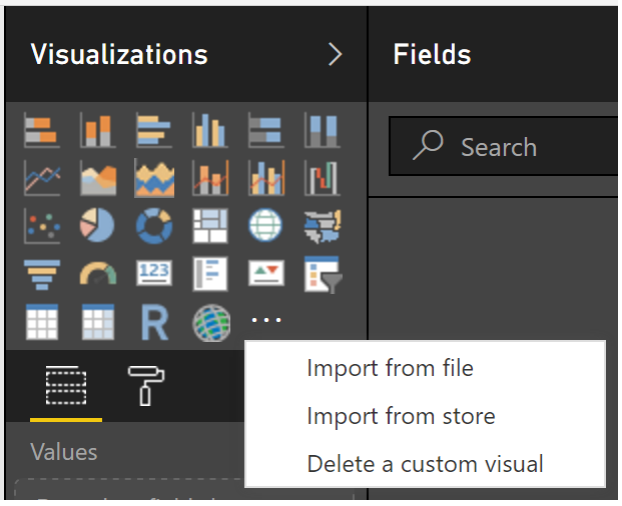
In a new Excel sheet, create a table (Insert – Table) with 13 rows and 5 columns, as shown in the screenshot below. Notice that in order to enter all 12 costs, labels for camps, bases, required troops, and availabletroops were repeated.

	A	B	C	D	E
1	**camps**	**bases**	**cost**	**requiredtroops**	**availabletroops**
2	camp1	base1	34	200	500
3	camp1	base2	26	250	500
4	camp1	base3	29	350	500
5	camp1	base4	31	300	500
6	camp2	base1	42	200	400
7	camp2	base2	33	250	400
8	camp2	base3	28	350	400
9	camp2	base4	35	300	400
10	camp3	base1	36	200	400
11	camp3	base2	29	250	400
12	camp3	base3	32	350	400
13	camp3	base4	38	300	400

In addition, each column heading matches the index sets used in the PsiDataSrc() functions. Rename the worksheet "AllData" then save the workbook as TroopMovementData.xlsx.

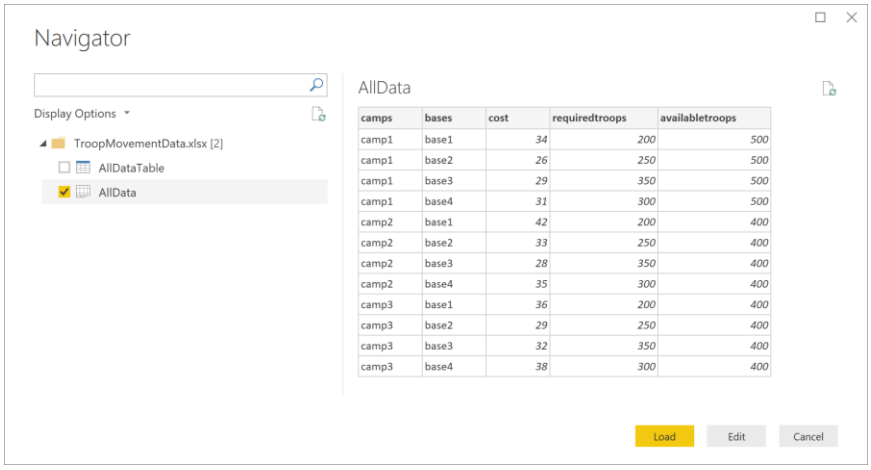
Now let's click back to Power BI, to import the new custom visual and the data.

Click the three dots under Visualizations and select Import from file.



Once the Frontline Solvers icon is inserted under Visualizations, click the icon to open the custom visual.

Then click Get Data – Excel. Browse to the folder where the TroopMovementData.xlsx file was saved, and open the file. Select AllData, then click Load.



Now it is time to drag the data into the data wells. Drag:

availabletroops → available

bases → bases

camps → camps

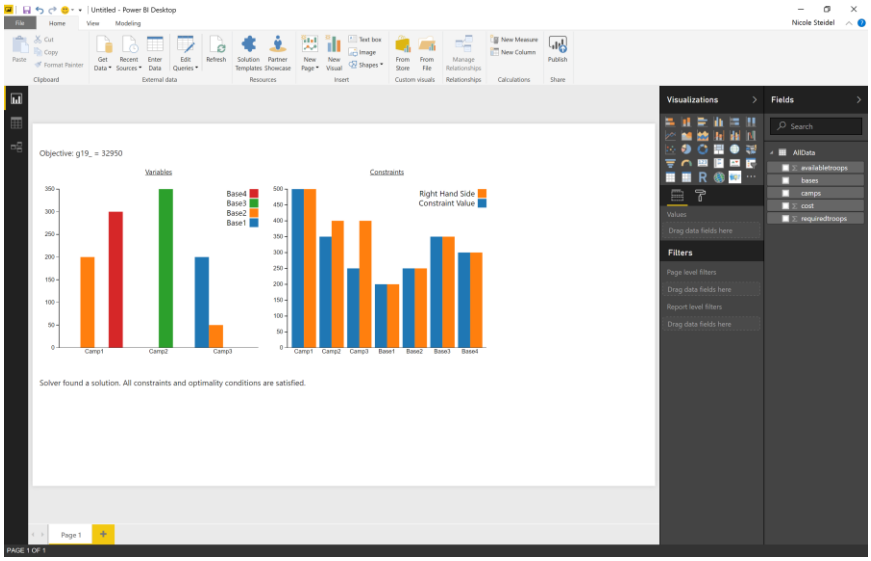
cost → MovingCost

requiredtroops → required

requiredtroops → TroopsMoved

Note: Since "TroopsMoved" holds the variable values, we can simply drag "requiredtroops", which contains the same number of rows and columns as TroopsMoved, as a starting point for the algorithm. A starting point for this model is not needed because our model is linear, however, if our model was nonlinear or nonsmooth, this would be more important.

The resultant Power BI custom visual is shown in the screenshot below. Now each time new data is imported into Power BI, the Troop Movement example data will be solved from within Power BI.

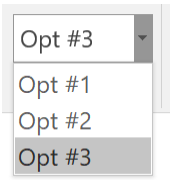


Using Optimization Parameters in Power BI

Now what happens when we would like to see how our final variable values and objective function value change as the number of troops required changes. For this type of "What If" analysis, we can use the PsiOptParam() optimization parameter. Recall from the chapter, Examples: Parameters and Sensitivity Analysis, an **optimization parameter** (PsiOptParam) is automatically varied when you perform multiple optimizations. You do this by clicking the Optimize button on the Ribbon, or the green arrow in the Task Pane, with the Number of Optimizations set to a value greater than 1.

Let's go back to our example Excel model and enter an optimization parameter for the number of troops required in Base 1. In cell C13, enter "=PsiOptParam({34,24,14})", then click the Platform tab in the Solver Task pane and change the Number of Optimizations to "3". When I click Solve, Analytic Solver will solve 3 optimizations. In the first optimization, cell C13 will be set to 34, in the second, 24, and in the third, 14.

Click the Output tab, then click the green arrow to solve the model. After the solving process is over, we can select the three different optimizations in the Optimization drop down menu (in the Tools section of the Analytic Solver ribbon), to see how the objective function changes according to the value set for this parameter.

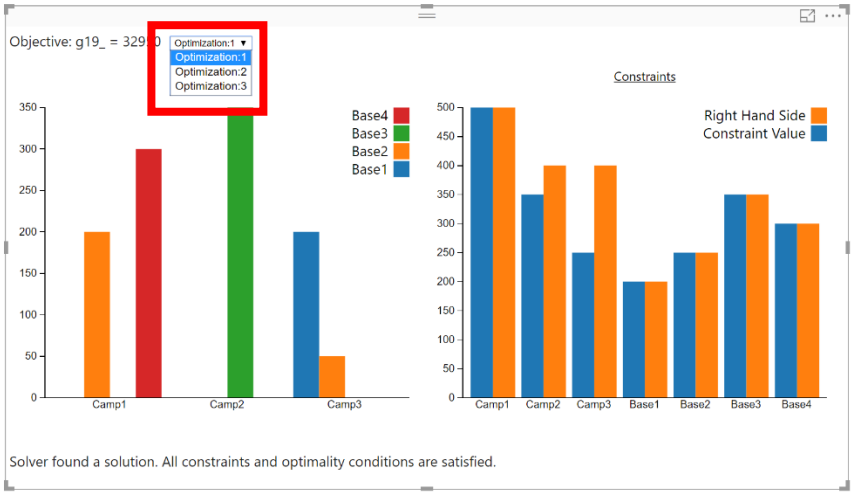


In the first optimization, cell C13 = 34 and the resultant objective function value was $32,950. In the second optimization, cell C13 = 24 and the resultant objective function value was $31,150 and in the third optimization cell C13 j = 14 with an objective function value of 29,150.

Save the Excel file, then click Create App – Power BI to create a new custom visual file. This time, we will name the custom visual file, TroopRotationOptParam.pbiviz.

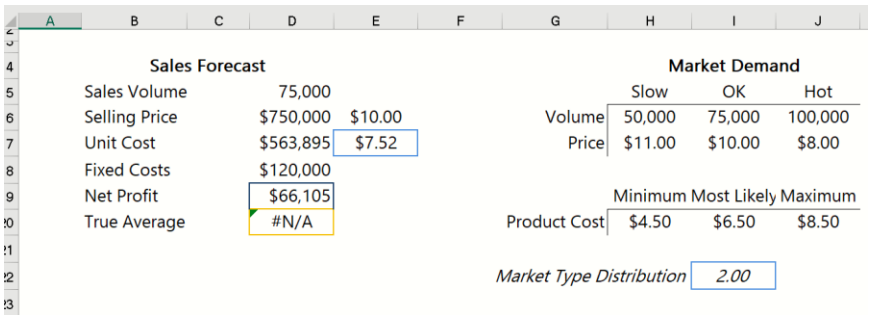
Click back to Power BI and import the newly created custom visual file. Click the new Frontline Solvers icon to open the custom visual. Immediately, the model will solve and the results will be displayed in the Power BI window. To view each solution, click the down arrow within the newly added Multiple Optimization drop-down menu.

Note: When entering PsiOptParam manually (i.e. simply typing the function into an Excel cell) in Analytic Solver Cloud, the taskpane must be refreshed before performing a parameter analysis report.



Simulation Example Model

Now let's create a custom visual from a simulation example. The process is exactly the same when using an optimization model. Open the Business Forecast Example by clicking Help – Examples – Simulation Models, click the Business Forecast hyperlink to open the file, then click the Forecast with Uncertainty tab.



Sales Forecast		
Sales Volume	75,000	
Selling Price	$750,000	$10.00
Unit Cost	$563,895	$7.52
Fixed Costs	$120,000	
Net Profit	$66,105	
True Average	#N/A	

Market Demand			
	Slow	OK	Hot
Volume	50,000	75,000	100,000
Price	$11.00	$10.00	$8.00

	Minimum	Most Likely	Maximum
Product Cost	$4.50	$6.50	$8.50

Market Type Distribution 2.00

First, we will use a PsiDataSrc() function to generate data wells for use in the Power BI custom visual.

Click a blank cell, such as cell G24, then type: "=PsiDataSrc("market_src", "market", H16:J17, "parameters", G16:G17, "mktdemand", H15:J15)

where:

market_src – Is the name used to identify the text file that will be submitted to the RASON server.

market – Will be the name of the data well in Power BI.

H16:J17 – Is the data range for "market".

parameters – Is the name of the 1st index set for the data specified in the "data" argument, market.

G16:G17 – Is the Excel range where the data for "parameters" is located.

mktdemand – Is the name of the 2nd index set for the data specified in the "data" argument.

H15:J15 – Is the Excel range where the data for "mktdemand" is located.

Type ")" to close the formula and then press the Enter key to enter the formula into the Excel cell.

Click a 2nd blank cell, such as G25, then enter the following function.

=PsiDataSrc("price_src", "mktprice", H20:J20, "price", H19:J19)

where:

price_src – Is the name used to identify the text file that will be submitted to the RASON server.

mktprice – Will be the name of the data well in Power BI.

H20:J20 – Is the data range for "mktprice".

price – Is the name of the 2nd index set for the data specified in the Data argument, market.

H19:J19 – Is the Excel range where the data for "price" is located.

Click Create App – Power Bi to create a new Power BI custom visual file with a name, such as BusinessForecast1.pbiviz.

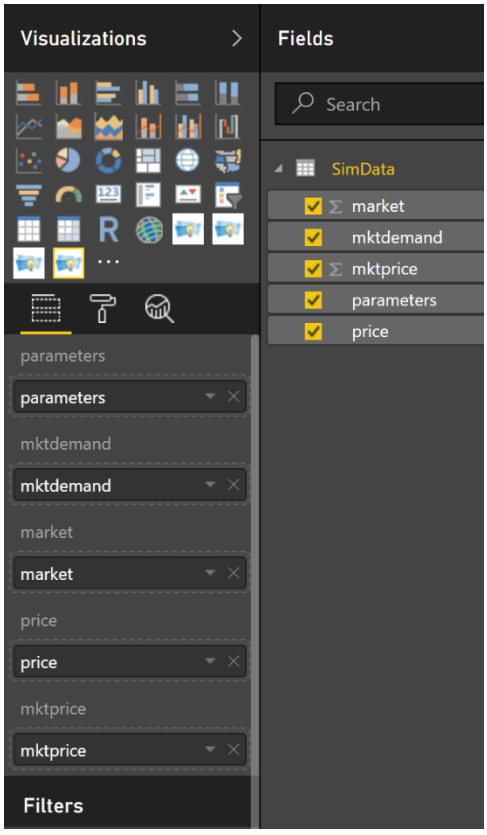
Click back to Excel and open a new workbook to enter the following data **into an Excel table**. Then save the workbook as BusinessForecastData.xlsx.

	A	B	C	D	E
1	parameters	mktdemand	market	price	mktprice
2	volume	slow	50,000	minimum	4.50
3	volume	ok	75,000	most likely	6.50
4	volume	hot	100,000	maximum	8.50
5	price	slow	11	minimum	4.50
6	price	ok	10	most likely	6.50
7	price	hot	8	maximum	8.50

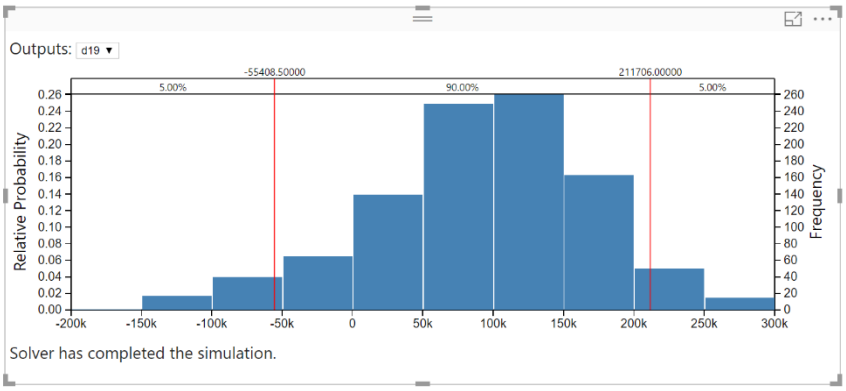
Open Power BI and add in the custom visual, then click Get Data – Excel to import the data. Afterwards, drag the data fields to the appropriate data wells as shown in the table below.

Fields	Data Wells
market	market
mktdemand	mktdemand
mktprice	mktprice
parameters	parameters
price	price

Your task pane should match the following screenshot.

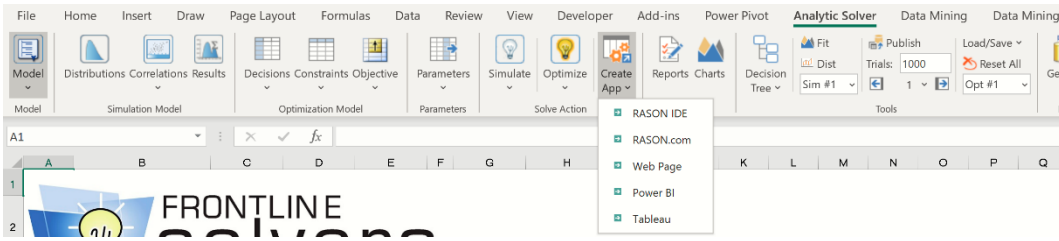


Immediately, once the data wells are filled with the appropriate data fields, a simulation will be run.



Advanced Settings

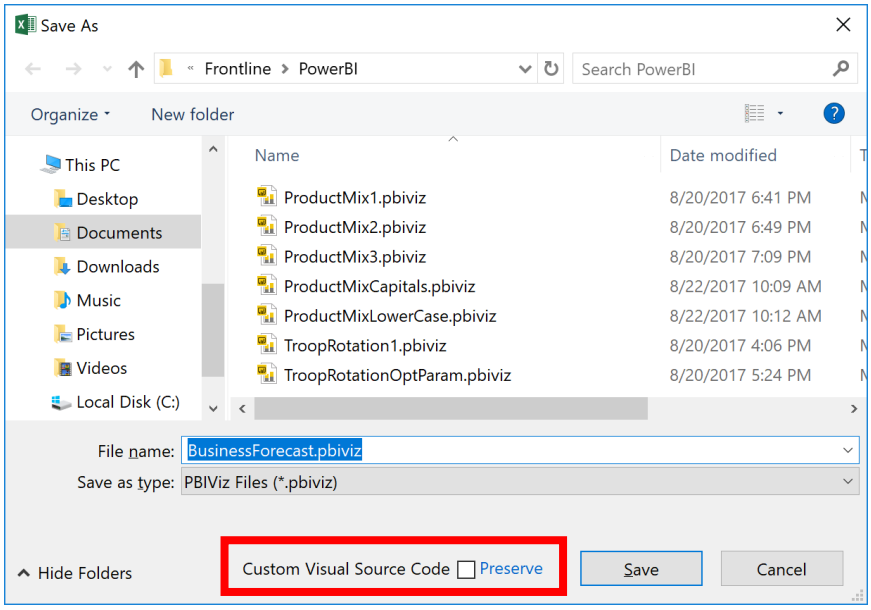
Recall from the examples above, once you click Power BI – Create App in the Excel worksheet, the Save As dialog appears.

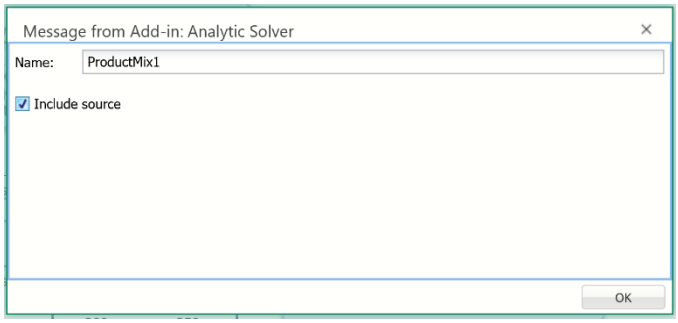


At the bottom of this dialog is the Custom Visual Source Code Preserve checkbox. When this option is selected, a folder is created in the same location as the .pbiviz file. This folder will contain the source code for the custom visual.

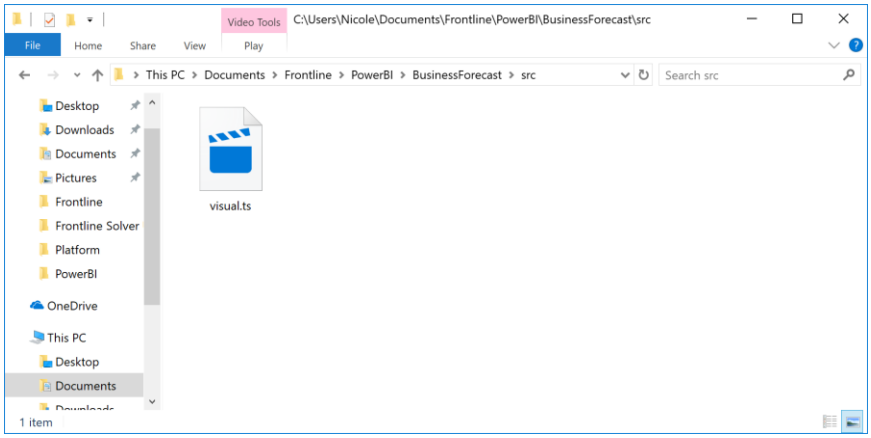
In the screenshots below, new folders, BusinessForecast in Analytic Solver Deeskop and ProductMix1 in Analytic Solver Cloud, will be created at the same time as the BusinessForecast.pbiviz and ProductMix1.pbiviz files.

Analytic Solver Desktop

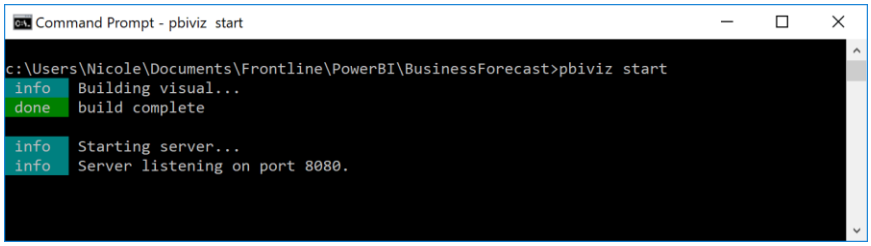




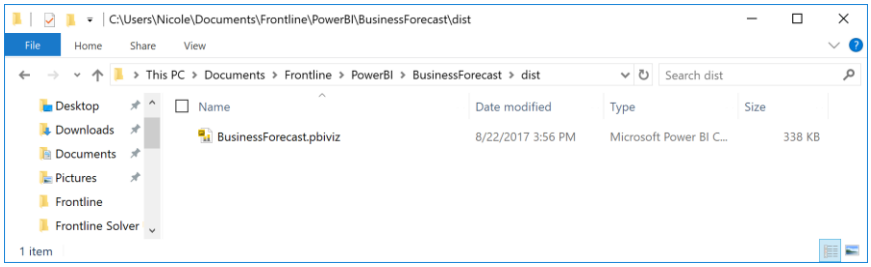
You will find the type script file, visual.ts within the src folder. Users can manipulate this file to customize the look and feel of the custom visual, such as the face of the custom visual icon (within Visualizations), alter the RASON model, etc. For more information on customizing the visual.ts file, see the webpage: https://powerbi.microsoft.com/en-us/documentation/



Note: If the visual.ts file is altered, a new pbiviz package must be created. To do so, open a command prompt, change the directory to the root directory of the custom visual, and enter "pbiviz package", as shown in the screenshot below.



The new custom visual file (.pbiviz) will be saved to the Dist folder.



Error Messages

If you've made an error in your PsiDataSrc() function or in your data file, your custom visual will display an error such as "Inconsistent Data source definition PSI could not parse Excel formulas" or "Invalid binding source definition PSI could not parse Excel formulas".

If your custom visual is displaying either of these errors or a different error, first, check the PsiDataSrc() function in your Excel model to make sure that you have not mixed up the order of your index sets. In addition, check your data to make sure that it is 1. Contained within an Excel table, 2. That the column headings match the index sets defined in PsiDataSrc() and 3. That your model parameters match the elements in your data table.

For more information on an error message displayed in your custom visual, contact Frontline Systems Support Team by emailing support@solver.com or by calling 888-831-0333.

Creating Custom Extensions in Tableau

Introduction

Starting with V2018, Analytic Solver includes the ability to turn your Excel-based optimization or simulation model into a **Tableau Dashboard Extension**, with just a few mouse clicks! This is quite similar to the ability to create Power BI Custom Visuals as discussed in the previous chapter. *This feature is only compatible with versions of Tableau version 2018.2 or later.*

To start, simply select rows or columns of data to serve as changeable parameters, then choose **Create App – Tableau**, and save the file created byAnalytic Solver. In Tableau, you'll see the newly-created file under **Extensions** on the left side of the dashboard, where you can drag it onto your dashboard. You'll be prompted to match the parameters your model needs with data in Tableau. What you get isn't just a chart – it's your *full optimization or simulation model*, ready to accept Tableau data**, run on demand** (using our **RASON** server), and display visual results in Tableau!

Installing Tableau

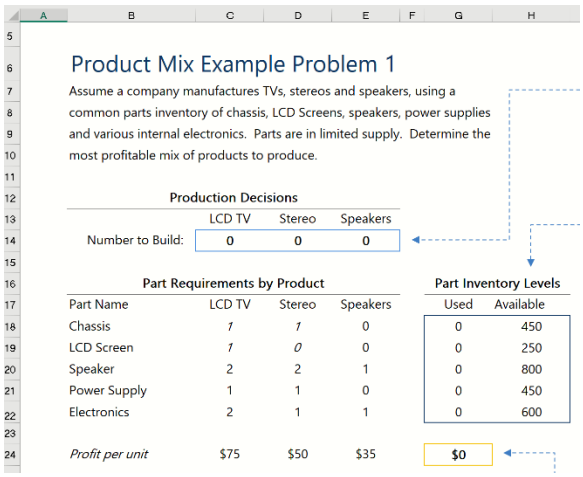
Tableau is an industry leading desktop or cloud-based interactive business intelligence tool that centers on data visualization, dashboarding and data discovery. In past versions of Analytic Solver, users have only been able to upload their model parameters (or their model data) to Tableau after solving an optimization or simulation model. However, starting with V2018, Analytic Solver now includes the ability to turn your Excel based optimization or simulation model into a Tableau Extension, that is your full optimization or simulation model, ready to accept Tableau data, run on demand on the web (using our RASON server) and display visual results in Tableau.

In order to use this new feature in Analytic Solver, you must first install Tableau V2018.2 or later or open the free cloud based version of Tableau. For more information on this business intelligence tool, see the following website: https://www.tableau.com/

Solving Optimization Models in Tableau

In this section, we will create a custom Tableau Extension using the Product Mix example model.

Open the Product Mix.xlsx model, previously discussed in the Conventional Optimization and Power BI chapters, by clicking Help – Examples on the ribbon, clicking Optimization Examples and then the Product Mix link. Recall that this example model determines the optimal mix of products that a company should produce in order to maximize profits.



Product Mix Example Problem 1

Assume a company manufactures TVs, stereos and speakers, using a common parts inventory of chassis, LCD Screens, speakers, power supplies and various internal electronics. Parts are in limited supply. Determine the most profitable mix of products to produce.

Production Decisions

	LCD TV	Stereo	Speakers
Number to Build:	0	0	0

Part Requirements by Product

Part Name	LCD TV	Stereo	Speakers
Chassis	1	1	0
LCD Screen	1	0	0
Speaker	2	2	1
Power Supply	1	1	0
Electronics	2	1	1
Profit per unit	$75	$50	$35

Part Inventory Levels

Used	Available
0	450
0	250
0	800
0	450
0	600
$0	

The optimization model is included in the Model tab in the Solver Task Pane. This model written in algebraic form is below.

Maximize: Total Profit = $75x1 + $50x2 + $35x3

Subject To:

Chassis: 1x1 + 1x2 + 0x3 <= 450

LCD Screen: 1x1 + 0x2 + 0x3 <= 250

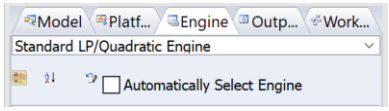
Speaker: 2x1 + 2x2 + 1x3 <= 800

Power Supply: 1x1 + 1x2 + 0x3 <= 450

Electronics: 2x2 + 1x2 + 1x3 <= 600

x1, x2, x3 > 0

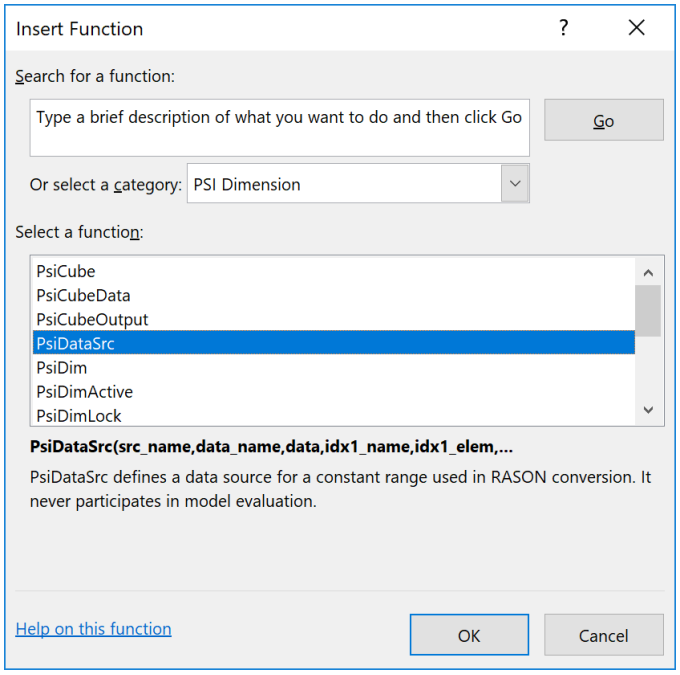
The engine selected to solve this model is the Standard LP/Quadratic Engine as shown on the Engine tab in the Solver Task Pane. This is the engine that will be used to solve the model within Tableau.



In past versions of Analytic Solver, you only had the option of uploading your final solution values (final variable, constraint and objective values) to Tableau. As a result, any time there was a change to the model, the model had to be solved in Excel first and then the data could be (again) uploaded to Tableau. All of this changed with V2018. Now you can change your model parameters and resolve your model *within* Tableau - without ever having to go back to Excel!

To start, we will use the PsiDataSrc() function to "flag" or specify the parameters in the Excel model that might possibly change in the future; for example, in the product mix model, the amount of inventory on hand for each part, the profit point for each product or the number of parts that makeup each product.

Select a blank cell on the Product Mix Example 1 tab, say J6. Click Formulas – Insert Function to open the Insert Function dialog, then select Psi Dimension for Category. Afterwards, highlight the function PsiDataSrc, and click OK.



The Function Arguments dialog opens displaying 5 arguments: Src_name, Data_name, Data, Idx1_name, and Idx1_elem. We will use this dialog to create a PsiDataSrc() in cell J6 that will allow us the ability to change the inventory values and resolve the Product Mix example model not in Excel, but within Tableau.

PsiDataSrc() Arguments

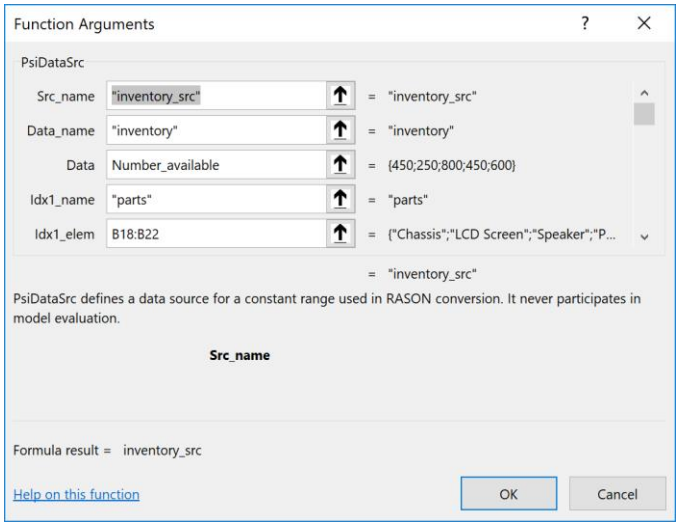
Src_name – This argument names the text file, created by the Extension, which is submitted, along with the RASON model, to the RASON server. For this example, type: inventory_src.

Data_name – The available data in Tableau must be mapped to the data source we create in the Excel workbook. This field provides the name of the data repository that will appear in Tableau. For this example, type: inventory. *Note: Names passed to Data_name are case sensitive.*

Data – Enter the Excel range where the data is located on the spreadsheet for this argument. For this example, use your mouse to click the upward pointing arrow to the right of the Data argument and select cells H18:H22. You can also simply type this range into the edit box. Notice that if you select cells H18:H22 in the spreadsheet when entering the range into the Data argument, the selection automatically changes to "Number_available" in the Function Arguments dialog. This is because cells H18:H22 have been assigned to the Excel defined name, Number_available.

Idx1_name – Enter the name of the (1st) index set for the data specified in the Data argument. In this example, our Index set is simply the inventory available for each Part. Therefore, enter "parts" for this argument. *Note: Index set names are case sensitive.*

Idx1_elem – Enter the Excel range containing the data (or elements) for the first index set. For this example, either type or select cells: B18:B22



Since this index set is 1-dimensional, nothing further is needed and we can click OK to enter the PsiDataSrc() function into cell J6.

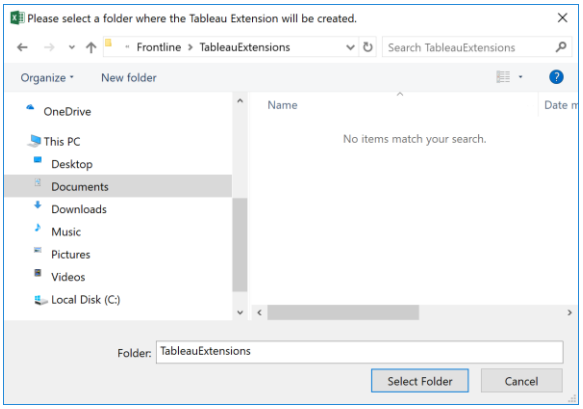
In Analytic Solver Cloud or AnalyticSolver.com, you can type the formula directly into cell J226.

```
=PsiDataSrc("inventory_src", "inventory",
Number_available, "parts", B18:B22)
```

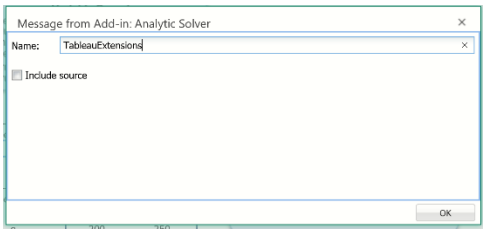
Afterwards, cell J26 will display the value given to the Src_name argument, inventory_src. Save the Excel model and then click Create App – Tableau to save a new Tableau Extension file.

- In Analytic Solver Desktop, immediately, the Save As dialog appears. Select a folder to save the tableau extension files to, and then click Save. For example, the screenshot below displays a folder name of "TableauExtensions".

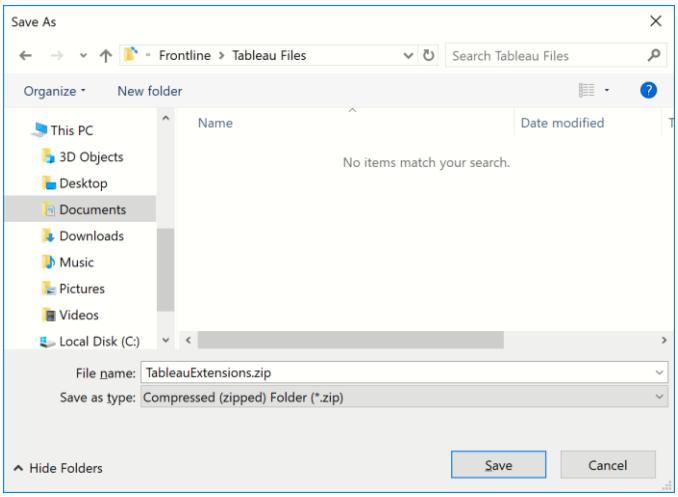
  Analytic Solver Desktop



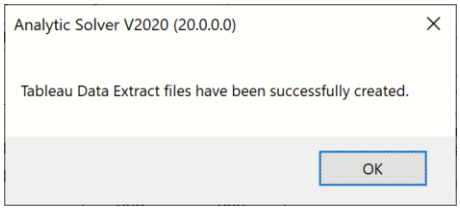
- In Analytic Solver Cloud, first, you will receive the following dialog. Type the filename of the folder, for example, TableauExtensions.



After the file is downloading, you'll be asked if you'd like to open or save the file, choose Save As, then save the file in the desired location.



Click Select Folder or Save. At this point your Excel model is translated into the **RASON**® modeling language, and your Tableau extension is created. After a moment, the following message appears.



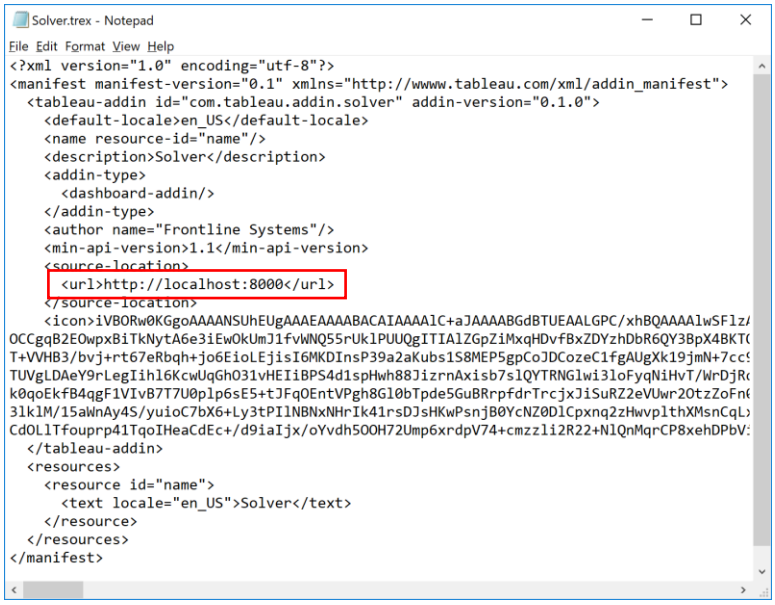
NOTE 1: There is no need to solve the model first unless a change has been made to an already existing RASON model. If a change has been made to the workbook after a RASON model has been created, or since Create App – RASON IDE/RASON.com/Web Page/Power Bi/Tableau has been selected, then you MUST either solve or diagnose the Excel model in order for the changes to be reflected in the new RASON model.

NOTE 2: When creating a RASON model through desktop Analytic Solver or AnalyticSolver.com, model elements (objective function and all variables and constraints) may now exist on multiple worksheets within the same Excel workbook.

Viewing the Tableau Extension File

Open File Explorer and browse to the folder where you saved the Tableau extension. Within in that folder will be an Extensions folder. Click that folder and open the Solver.trex file using Notepad.

This file contains information such as the extensions name (or how it will appear in Tableau) and the url where the extension is hosted. To publish the html file to a website, simply replace http://localhost:8000 with the desired url.



Starting up the Server

Since Tableau extensions are simply web pages, we will first need to start up a web server to serve our content. For this example, we will serve up the webpage to the default location. To do so, open a command prompt, navigate to the root of the extensions repository and run "http-server -p 8000".

This command starts up a simple http server listening on port 8000.

Creating a Data File

In order to provide the data for the Product Mix example file to Tableau, we must create a data file. Within this file, we will pass the inventory levels by part. This data file can be of any format supported by Tableau such as a CSV file, a text file, a database, etc. In this example, we will use an Excel workbook to hold the data. For more information on the types of files supported by Tableau, please see the Tableau documentation at:
http://onlinehelp.tableau.com/current/pro/desktop/en-us/default.html

Open a blank worksheet and create a table with two columns. List the parts by name in the first column using the column heading "parts" and the inventory levels in the second column using the column heading "inventory", as shown in the screenshot below.

	A	B
1	parts	inventory
2	Chassis	450
3	LCD Screen	250
4	Speaker	800
5	Power Supply	450
6	Electronics	600

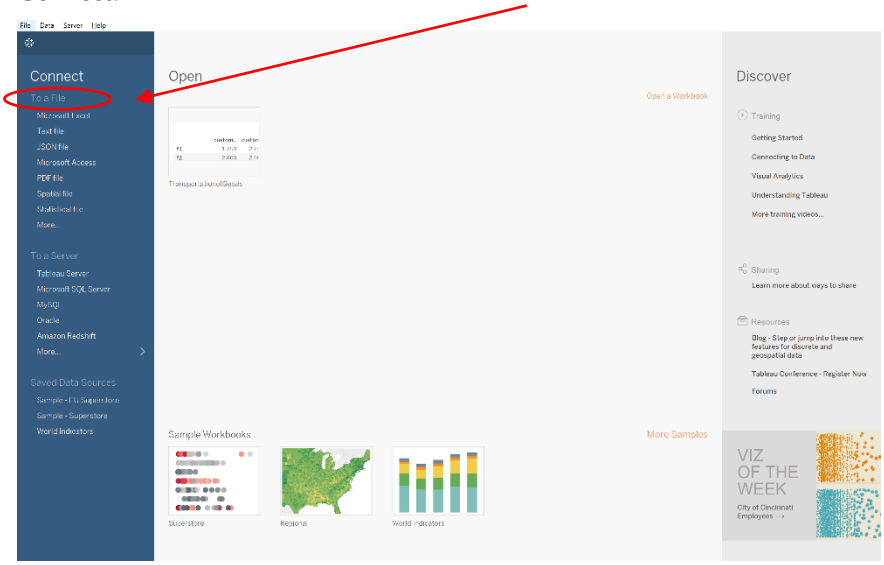
*Note: Column headings **must be identical** to the names of the Index Sets passed to the PsiDataSrc() function. Make sure there are no spaces before or after column headings or row elements.*

```
=PsiDataSrc("inventory_src","inventory",Number_available,"parts",B18:B22)
```

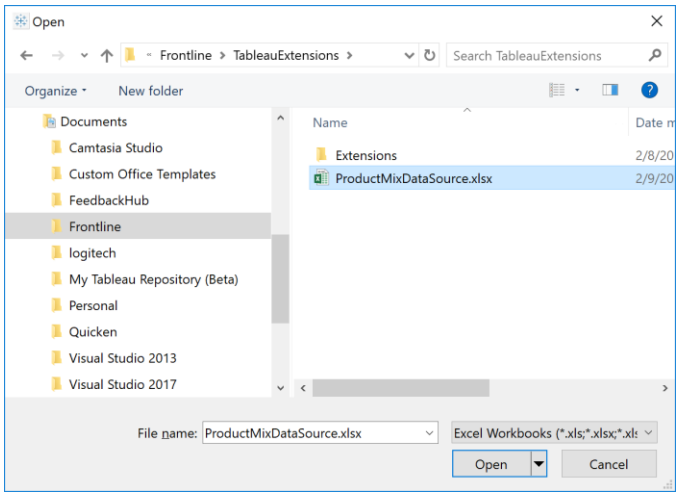
Recall that we labeled the IndexSet as "parts" (4th argument of PsiDataSrc) and Data_name as "inventory" (2nd argument of PsiDataSrc) so the title for column A must be "parts" and the title for column B must be "inventory". Now save the workbook to a desired location.

Opening Extension within Tableau

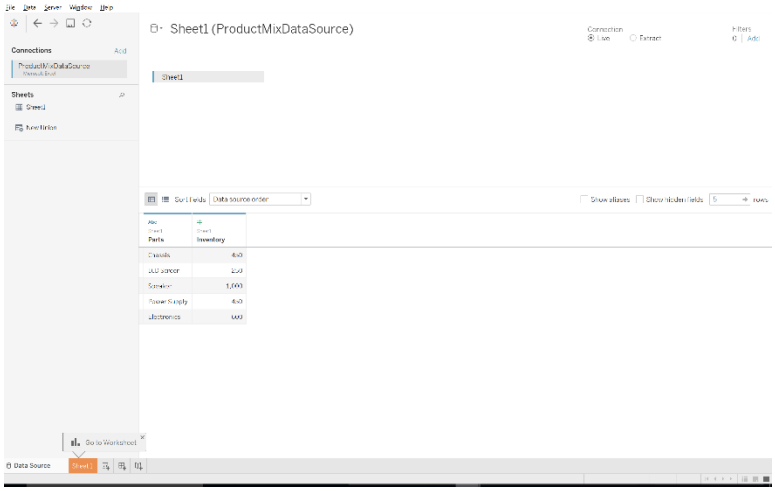
Open either desktop, server or cloud-based Tableau. The screenshot below depicts the opening screen of desktop Tableau. Click *Microsoft Excel* under **Connect**.



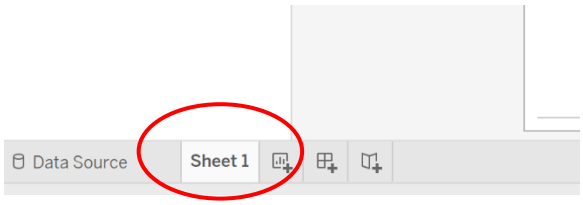
An Open dialog opens.



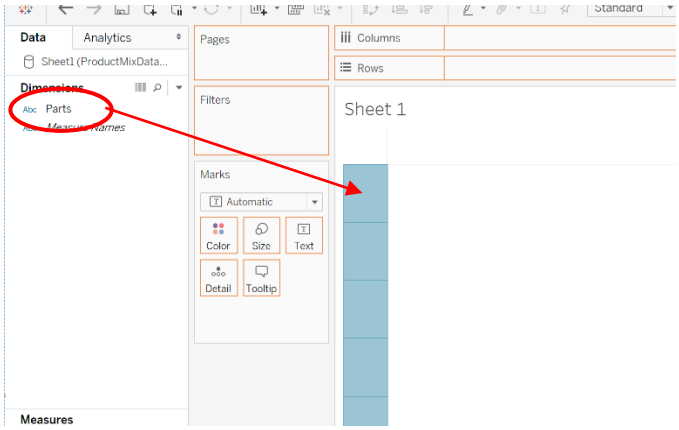
Browse to the location of your data file and click Open.



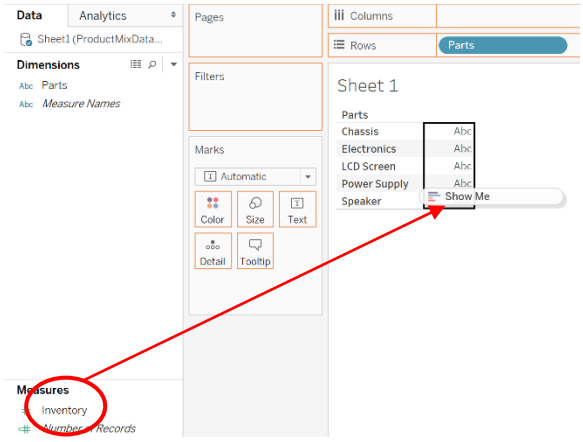
A new worksheet, Sheet 1, is automatically created. Click on the Sheet 1 tab.



On Sheet 1, drag Parts (under Dimensions) to Sheet 1 rows…



… and then drag Inventory (under Measures) to



Hover over SUM(Inventory), click the down arrow that appears to the right, then select Dimensions from the menu.

Note that the information in ProductMixDataSource matches the data in Sheet 1.

ProductMixDataSource.xlsx

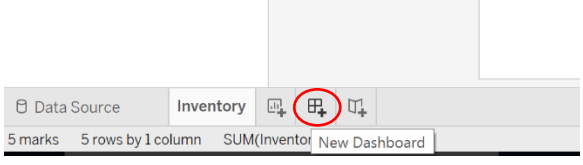
	A	B
1	Parts	Inventory
2	Chassis	450
3	LCD Screen	250
4	Speaker	800
5	Power Supply	450
6	Electronics	600

Tableau Sheet 1

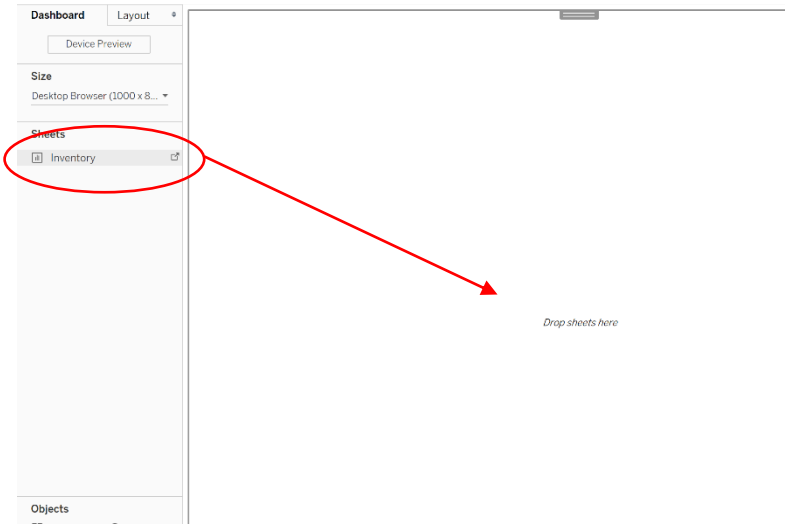
Sheet 1

Parts	
Chassis	450
Electronics	600
LCD Screen	250
Power Supply	450
Speaker	800

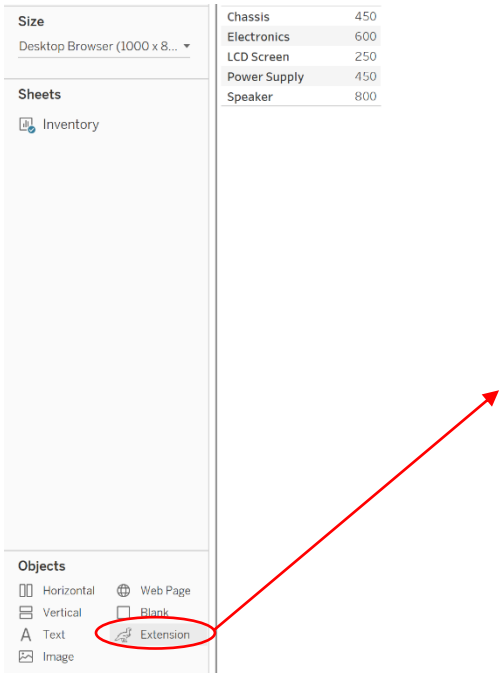
Right click the Sheet 1 tab and rename the worksheet to "Inventory", then click the New Dashboard icon at the bottom of Tableau to open a new dashboard.



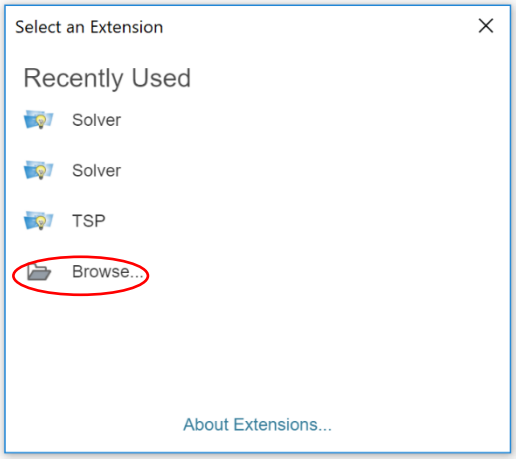
First, drag the Inventory worksheet onto the dashboard canvas.



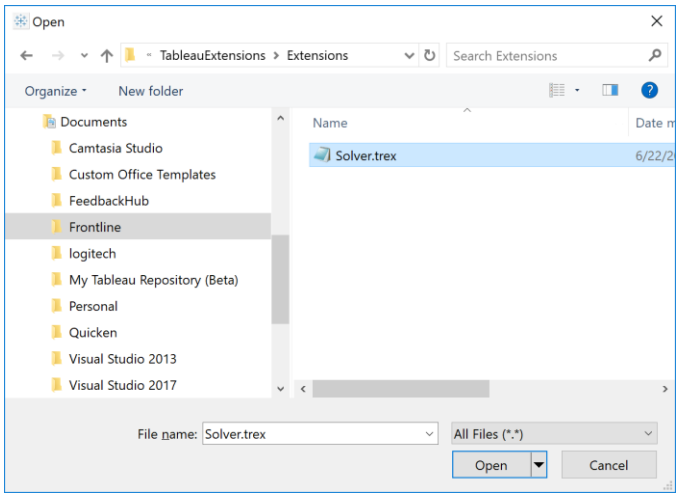
Then drag the Extension icon, under Objects, onto the canvas.



On the *Select an Extension* dialog, click Browse…

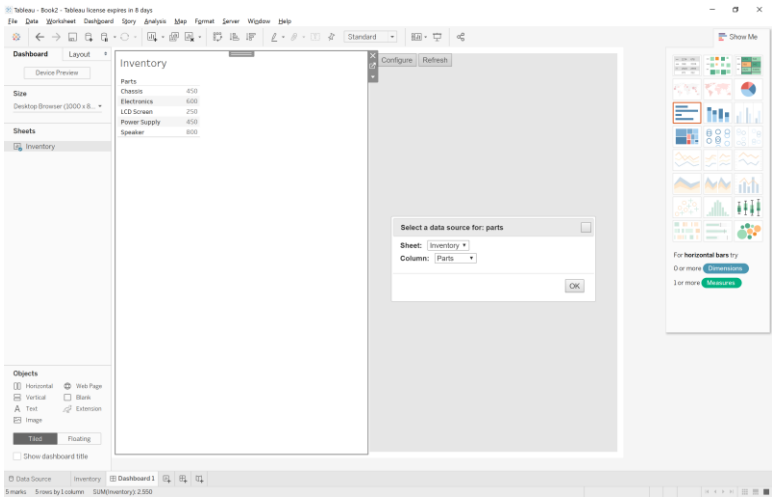


… and browse to the location of the Tableau Extension file (Solver.trex). In this example, the file was saved to the TableauExtensions folder. Within this folder, select All Files, then double click the Extensions folder and select the Solver.trex file.

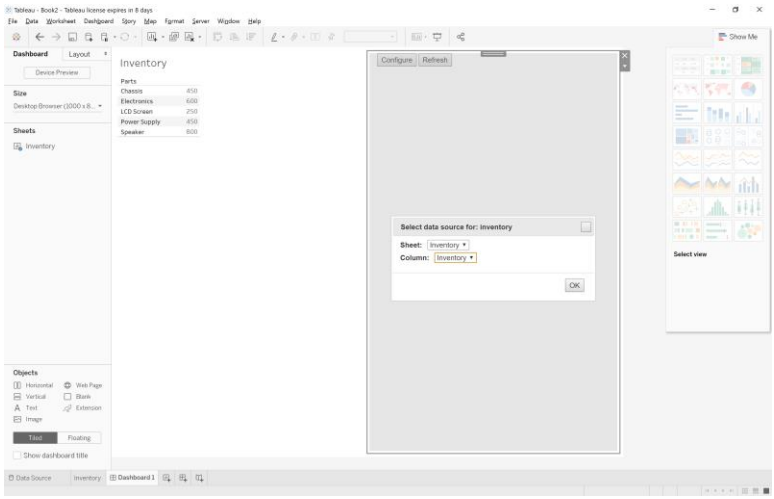


Click Open to open the Tableau extension. A dialog opens asking to select a data source for "parts". Confirm that "Inventory" is selected for "Sheet" and "Parts" is selected for "Column". Note that these are the same names passed to the PsiDataSrc() function in the Excel Product Mix.xlsx workbook.

```
=PsiDataSrc("inventory_src","inventory",Number_available,"parts",B18:B22)
```

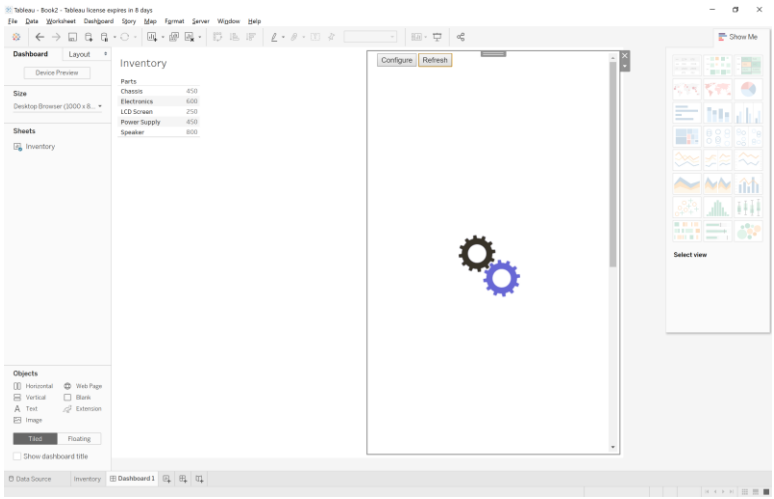


Click OK.

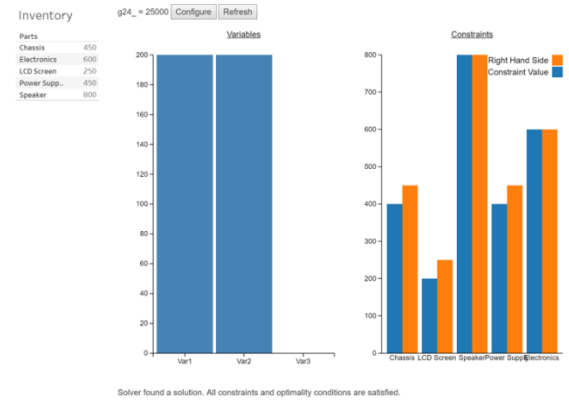


On the *Select data source for: inventory* dialog, select "Inventory" for "Sheet" and "Inventory" for "Column". Then click OK.

Immediately, two gears appear and start to turn while the model is sent to the RASON server, solved with the LP/Quadratic engine, and the final values are returned. Your screen should appear similar to the screenshot below.



Once the RASON server has imported the final solution values into Tableau, Solver's result message, "Solver found a solution. All constraints and optimality conditions are satisfied", is displayed at the bottom of the Extension window. In the Variables chart, we see that the final variable values are: Var1 (LCD TV) equal to 200, Var2 (Stereo) equal to 200 and Var3 (Speakers) equal to 0. These variable values result in an objective function value equal to $25,000. In the chart to the right, we see the final constraint values are: Con1 (number of Chassis used) = 400, Con2 (number of LCD Screens used) = 200, Con3 (number of Speakers used) = 800, Con4 (number of Power Supplies used) = 400, and Con5 (number of Electronics used) = 600.



Now let's go back to the Excel Model and see what happens when we change a few parameters such as increasing the inventory of speakers from 800 to 1,000, adding 2 more speakers to a Stereo during manufacturing and increasing the Stereo's selling price to $100.

First, we will use a 2nd PsiDataSrc() function to denote that new data (an increased selling price for Stereos) will be available in Tableau. Click back to the ProductMix(Opt) example model, select cell J27 and then click Formulas – Insert Function, select Psi Dimension for Category, select PsiDataSrc, then click OK.

Enter the following for the arguments appearing on the Function Arguments dialog.

Src_name – Enter "profit_src" to name the text file, created by the custom visual, which will be submitted, along with the RASON model, to the RASON server.

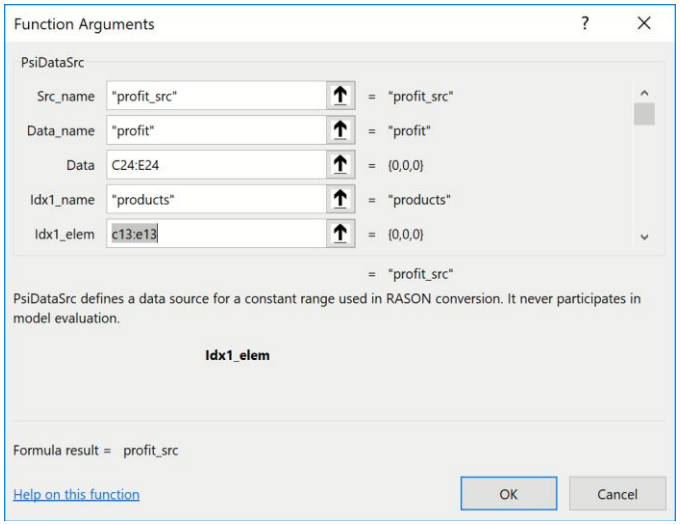
Data_name – Enter "Profit" for the data repository name. *Note: Names passed to Data_name are case sensitive.*

Data – Enter the Excel range, C24:E24.

Idx1_name – Enter "Products" which is the name of the 1st index set for the data specified in the Data argument. In this example, our Index set is simply the selling price for each product. *Note: Index set names are case sensitive.*

Idx1_elem – Enter the Excel range containing the data for the first index set, C13:E13.

Since this index set is 1-dimensional, nothing further is needed and we can click OK to enter the PsiDataSrc() function into cell J7. Afterwards, cell J7 will display the value given to the Src_name argument, profit_src.



In Analytic Solver Cloud or AnalyticSolver.com, you can type the formula directly into cell J27.

```
=PsiDataSrc("profit_src", "profit", C24:E24,
"products", C13:E13)
```

Finally, we will use a 3rd PsiDataSrc() function to denote that new data (an increase in the number of speakers to be included in the building of a stereo) will be available in Tableau. This time, we will simply enter the formula directly into cell J28.

First type "=PsiDataSrc(", then enter the arguments below.

Src_name – Enter "reqparts_src" to name the text file which will be submitted, along with the RASON model, to the RASON server.

Data_name – Enter "requiredparts" for the data repository name. *Note: Names passed here are case sensitive.*

Data – Enter the Excel range, C18:E22.

Idx1_name – Enter "parts" which is the name of the 1st index set for the data specified in the Data argument. In this example, there are two index sets. When data is 2-dimensional, we must enter the index set that describes the rows first. *Note: Index set names are case sensitive.*

Idx1_elem – Enter the Excel range containing the data for the first index set, B18:B22.

Idx2_name – Enter "products" which is the name of the 2nd index set for the data specified in the Data argument.

Idx2_elem – Enter the Excel range containing the data for the second index set, C13:E13. *Note: Index set names are case sensitive.*

Now we can type ")" to close the function, then press Enter to enter the PsiDataSrc() function into cell J28. Afterwards, cell J228 will display the value given to the Src_name argument, reqparts_src.

Your PsiDataSrc function should be similar to the screenshot below.

```
=PsiDataSrc("reqparts_src", "requiredparts", C18:E22, "parts", B18:B22, "products", C13:E13)
```

At this point, cell J26 displays "inventory_src", cell J27 displays "profit_src" and cell J28 displays "reqparts_src". Save the Excel model and then click Create App – Tableau to save a new file Tableau extension file, Solver.trex.

Now we are ready to add a new data table to the ProductMixDataSource.xlsx file.

Open the ProductMixDataSource.xlsx workbook.

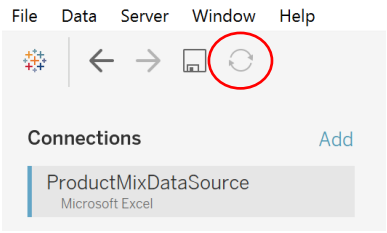
Important Note: In Tableau, unlike when creating a Power BI custom visual, it is not necessary that all data be contained within the same Excel table or from within multiple tables with the same number of rows and columns. However, for ease of use, this example includes all data within the same Excel table.

In a new Excel sheet, create a table (Insert – Table) with 16 rows and 5 columns, then list the products in the first column using the column heading "products", the parts by name using the column heading "parts" in the 2nd column, the parts required per product (requiredparts) in the 3rd column, the selling price or "Profit" per product in the 4th column, and the part inventory for each product in the last column. Make sure to pass the new selling price for Stereos ($100) and the increased number of speakers per stereo (4).

	A	B	C	D	E
1	products	parts	requiredparts	profit	inventory
2	LCD TV	Chassis	1	75	450
3	LCD TV	LCD Screen	1	75	250
4	LCD TV	Speaker	2	75	1,000
5	LCD TV	Power Supply	1	75	450
6	LCD TV	Electronics	2	75	600
7	Stereo	Chassis	1	100	450
8	Stereo	LCD Screen	0	100	250
9	Stereo	Speaker	4	100	1,000
10	Stereo	Power Supply	1	100	450
11	Stereo	Electronics	1	100	600
12	Speakers	Chassis	0	35	450
13	Speakers	LCD Screen	0	35	250
14	Speakers	Speaker	1	35	1,000
15	Speakers	Power Supply	0	35	450
16	Speakers	Electronics	1	35	600

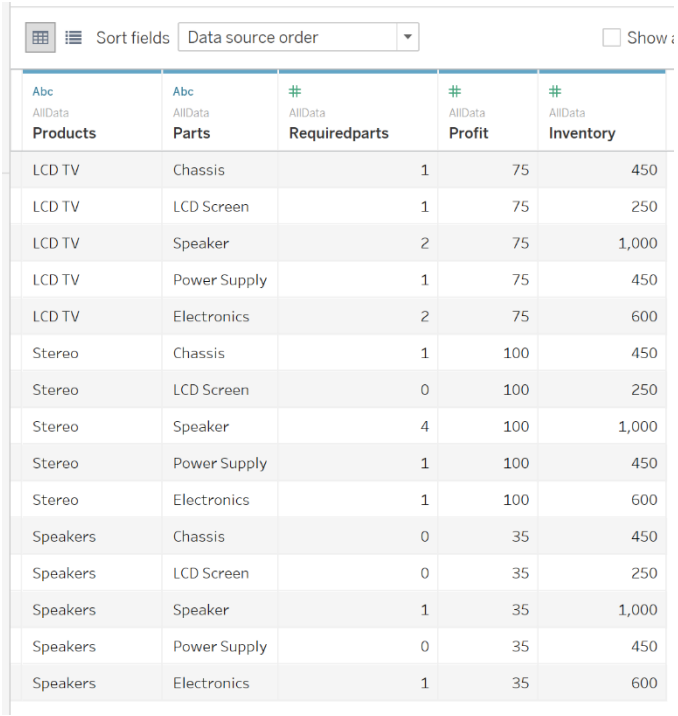
Notice that in order to list all of the required parts for each product, we must list each part and selling price for each part. In addition, each column heading matches the index sets used in the PsiDataSrc() functions. Rename the worksheet "AllData" then save the workbook. *If there are any leading or trailing spaces for the column headings or elements, Tableau will stop with an error.*

Click back to Tableau and click Refresh in the top left hand corner.



You will notice that the "AllData" sheet is added beneath Sheets. Drag this sheet to the window.

Tableau displays information from the Excel table at the bottom of the window.

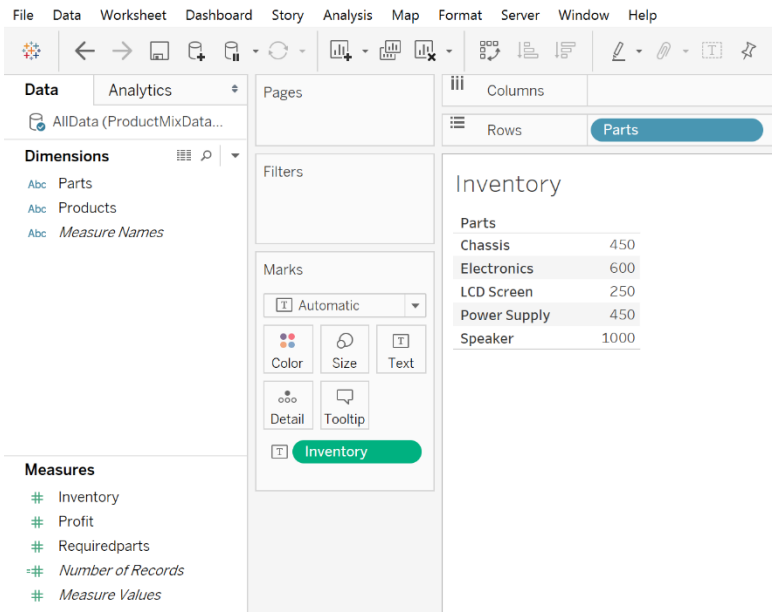


Products	Parts	Requiredparts	Profit	Inventory
LCD TV	Chassis	1	75	450
LCD TV	LCD Screen	1	75	250
LCD TV	Speaker	2	75	1,000
LCD TV	Power Supply	1	75	450
LCD TV	Electronics	2	75	600
Stereo	Chassis	1	100	450
Stereo	LCD Screen	0	100	250
Stereo	Speaker	4	100	1,000
Stereo	Power Supply	1	100	450
Stereo	Electronics	1	100	600
Speakers	Chassis	0	35	450
Speakers	LCD Screen	0	35	250
Speakers	Speaker	1	35	1,000
Speakers	Power Supply	0	35	450
Speakers	Electronics	1	35	600

Right click the Inventory sheet and again drag "Parts", under Dimensions, to Rows and "Inventory", under Measures, to the right of the rows.

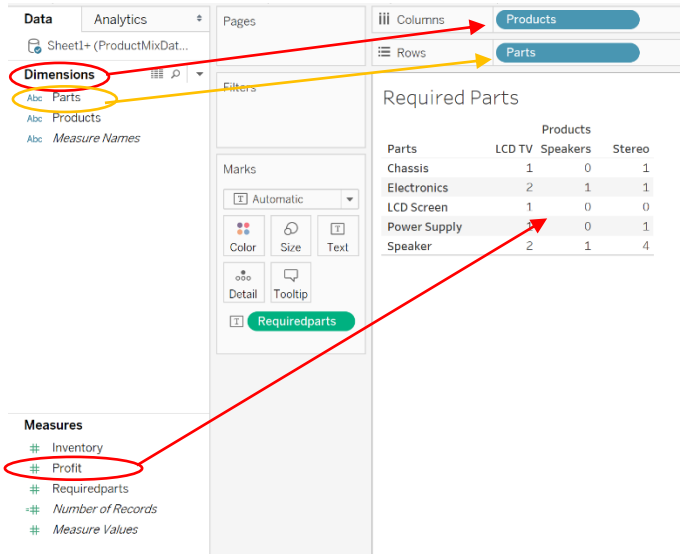
Hover over

, click the down arrow that appears to the right, and select Dimensions from the menu.



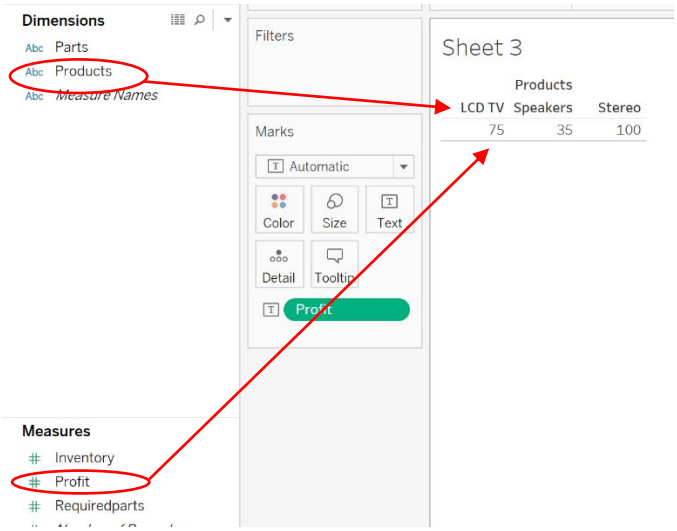
Add a new worksheet and drag "Parts", under Dimensions, to Rows and "Products", under Dimensions, to "Columns". Then drag "RequiredParts", under Measures, to the field elements.

Hover over SUM(Required..), click the down arrow that appears to the right, and select Dimensions from the menu.



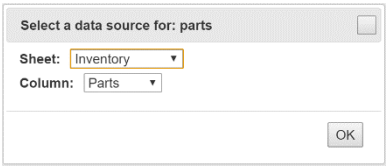
Name the sheet "Required Parts" and then add a third sheet. In Sheet 3, drag "Products", under Dimensions, to "Columns" and drag "Profit", under Measures, to the column elements.

Hover over SUM(Profit), click the down arrow that appears on the right then select Dimensions from the menu.



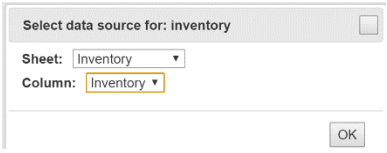
Rename the sheet from Sheet 3 to Profit and then create a new dashboard. Drag all three sheets, Inventory, Required Parts and Profit, to the canvas and then drag a new Extension to the canvas. Open the Solver.trex file in …\TableauExtensions\Extensions.

At this point we will connect the dimensions created by the PsiDataSrc() function in Excel with the actual data in Tableau. A dialog appears asking to "Select a datasource for: parts". Select "Inventory" for Sheet and "Parts" for Column to match the "parts" dimension in the Excel sheet to the "Parts" dimension in the Tableau Inventory sheet.



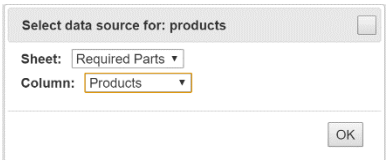
Click OK.

On the "Select data source for: inventory" dialog, select "Inventory" for Sheet and "Inventory" for Column to match the "inventory" dimension in the Excel sheet to the "Inventory" dimension in the Tableau Inventory sheet.



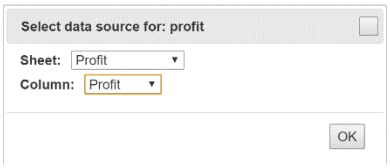
Click OK.

On the "Select data source for: products" dialog, select "Required Parts" for Sheet and "Products" for Column to match the "products" dimension in the Excel sheet to the "Products" dimension in the Tableau Required Parts sheet.



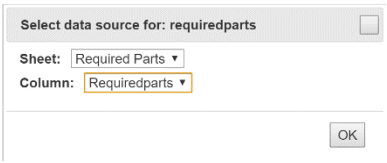
Click OK.

On the “Select data source for: profit” dialog, select “Profit” for Sheet and “Profit” for Column to match the “profit” dimension in the Excel sheet to the “Profit” dimension in the Tableau Profit sheet.



Click OK.

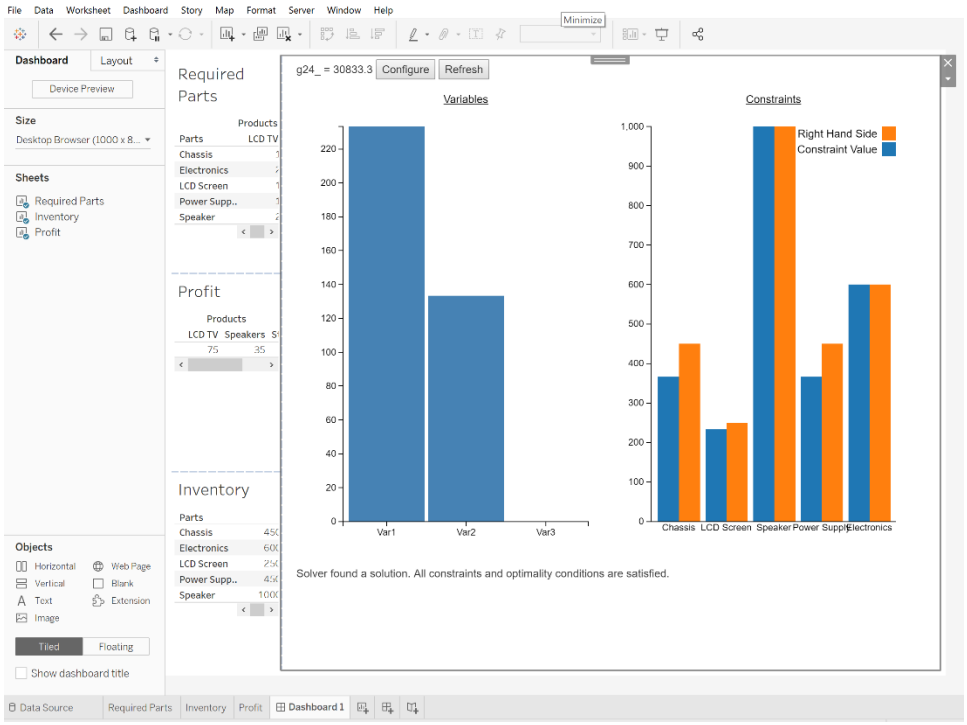
On the “Select data source for: requiredparts” dialog, select “Required Parts” for Sheet and “RequiredParts” for Column to match the “requiredparts” dimension in the Excel sheet to the “RequiredParts” dimension in the Tableau Required Parts sheet.



Click OK.

Immediately, the RASON model is submitted to the RASON Server, the model is solved with the LP/Quadratic engine and the final variable values are imported back into Tableau.

At the bottom of the extension, we find Solver’s result message: Solver found a solution. All constraints and optimality conditions are satisfied. In the Variables chart, we see that the final variable values are: Var1 (LCD TV) equal to 233, Var2 (Stereo) equal to 133 and Var3 (Speakers) equal to 0. These variable values result in an objective function value equal to 30,833. In the chart to the right, we see the final constraint values are: Con1 (number of Chassis used) = 367, Con2 (number of LCD Screens used) = 233, Con3 (number of Speakers used) = 1,000, Con4 (number of Power Supplies used) = 367, and Con5 (number of Electronics used) = 600. Notice that with the addition of 2 more speakers required to manufacturing Speakers, the increased unit profit of Stereos to $100 and the added Speaker inventory, our profit has increased by $5,833.



Troop Rotation Optimization Example

In this example, we will create a Tableau Extension using a slightly more complex example. In this section, we will create an Extension using the Troop Rotation example model by clicking Help – Examples on the Analytic Solver ribbon, then clicking Optimization Models and scrolling down to Troop Rotation. Click the hyperlink to open the example model. This example model determines how army troops should be moved to minimize costs.

Moving Cost per Soldier

	Base 1	Base 2	Base 3	Base 4
Camp 1	34	26	29	31
Camp 2	42	33	28	35
Camp 3	36	29	32	38

Number of Troops Moved

	Base 1	Base 2	Base 3	Base 4	Total	Available
Camp 1	0	0	0	0	0	500
Camp 2	0	0	0	0	0	400
Camp 3	0	0	0	0	0	400
Total	0	0	0	0		
Required	200	250	350	300		
Cost	$0	$0	$0	$0	$0	

The optimization model is included in the Model tab in the Solver Task Pane. This model written in algebraic form is below.

Minimize: Total Cost = 34 * x1 + 42 * x5 + 36 * x9 + 26 * x2 + 33 * x6 + 29 * x10 + 29 * x3 + 28 * x7 + 32 * x11 + 31 * x4 + 35 * x8 + 38 * x12

Subject To:

Number of troops from Camps 1, 2 and 3 moved to Bases 1, 2, 3 and 4 must not exceed the number of troops available

Camp1: x1 + x2 + x3 + x4 <= 500

Camp2: x5 + x6 + x7 + x8 <= 400

Camp3: x9 + x10 + x11 + x12 <= 400

Number of troops assigned per base must not be less than the amount required.

Base 1: x1 + x5 + x9 >= 200

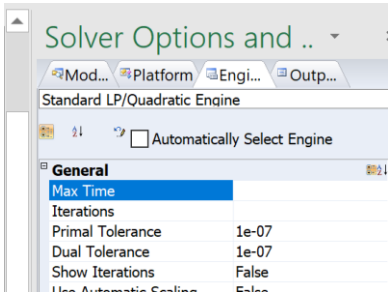
Base 2: x2 + x6 + x10 >= 250

Base 3: x3 + x7 + x11 >= 350

Base 4: x4 + x8 + x12 >= 300

x1, x2, x3, x4, x5, x6, x7, x8, x9, x10, x11, x12 > 0

The engine selected to solve this model is the Standard LP/Quadratic Engine as shown on the Engine tab in the Solver Task Pane. This is the engine that will be used to solve the model within Tableau.



Next, we will enter three PsiDataSrc() functions into cells P27, P28, and P29.

In cell P27, we will expose the moving costs per soldier according to the base and camp dimensions in cells C12:F112. To open the Function Arguments dialog, click Formulas – Insert Function, select Psi Dimension for Category, select PsiDataSrc, then click OK.

Src_name = Enter "cost_src" for this argument. This names the text file that will be submitted to the RASON server, along with the RASON model.

Data_name – Enter "cost" for this argument. This will be the name of the data repository associated with the data passed in the next argument.

Data – Enter C13:F15 which is the actual cells containing the moving price per soldier.

Idx1_name – Enter "camps" which is the name of the 1st index set, the row-wise index set. Remember, you must pass the row-wise index set before the column-wise index set.

Idx1_elem – Enter the elements of the "camps" index set. These appear in cells B13:B15.

Idx2_name – Enter "bases" which is the name of the 2nd index set, the column wise index set.

Idx2_elem – Enter the elements of the "bases" index set. These appear in cells C12:F12.

The Function Arguments dialog should now appear as shown in the screenshots below.

Click OK to save this function to cell P27.

In Analytic Solver Cloud or AnalyticSolver.com, you can type the formula directly into cell J27.

```
=PsiDataSrc("cost_src", "cost", C13:F15, "camps",
B13:B15)
```

Click cell P28 and open the Function Arguments dialog to enter the next PsiDataSrc() function.

Let's enter the last two PsiDataSrc() functions by typing the formulas directly into the Excel cells, starting with the function in cell P28 that will expose the number of troops available for movement.

In cell P28, enter: "=PsiDataSrc("

First the first argument, Src_name, enter "available_src".

For the second argument, Data_name, enter: "availabletroops". The Data Well associated with this data will be given this name.

For the Data argument, the third argument, enter: "Troops_available". This is the defined name for cells H19:H21. Alternatively, we could have typed this Excel range.

Type "camps" for the 4th argument, Idx1_name, which is the name given to the row-wise index set.

Enter the range for this index set, B13:B15, for Idx1_elem.

Your PsiDataSrc() function should match the one in the screenshot shown below.

Click Enter to enter the PsiDataSrc() function into cell P28.

Finally, the last PsiDataSrc() function in cell P9 should be entered as:

=PsiDataSrc("required_src","requiredtroops",Troops_required,"bases",C12:F12)

Where:

Data_src = "required_src"

Data_name = "requiredtroops" This is the name that will appear for the data repository associated with this data in Tableau

Data = Troops_required This is the data associated with Data_name.

Idx1_name = “bases” This is the name of the index set that is associated with the data passed to the Data argument.

Idx1_elem – C12:F12 This is the Excel range where the elements for Idx1_name are located on the worksheet.

Now we are ready to create the Tableau Extension.

Click Create App on the ribbon, then select Tableau. Since this is the first time we are creating an Extension from this model, there is no need to solve the model first. If, however, we make a change to the Troop Rotation model, then we would need to either diagnose or solve the model first to ensure that the changes are captured in the new extension.

Save the Solver.trex file (the Tableau Extension file) in a location of your choice.

Next, we will create the data file. Open a new Excel workbook.

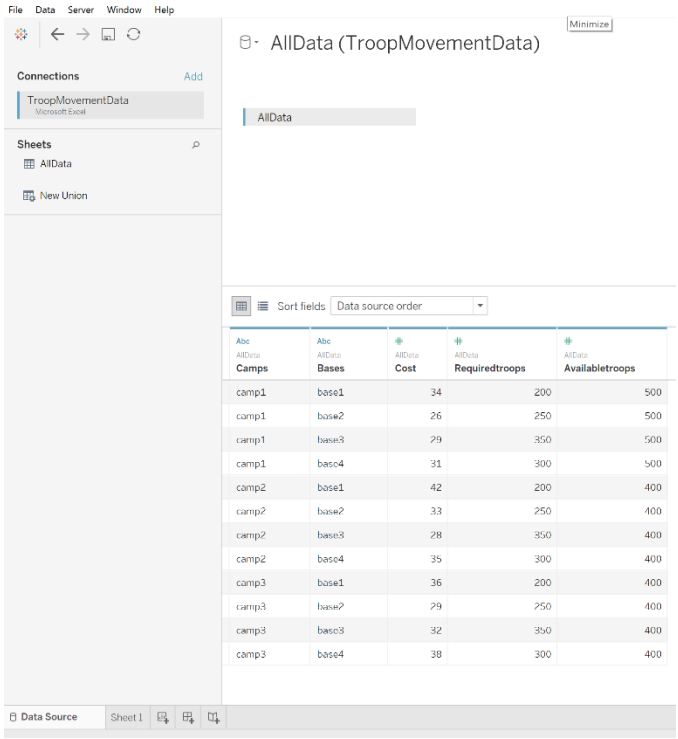
For convenience sake, in this example, we will pass all data in one Excel table.

In a new Excel workbook, create a table (Insert – Table) with 13 rows and 5 columns, as shown in the screenshot below. Notice that in order to enter all 12 costs, labels for camps, bases, required troops, and availabletroops were repeated.

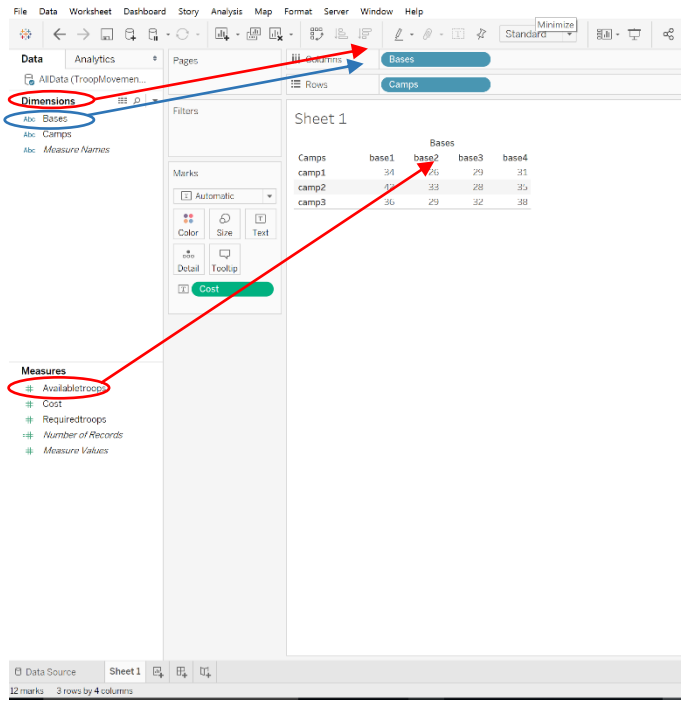
	A	B	C	D	E
1	camps	bases	cost	requiredtroops	availabletroops
2	camp1	base1	34	200	500
3	camp1	base2	26	250	500
4	camp1	base3	29	350	500
5	camp1	base4	31	300	500
6	camp2	base1	42	200	400
7	camp2	base2	33	250	400
8	camp2	base3	28	350	400
9	camp2	base4	35	300	400
10	camp3	base1	36	200	400
11	camp3	base2	29	250	400
12	camp3	base3	32	350	400
13	camp3	base4	38	300	400

Note that each column heading matches the index sets used in the PsiDataSrc() functions. Rename the worksheet “AllData” then save the workbook as TroopMovementData.xlsx.

Now let’s click back to the Data Source tab in Tableau, to import the new Extension and the data. First, just to keep our choices limited to the Troop Movement example, hover over ProductMixDataSource, click the down arrow that appears on the right and select remove. Right click the Extension tab and select Delete, then Delete all worksheets associated with the Product Mix extension. Then, on the Data Source tab, click Add – Microsoft Excel, browse to the location of TroopMovementData.xlsx and click Open.

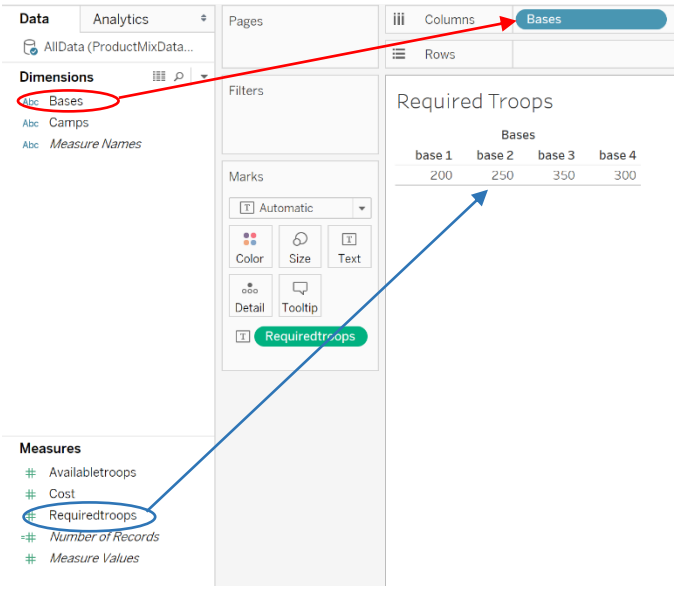


The AllData sheet appears under Sheets and the data from that sheet appears at the bottom of the Tableau window. Click Sheet 1. Under Dimensions, drag "Bases" to Columns and "Camps" to Rows. Under Measures, drag "Cost" to the table elements. Hover over SUM(Cost) (in the Marks section), click the down arrow that appears to the right, and select Dimension.



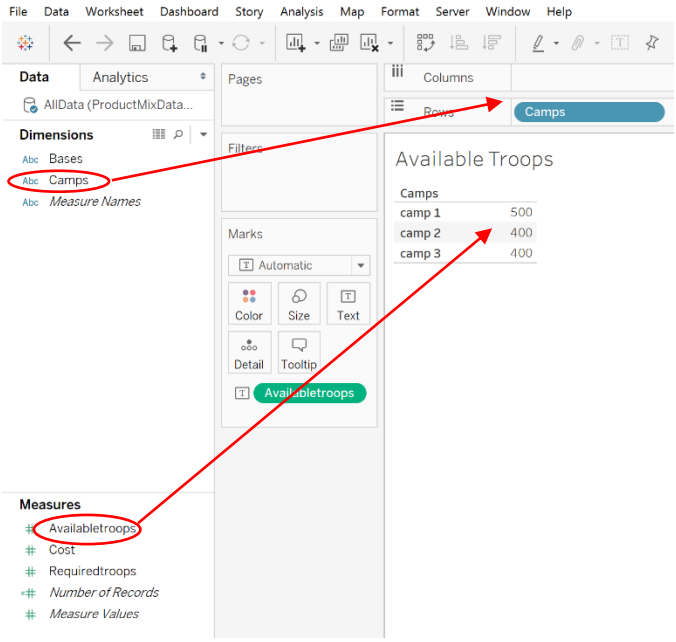
Rename the worksheet to Cost and then add a new Sheet.

On Sheet 2, drag “Bases”, under Dimensions, to Columns and “Requiredtroops”, under Measures, as the table elements. Hover over SUM(Required.., click the down arrow that appears to the right, then select Dimensions from the menu.



Raname the worksheet to Required Troops and then add a new Sheet.

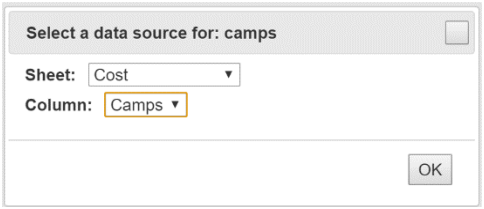
On Sheet 3, drag “Camps”, under Dimensions, to Rows and “Availabletroops”, under Measures, to the table elements. Hover over SUM(Available.., click the down arrow that appears to the right, then select Dimensions from the menu.

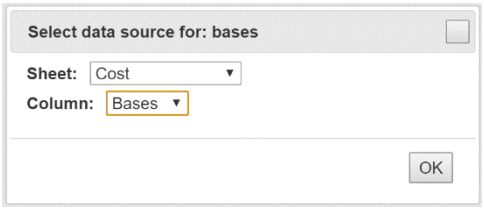


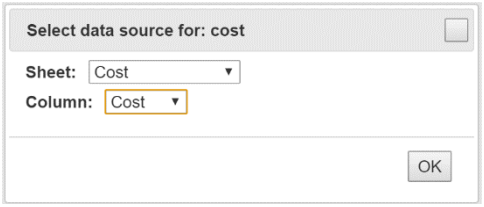
Rename the sheet to Available Troops and then open a new Dashboard.

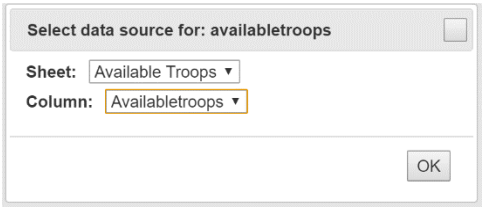
Drag each of the three sheets (Cost, Required Troops and Available Troops) and the Extension to the Tableau canvas as described in the Product Mix example.

Match the dimensions from the Excel sheet to the dimensions and measures in the Tableau sheets as follows.

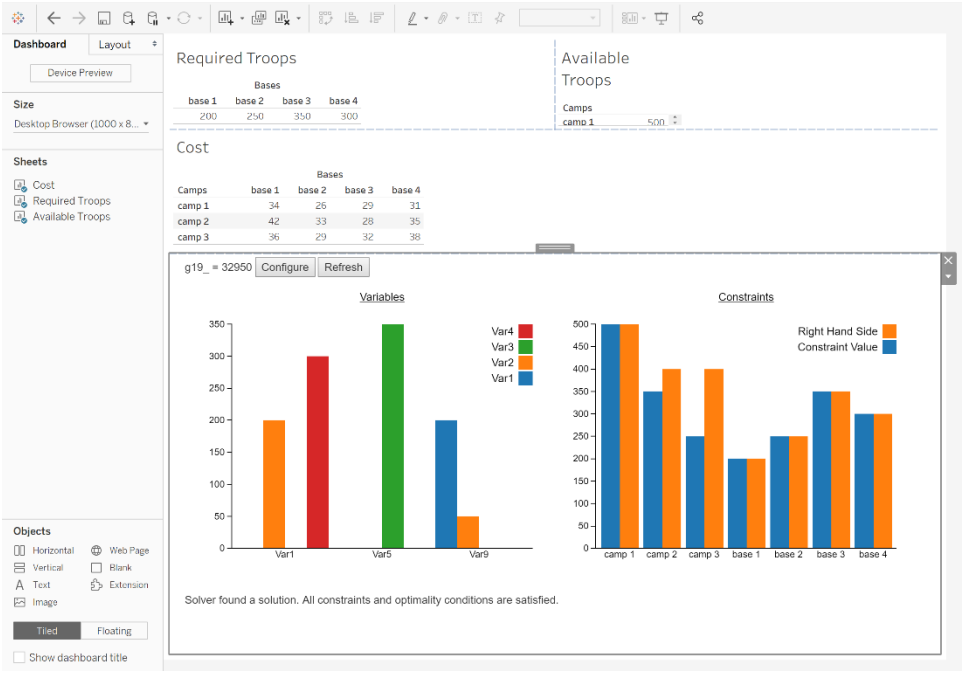








The resultant Tableau Extension is shown in the screenshot below. Now each time new data is imported into Tableau, the Troop Movement example data will be solved from within Tableau without the need to ever return to the original Excel workbook.

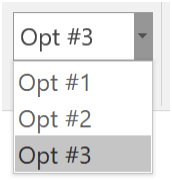


Using Optimization Parameters in Tableau

Now what happens when we would like to see how our final variable values and objective function value change as the number of troops required changes. For this type of "What If" analysis, we can use the PsiOptParam() optimization parameter. Recall from the chapter, Examples: Parameters and Sensitivity Analysis, an **optimization parameter** (PsiOptParam) is automatically varied when you perform multiple optimizations. You do this by clicking the Optimize button on the Ribbon, or the green arrow in the Task Pane, with the Number of Optimizations set to a value greater than 1.

Let's go back to our example Troop Movement Excel model and enter an optimization parameter for the number of troops required in Base 1. In cell C13, enter "=PsiOptParam({34,24,14})", then click the Platform tab in the Solver Task pane and change the Number of Optimizations to "3". When I click Solve, Analytic Solver will solve 3 optimizations. In the first optimization, cell C13 will be set to 34, in the second, 24, and in the third, 14.

Click the Output tab, then click the green arrow to solve the model. After the solving process is over, we can select the three different optimizations in the Optimization drop down menu (in the Tools section of the Analytic Solver ribbon), to see how the objective function changes according to the value set for this parameter.

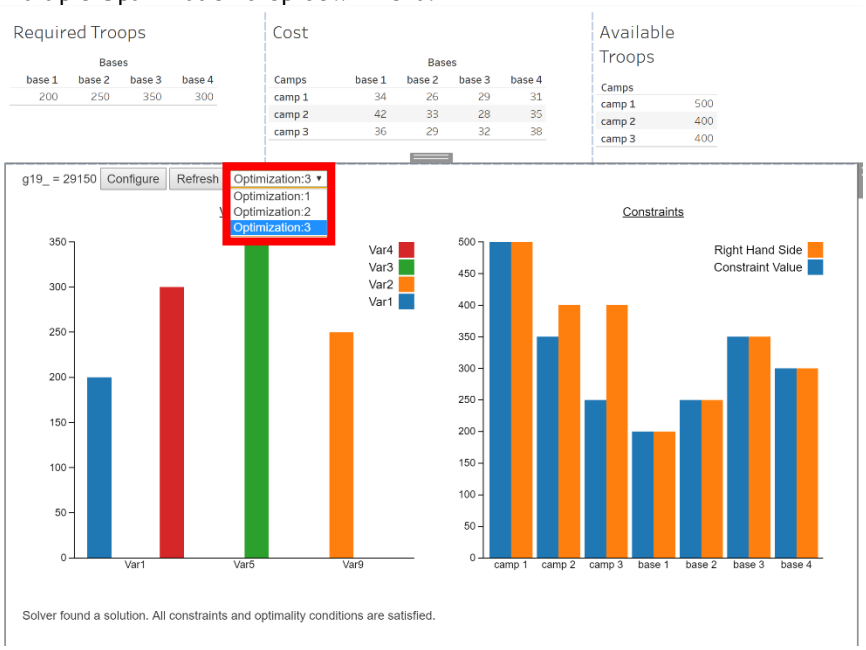


In the first optimization, cell C13 = 34 and the resultant objective function value was $32,950. In the second optimization, cell C13 = 24 and the resultant objective function value was $31,150 and in the third optimization cell C13 = 14 with an objective function value of 29,150.

Save the Excel file, then click Create App – Tableau to create a new Tableau Extension.

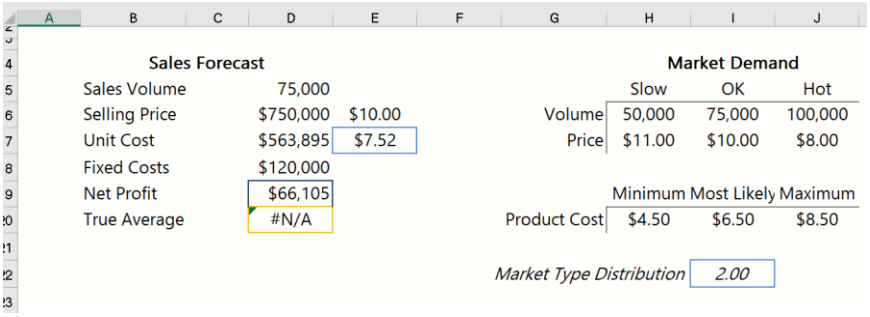
Click back to Tableau and import the newly created Tableau Extension.

Immediately, the model solves and the results will be displayed on the Tableau canvas. To view each solution, click the down arrow within the newly added Multiple Optimization drop-down menu.



Simulation Example Model

Now let's create a Tableau extension using a simulation example. The process is exactly the same as when using an optimization model. Open the Business Forecast Example by clicking Help – Examples – Simulation Models, click the Business Forecast hyperlink to open the file.



First, we will use a PsiDataSrc() function to generate data repositories for use in the Tableau Extension.

Click a blank cell, such as cell G24, then type: "=PsiDataSrc("market_src", "market", H16:J17, "parameters", G16:G17, "mktdemand", H15:J15)

where:

market_src – Is the name used to identify the text file that will be submitted to the RASON server.

market – Will be the name of the data repository in Tableau.

H16:J17 – Is the data range for "market".

parameters – Is the name of the 1st index set for the data specified in the "data" argument, market.

G16:G17 – Is the Excel range where the data for "parameters" is located.

mktdemand – The name of the 2nd index set for the data specified in the "data" argument.

H15:J15 – Is the Excel range where the data for "mktdemand" is located.

Type ")" to close the formula and then press the Enter key to enter the formula into the Excel cell.

Click a 2nd blank cell, such as G25, then enter the following function.

=PsiDataSrc("price_src", "mktprice", H20:J20, "price", H19:J19)

where:

price_src – Is the name used to identify the text file that will be submitted to the RASON server.

mktprice – Is the name of the data repository in Tableau.

H20:J20 – Is the data range for "mktprice".

price – Is the name of the 2nd index set for the data specified in the Data argument, market.

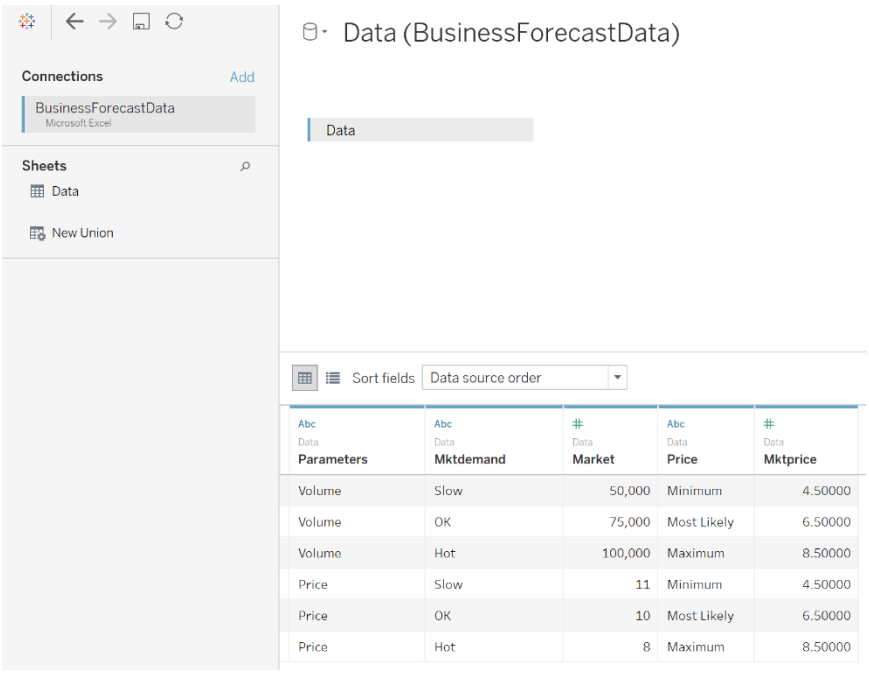
H19:J19 – Is the Excel range where the data for "price" is located.

Click Create App – Tableau to create a new Tableau Extension, Solver.trex.

Click back to Excel and open a new workbook to enter the following data into an Excel table. Rename the worksheet as "Data" and save the workbook as BusinessForecastData.xlsx.

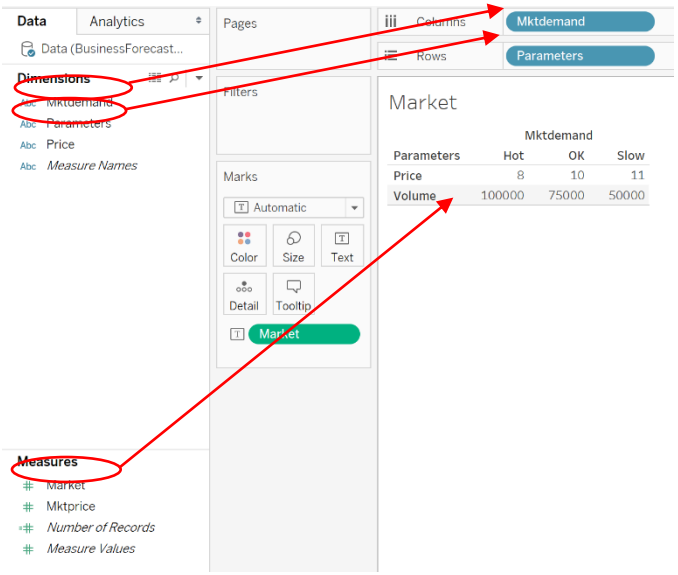
	A	B	C	D	E
1	parameters	mktdemand	market	price	mktprice
2	Volume	Slow	50,000	Minimum	4.50
3	Volume	OK	75,000	Most Likely	6.50
4	Volume	Hot	100,000	Maximum	8.50
5	Price	Slow	11	Minimum	4.50
6	Price	OK	10	Most Likely	6.50
7	Price	Hot	8	Maximum	8.50

Open Tableau, connect to Microsoft Excel, browse to the location of the BusinessForecastData.xlsx file, then click Open.



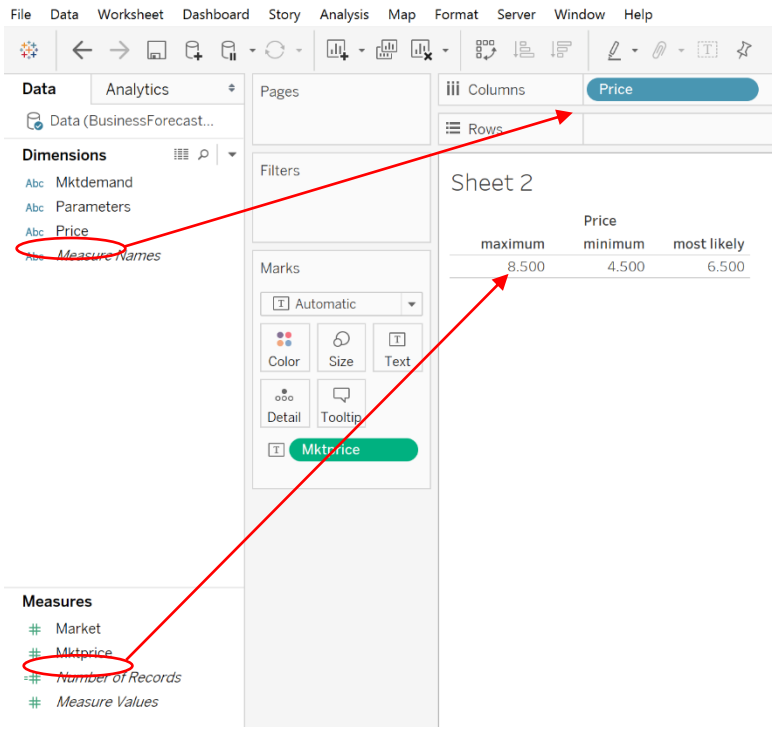
Parameters	Mktdemand	Market	Price	Mktprice
Volume	Slow	50,000	Minimum	4.50000
Volume	OK	75,000	Most Likely	6.50000
Volume	Hot	100,000	Maximum	8.50000
Price	Slow	11	Minimum	4.50000
Price	OK	10	Most Likely	6.50000
Price	Hot	8	Maximum	8.50000

Click on the Sheet 1 tab, under Dimensions, drag "Mktdemand" to Columns and "Parameters" to Rows. Then, under Measures, drag "Market" to the table elements. Hover over SUM(Market), click the down arrow that appears to the right and select Dimension.



Market	Mktdemand		
Parameters	Hot	OK	Slow
Price	8	10	11
Volume	100000	75000	50000

Rename Sheet 1 to Market and add a new worksheet. On Sheet 2, under Dimensions, drag "Price" to Columns. Under Measures, drag "Mktprice" to the table elements. Hover over SUM(Mktprice), click the down arrow that appears to the right and select Dimension.

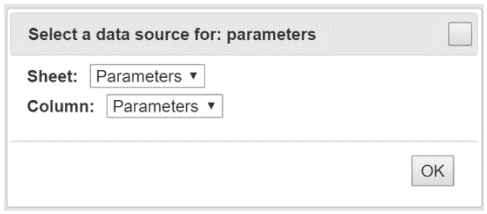


Rename Sheet 2 to Price and create a new dashboard.

Drag both the Parameters and Price Sheets to the Tableau canvas. Drag the Extension icon to the canvas, browse to where the Solver.trex file was saved and click Open.

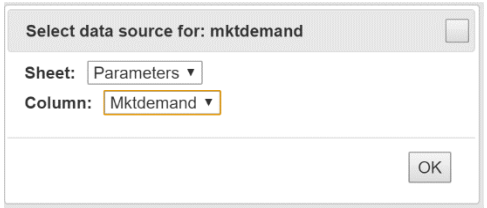
On the "Select data source for: parameters" dialog, select "Parameters" for both Sheet and Column to match the "parameters" dimension in the Excel sheet to the "Parameters" dimension in the Tableau Parameters sheet.

. Then click OK.

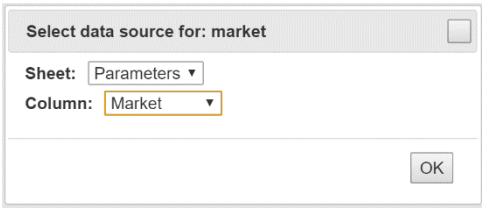


On the "Select data source for: mktdemand", select "Parameters" for Sheet and "Mktdemand" for Column to match the "mktdemand" dimension in the Excel sheet to the "Mktdemand" dimension in the Tableau Parameters sheet.

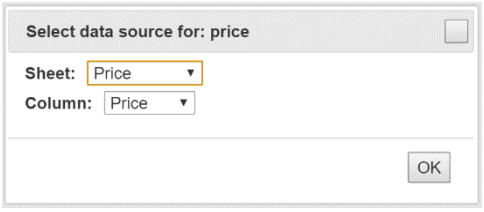
. Then click OK.



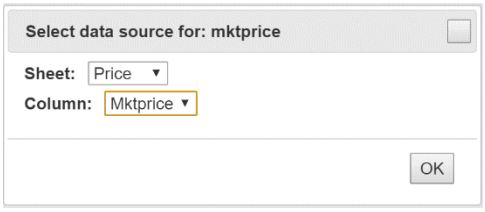
On the “Select data source for: market”, select “Parameters” for Sheet and “Market” for Column to match the “market” dimension in the Excel sheet to the “Market” measure in the Tableau Parameters sheet.



On the “Select data source for: price”, select “Price” for both Sheet and Column, then click OK to match the “price” dimension in the Excel sheet to the “Price” dimension in the Tableau Price sheet. .



On the “Select data source for: mktprice”, select “Price” for Sheet and “Mktprice” for Column, then click OK to match the “mktprice” dimension in the Excel sheet to the “Mktprice” measure in the Tableau Price sheet.



Immediately, once the data repositories are filled with the appropriate data fields, a simulation will be run.

Error Messages

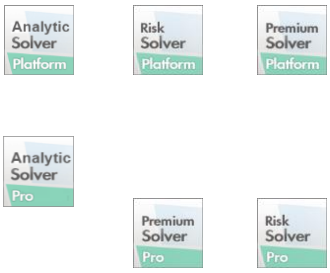
If you've made an error in your PsiDataSrc() function or in your data file, your Tableau extension will display an error such as "Inconsistent Data source definition PSI could not parse Excel formulas" or "Invalid binding source definition PSI could not parse Excel formulas".

If your Tableau extension is displaying either of these errors or a different error, first, check the PsiDataSrc() function in your Excel model to make sure that you have not mixed up the order of your index sets. In addition, check your data to make sure that it is 1. Contained within an Excel table, 2. That the column headings match the index sets defined in PsiDataSrc() and 3. That your model parameters match the elements in your data table.

For more information on an error message displayed in your custom visual, see the Frontline Solvers Reference Guide or contact Frontline Systems Support Team by emailing support@solver.com or by calling 888-831-0333.

Examples: Parameters and Sensitivity Analysis

Introduction



This chapter introduces the use of **parameters**, and functions for **sensitivity analysis** in Analytic Solver, with examples. In Version 11, the role of parameters – for optimization, simulation, and sensitivity analysis – was enhanced, and the sensitivity analysis functions were introduced. The use of parameters and sensitivity analysis has also been extended to Analytic Solver Cloud.

Sensitivity analysis is designed to help you explore a conventional Excel spreadsheet model, often before you define an optimization or simulation model. The goal of sensitivity analysis is to identify the key input parameters that have the *greatest impact* on results of interest in your model (such as Net Profit), and to see the effect of varying these key input parameters over a range, in reports and graphs. Analytic Solver helps you *automatically identify* sensitivity parameters, and *automatically vary* them to produce reports and graphs.

Parameters and Results

All Analytic Solver products support three kinds of parameters:

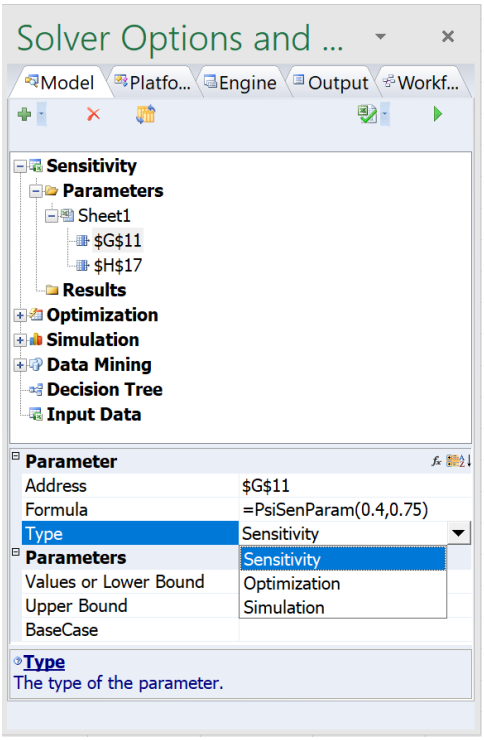
- A **sensitivity parameter** (PsiSenParam) is automatically varied when you perform a sensitivity analysis. You do this by selecting **Sensitivity** from the Reports or Charts galleries on the Ribbon.
- An **optimization parameter** (PsiOptParam) is automatically varied when you perform multiple optimizations. You do this by clicking the Optimize button on the Ribbon, or the green arrow in the Task Pane, with the Number of Optimizations set to a value greater than 1. (Not available in Analytic Solver Simulation.)
- A **simulation parameter** (PsiSimParam) is automatically varied when you perform multiple simulations. You do this by clicking the Simulate button on the Ribbon, or the green arrow in the Task Pane, with the Number of Simulations set to a value greater than 1. (Not available in Analytic Solver Optimization.)

Note: When entering PsiOptParam, PsiSenParam PsiSimParam manually (i.e. simply typing the function into an Excel cell) in Analytic Solver Cloud, the taskpane must be refreshed before performing a parameter analysis report.

Viewing Parameters in the Task Pane

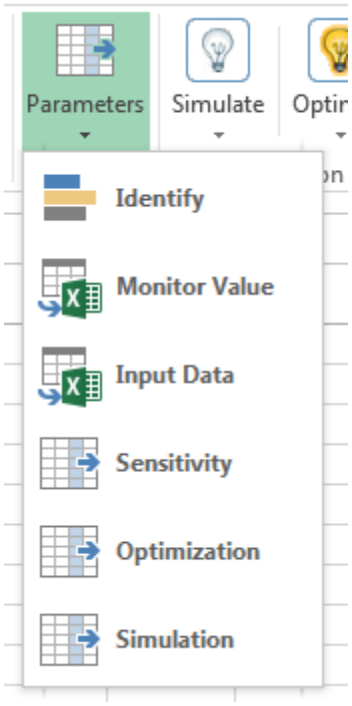
All three types of parameters appear in the Task Pane Model outline. In the example on the next page, two sensitivity parameters at G11 and H17 have been defined by the user. Parameter G11 is selected, and its properties are shown in the lower part of the Task Pane. It is possible to **change the type** of a

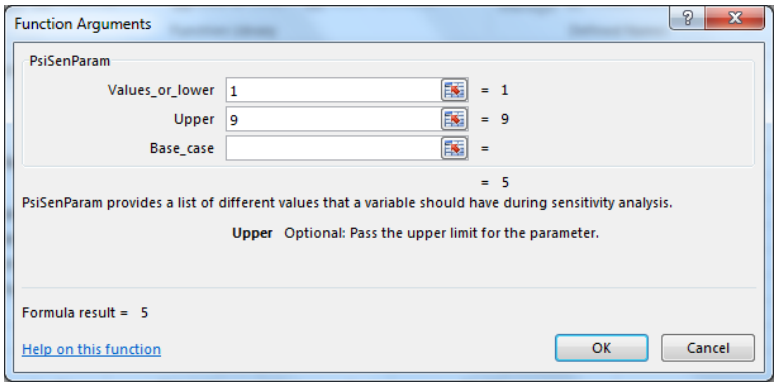
parameter, by simply selecting from the dropdown list in the lower part of the Task Pane as shown: For example, to use G11 in a simulation model, automatically varied across multiple simulations, you would select **Simulation** from the dropdown list.



Defining a Parameter

You can manually define an input cell as a parameter by simply selecting the cell, choosing **Parameters** and **Sensitivity**, **Optimization** or **Simulation** from the Ribbon, and entering a lower and upper limit on values for the parameter, or a list of explicit values for the parameter. In the example on the next page, we are defining a sensitivity parameter.





You can also simply type a formula such as =PsiSenParam(1,9) in a cell, which has the same effect as the above steps. In both cases, the parameter appears in the Task Pane Model outline.

If you specify a lower and upper limit, the **step size** for successive values is determined when you perform a parameterized sensitivity analysis, or multiple parameterized optimizations or simulations. Analytic Solver will subdivide the range from the lower to the upper limit into equal-size intervals.

For example, for the above sensitivity parameter, you would select **Reports** or **Charts** – **Sensitivity** – **Parameter Analysis** and specify the number of points on the major axis. If you specified 18 points, the step size would be 0.5.

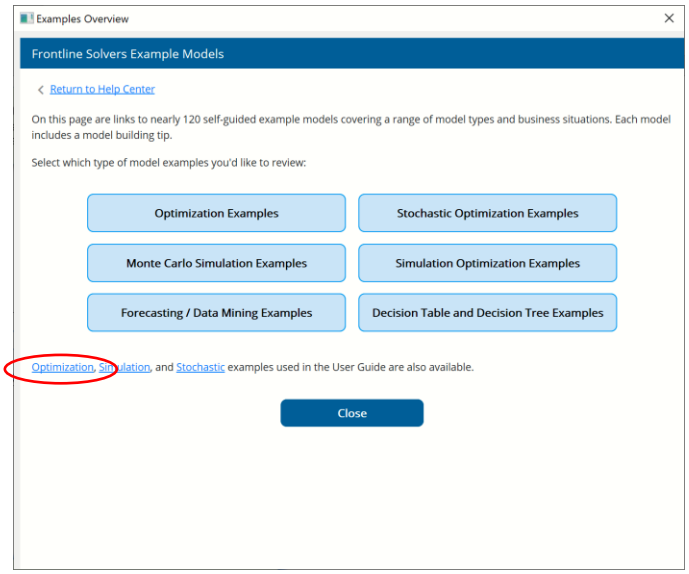
Automatic Parameter Identification

Analytic Solver can *automatically* find the input cells with the greatest impact on any selected formula cell. You can then choose one or more of these input cells to serve as sensitivity (or optimization or simulation) parameters.

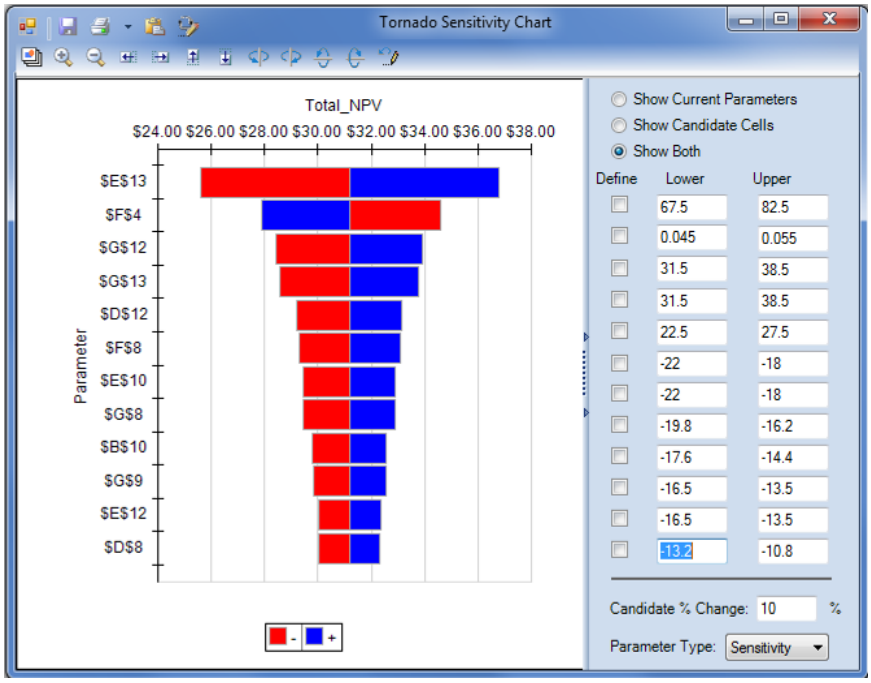
To do this, **select any formula cell in an Excel model, and choose Parameters – Identify from the Ribbon**.

Analytic Solver traces through all 'precedent' formulas to find input cells (leaves of the formula tree) on which the selected formula cell depends. It then varies each input cell independently, computing its impact on the selected formula cell. The input cells are ranked in descending order by (absolute) impact, and the highest-impact cells are displayed in the Tornado chart.

In the example below, we've clicked **Help – Examples** on the ribbon to open the StandardExamples.xlsx. nicole



Click the Example 8 tab and set cells B17:G17 to 1. (If these cells are all 0, then no projects are selected and the Total NPV is always 0). To see which cells have the greatest impact on Total NPV, we simply select cell (I28) and choose **Parameters – Identify** from the Ribbon. After a moment, a Tornado chart like the one below appears.

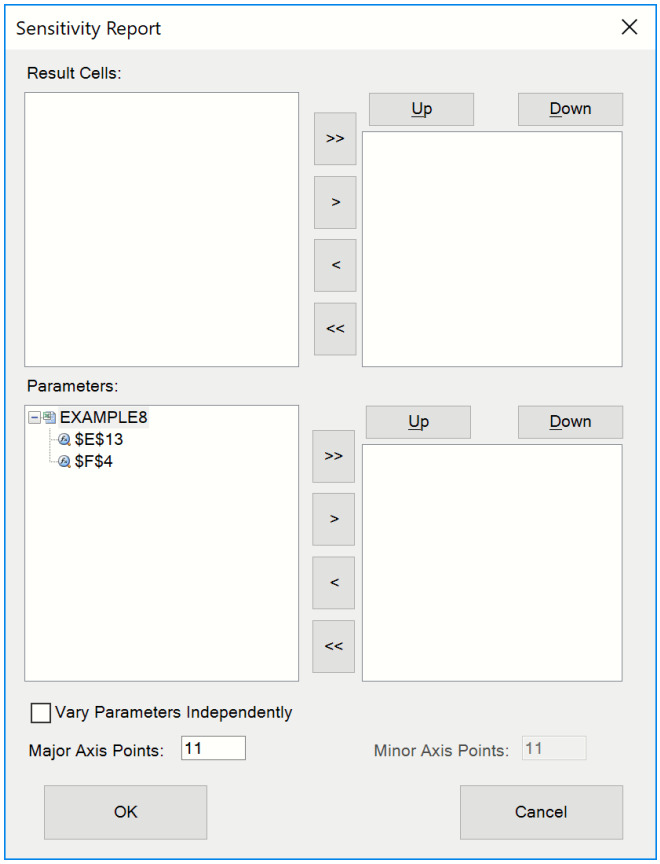


The chart shows us, at a glance, that Total NPV is most sensitive to cell E13 – which is a large positive cash flow in Year 6 for Opportunity 4. It is next most sensitive (in the opposite direction, decreasing when the parameter increases) to the interest rate in cell F4.

The right panel of the chart shows the lower value and upper value that were used for each input cell when computing the formula value. An ordinary cell containing a number is set to its current value – *n*% and its current value + *n*%, where *n*% (initially 10%) is specified in the edit box in the lower right corner of the chart. If any input cell is already *defined as a parameter*, the lower and upper limit arguments of its PsiXxxParam() call are used instead.

By choosing the radio button corresponding to "Show Current Parameters", "Show Candidate Cells", or "Show both" at the top of the right panel, you can show either one or both types of input cells in the Tornado chart. By **checking the box on the same row** as the cell, you can *define* a candidate cell as a **sensitivity parameter** (or, if you change the selection in the dropdown list in the lower right corner of the chart, an **optimization** or **simulation parameter**). These definitions take effect when you click the Save icon at the upper left corner of the chart. For this example, we'll check the boxes on the same rows as cells **E13** and **F4**; we'll also set F4's Lower value to **0.01** (1%) and the Upper Value to **0.10** (10%).

Now, when you click Charts – Sensitivity Analysis – Parameter Analysis, you'll see both parameters appear under Parameters in the Sensitivity Report dialog. Continue reading to discover how to create a parameter report using Analytic Solver.



The simplest way to remove a parameter is to select the parameter cell on the worksheet and press the DEL key – which erases its cell formula – or type a number value that will overwrite the formula in the cell. The parameter will then disappear from the Task Pane.

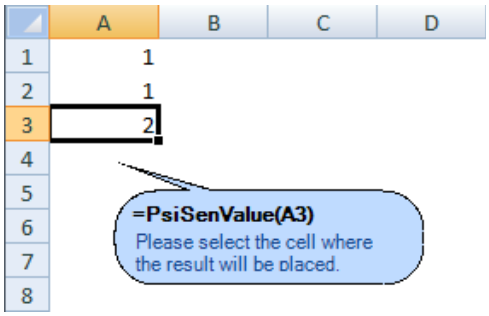
Defining Results

When you perform a sensitivity analysis (which will automatically vary sensitivity parameters), or multiple optimizations or simulations (which will vary optimization or simulation parameters), Analytic Solver will keep track of one or more result cell values, corresponding to each parameter value.

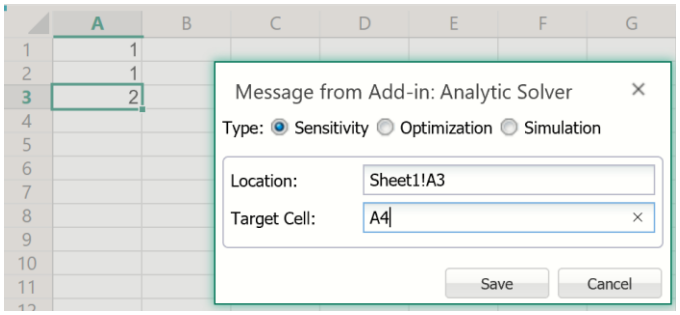
- For optimizations, Analytic Solver tracks the final objective and decision variable values found by the Solver; you can also track a constraint value by setting its Monitor property in the Task Pane.
- For simulations, Analytic Solver tracks the values of all uncertain functions (simulation outputs, referenced in PsiOutput() or PSI Statistics function calls).
- For sensitivity analysis, Analytic Solver tracks results from the cell *currently selected* at the time you perform the analysis, and any other results you define.

To define a sensitivity result cell in Analytic Solver Desktop, select the cell (such as A3 below – always a formula cell) on the worksheet, and choose **Parameters – Monitor Value** from the Ribbon. A small "balloon" will appear, containing a function call such as =PsiSenValue(A3). You can move the mouse to "drag and drop" this formula into an empty cell. When you do this, cell A3 is

defined as a sensitivity result cell, and appears in the Task Pane Model outline under Sensitivity Results.



To define a sensitivity result cell in Analytic Solver Cloud, select the cell (such as A3 below) on the worksheet, and choose **Parameters – Monitor Value** from the Ribbon. A small dialog will appear, containing the location of the selected cell, a second Target field and three radio buttons. Select the type of parameter you would like to add, Sensitivity, Optimization or Simulation, then enter an empty cell for the Target field, such as A4. Click Save to define cell A3 as a sensitivity result cell which will appear in the Task Pane Model outline under Sensitivity Results.



Sensitivity Analysis Reports and Charts

The **Parameters – Identify** step just described performs a simple kind of sensitivity analysis; in some situations, this may be all that you need. But it is often useful to document the sensitivity of some computed result to systematic variations in the values of one or more parameters. Analytic Solver can produce both reports and charts to document these results.

How Parameters are Varied

In reports and charts, Analytic Solver can automatically vary your parameters' values in two ways:

1. Varying **all parameters simultaneously**, from their respective lower to upper limits, for the number of steps that you specify.
2. Varying **two parameters independently**, from their lower to upper limits, computing a result for all combinations of the two parameters.

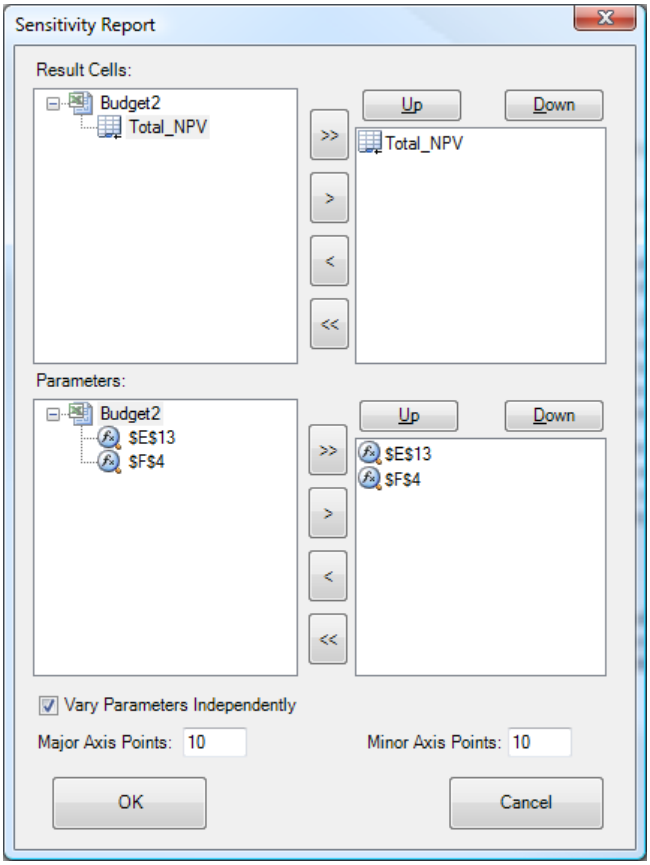
You select the second choice by checking the box "Vary Parameters Independently" at the bottom of the dialog shown on the next page. If you do this, you must select *exactly one* result cell, and *exactly two* parameter cells in

the dialog below. A report will appear as a two dimensional table, and a chart will appear in 3-D with the two parameters on the axes.

If you don't check this box – meaning that all parameters will be varied simultaneously – you can select one or more parameter cells, and one or more result cells in the dialog below. A report will contain a column for each parameter and each result, and a chart will contain a plot of each result cell.

Creating Sensitivity Reports

To create a sensitivity analysis report, select a formula cell on the worksheet (whose value should be computed in the report say, cell I28 (Total_NPV)), and choose **Reports – Sensitivity – Parameter Analysis** from the Ribbon. A dialog like the one shown below will appear.

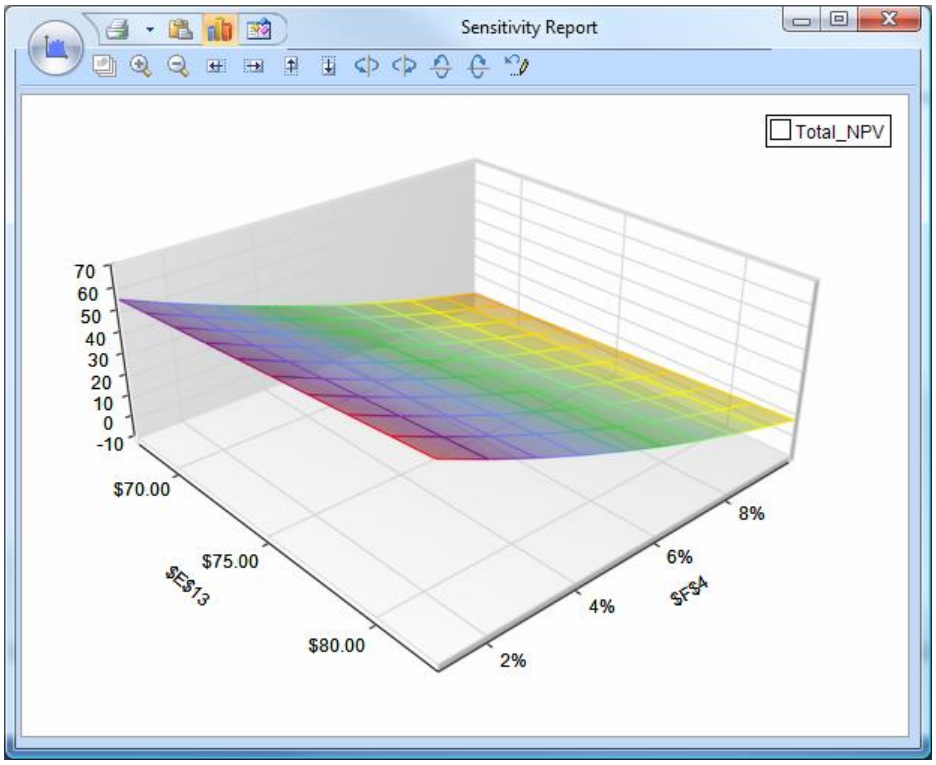


Use the arrow buttons in the top section to select one or more result cells (exactly one if you check the box "Vary Parameters Independently"). Use the arrow buttons in the bottom section to select one or more sensitivity parameter cells (exactly two if you check the box "Vary Parameters Independently"). Then click OK to produce the report, as a new worksheet in into your Excel workbook, just to the left of the active worksheet. An example is shown below.

	A	B	C	D	E	F	G	H	I	J	K
1	Total_NPV : $E$13 by $F$4										
2											
3											
4	$E$13	$F$4									
5		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
6	$67.50	$55.56	$47.19	$39.43	$32.25	$25.59	$19.41	$13.69	$8.38	$3.46	($1.11)
7	$69.17	$57.13	$48.67	$40.83	$33.56	$26.83	$20.59	$14.80	$9.43	$4.45	($0.17)
8	$70.83	$58.70	$50.15	$42.22	$34.88	$28.07	$21.76	$15.91	$10.48	$5.45	$0.78
9	$72.50	$60.27	$51.63	$43.62	$36.20	$29.32	$22.94	$17.02	$11.53	$6.44	$1.72
10	$74.17	$61.84	$53.11	$45.01	$37.51	$30.56	$24.11	$18.13	$12.58	$7.43	$2.66
11	$75.83	$63.41	$54.59	$46.41	$38.83	$31.80	$25.29	$19.24	$13.63	$8.43	$3.60
12	$77.50	$64.98	$56.07	$47.81	$40.15	$33.05	$26.46	$20.35	$14.68	$9.42	$4.54
13	$79.17	$66.55	$57.55	$49.20	$41.47	$34.29	$27.64	$21.46	$15.73	$10.41	$5.48
14	$80.83	$68.12	$59.03	$50.60	$42.78	$35.53	$28.81	$22.57	$16.78	$11.41	$6.42
15	$82.50	$69.69	$60.51	$51.99	$44.10	$36.78	$29.99	$23.68	$17.83	$12.40	$7.36

Creating Sensitivity Charts

To create a sensitivity analysis chart, select a formula cell on the worksheet (whose value should be computed in the chart), and choose **Charts – Sensitivity – Parameter Analysis** from the Ribbon. A dialog like the one on the previous page will appear. Follow the same steps as for sensitivity analysis reports, and click OK. A chart like the one below will appear:



You can use icons on the toolbar at the top of the chart to resize and rotate the chart, print the chart, or copy it to the Windows Clipboard (where you can paste it into other applications).

Optimization and Simulation Reports and Charts

Reports and charts for multiple parameterized optimizations and simulations work in much the same way as the reports and charts for sensitivity analysis shown in the previous section. But where for sensitivity analysis, Analytic Solver simply performs a **worksheet recalculation**, for these reports and charts, Analytic Solver performs a **complete optimization or simulation** for each set of parameter values.

To produce these reports and charts, select **Reports** or **Charts – Multiple Optimizations** from the Ribbon. For multiple parameterized simulations, select **Reports** or **Charts – Multiple Simulations** from the Ribbon.

When Optimizations and Simulations are Run

As shown in the earlier Examples chapters, optimizations are run when you click the Optimize button on the Ribbon, or the green arrow in the Task Pane, and simulations are run when you click the Simulate button on the Ribbon, or (assuming there's no optimization model) when you click the green arrow in the Task Pane. When you select Reports and Charts of Multiple Optimizations or Multiple Simulations *other than* Parameter Analysis, the results **cached in memory** from the last optimization or simulation run are used to create the reports or charts.

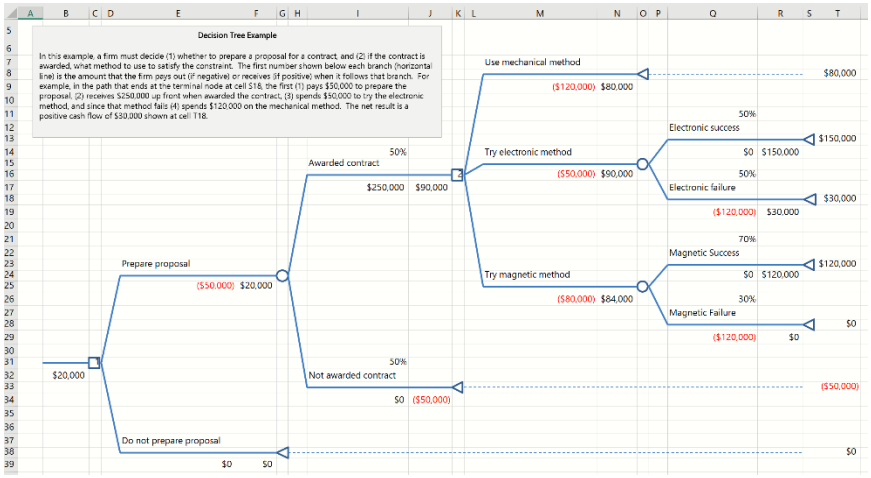
However, when you select Reports and Charts of Multiple Optimizations or Multiple Simulations with **Parameter Analysis**, which gives you greater control over how parameters are varied, Analytic Solver cannot use the results cached in memory. Instead, a new set of optimizations or simulations is run, varying the values of the parameters as you've specified; you can for example vary two parameters independently, yielding all combinations of these parameter values. The number of optimizations or simulations to run is independent of the settings you use for Number of Optimizations or Number of Simulations in the Task Pane Platform tab; it is the ***product*** of the number of **Major Axis Points** and **Minor Axis Points** you select in the Reports or Charts selection dialog. With the default value of 10 points each, 100 optimizations or simulations are required. This can take some time, especially for optimizations; a progress dialog is displayed during this process.

Examples: Decision Trees and Discriminant Analysis

Introduction

This chapter introduces **decision trees** in Analytic Solver. Such trees are a useful graphical and computational aid for problems that involve sequential decisions and events, where there are a small number of decision alternatives at each step, and a small number of alternative outcomes for each event.

In the example below, we've clicked **Help – Examples** on the ribbon, clicked **Decision Tree Examples** on the Overview Tab, and clicked on **TreeExample.xls**, which is based on an example by Prof. Mike Middleton.



In this example, a firm must decide (1) **whether to prepare a proposal** for a contract, and (2) if the contract is awarded, **what method to use** to satisfy the contract. The first number shown below each branch (horizontal line) is the amount the firm pays out (if negative) or receives (if positive) when it follows that branch. For example, in the path that ends at the terminal node at cell S18, the firm (1) pays $50,000 to prepare the proposal, (2) receives $250,000 up front when awarded the contract, (3) spends $50,000 to try the electronic method, and since that method fails, (4) spends $120,000 on the mechanical method. The net result is a positive cash flow of $30,000 shown at cell T18.

A decision tree is "solved" by Excel fomulas calculating each of the numbers you see on the worksheet. **Terminal values** such as T18 sum all the partial cash flows along the path leading to that terminal node. The tree is then **rolled back** by computing expected values (or certainty equivalents) at event nodes, and by maximizing (or minimizing) the alternative values at decision nodes. The rollback values appear below and just to the left of each node, showing the value of the subtree rooted at that node. The numbers "inside the boxes" at decision nodes show **which alternative is optimal** for that decision. In the example, the 1 in the decision node at C31 indicates that it is optimal to prepare the proposal, and the 2 in the decision node at K16 indicates the firm should try the electronic

method because that alternative leads to a higher expected value ($90,000) than the mechanical method ($80,000).

Since all the computations are performed with Excel worksheet formulas, a decision tree is a 'regular' Excel worksheet model, where you can ask what-if, perform sensitivity analysis, or create simulation or optimization models if desired. For example, the formula at cell F25, for the event where we are or are not awarded the contract, is =IF(ABS(1-SUM($I$14,$I$31))<=0.00001,SUM($I$14*$J$17,$I$31*$J$34),NA()) – an expected value calculation – and the formula at B32, for the decision whether to prepare a proposal, is simply =MAX(F25,F39), since we are maximizing EV.

The Task Pane Platform tab includes a Decision Tree group of options, where you can choose to maximize or minimize values at decision nodes, and to compute expected values (which are risk neutral) or certainty equivalents (which reflect risk aversion) at each node. If you choose certainty equivalents, you can specify the parameters of an exponential utility function.

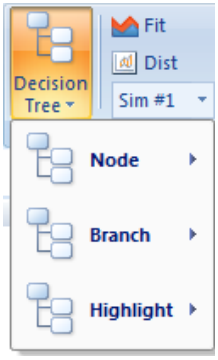
Creating Decision Trees

A decision tree consists of **nodes** and **branches**. Nodes may be either decision **nodes**, **event nodes**, or **terminal nodes**; branches represent alternative choices at decision nodes, and alternative outcomes at event nodes.

You create and edit a decision tree with the Decision Tree choice on the Ribbon.

Creating Trees in Analytic Solver Desktop

In Analytic Solver Desktop, click the Decision Tree icon on the Ribbon to open the menu choices.

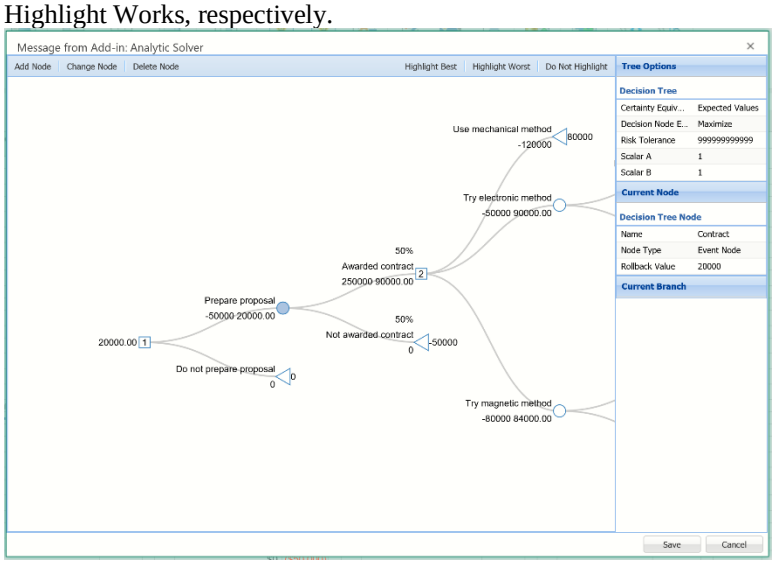


You can also create and edit a decision tree in Analytic Solver Desktop in the Task Pane Model tab, using the Add (+) and Remove (X) icons and the properties area at the bottom of the Task Pane; but you can highlight the best or worst decision strategy (see below) only from the Ribbon.

Create Trees in Analytic Solver Cloud

In Analytic Solver Cloud, click the Decision Tree icon on the Ribbon to open the Decision Tree dialog. You can create and edit decision trees in the Cloud app using menu items at the top of the dialog (Add Node, Change Node, and Delete Node) and also in the fields on the right under Decision Tree. To

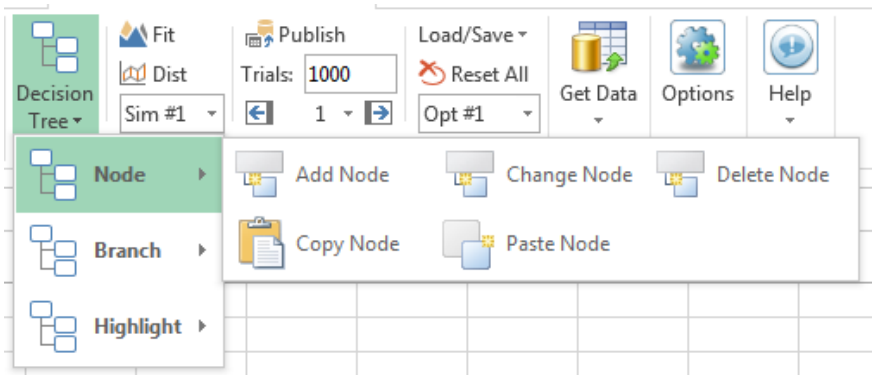
highlight the best and worst decision strategies, click Highlight Best or Highlight Works, respectively.



Creating and Editing Nodes

In Analytic Solver Desktop

Selecting **Node** in the dropdown presents choices for working with nodes:

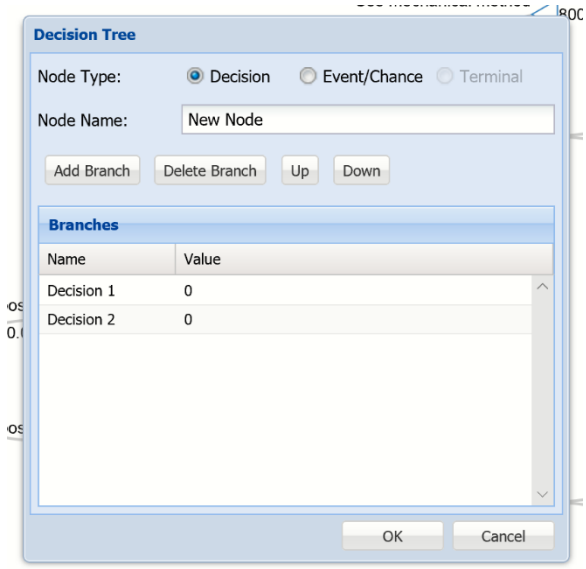


The **Add Node** and **Change Node** options display the dialog shown on the next page. To change a node, you must first *select* it on the Excel worksheet – you may select either the node graphic or one of the immediately adjacent cells.

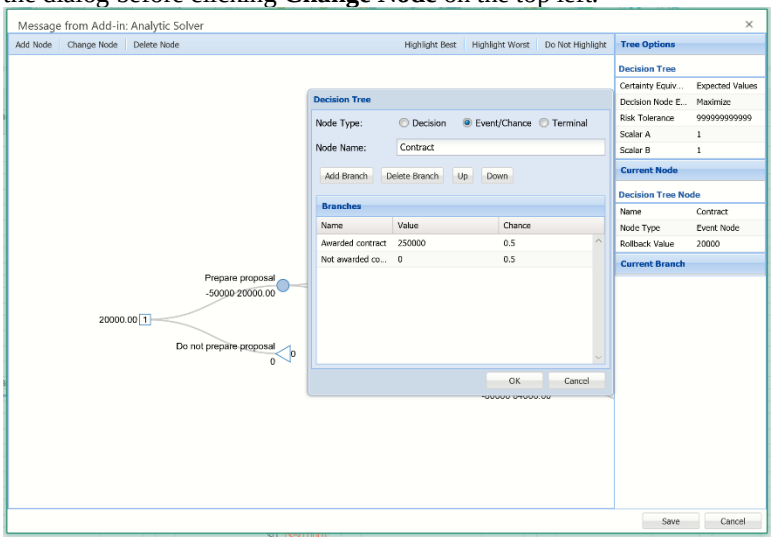
The **Copy Node** and **Paste Node** choices can be used to copy a subtree (rooted at the selected node) and paste the copy at another position in the decision tree; this is very useful when there are identical choices at later stages in the tree.

In Analytic Solver Cloud

In Analytic Solver Cloud, click **Add Node** to open the Add Node dialog.



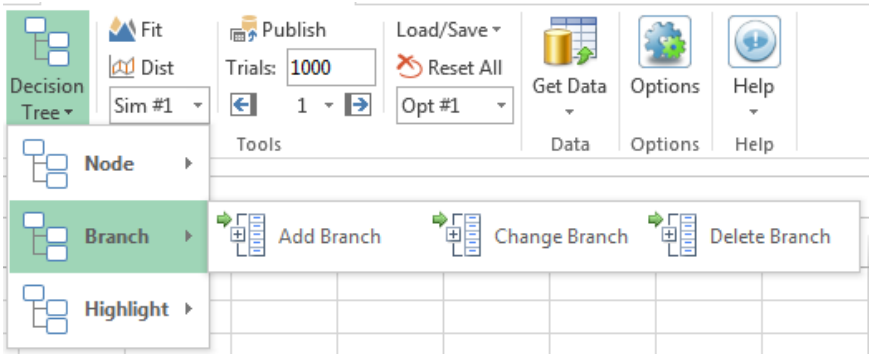
To change a node, you must first select the desired node on the Decision Tree dialog. In the example below, the *Prepare proposal* node has been selected in the dialog before clicking **Change Node** on the top left.



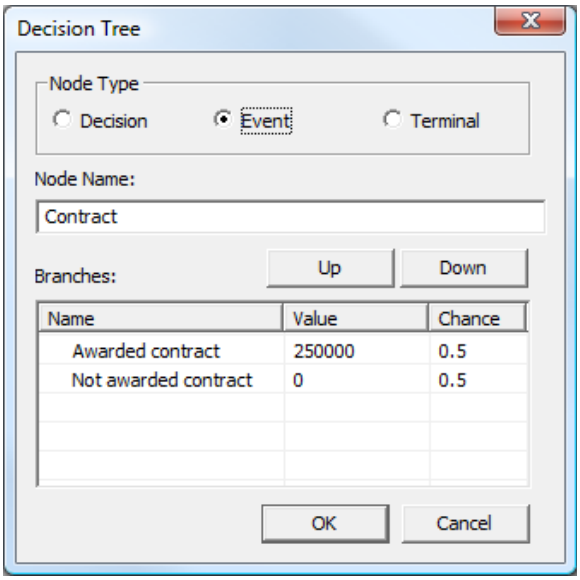
Creating and Editing Branches

In Analytic Solver Desktop

Selecting **Branch** in the dropdown presents choices for working with branches:



The **Add Branch** and **Change Branch** options display the Decision Tree dialog shown below. To change a branch, you must first *select* it on the Excel worksheet – you may select either the branch graphic or one of the immediately adjacent cells. Note that Add/Change Node and Add/Change Branch options display the *same* Decision Tree dialog: Branches are associated with the node to their left, and you can edit properties of the node and its branches in this dialog.



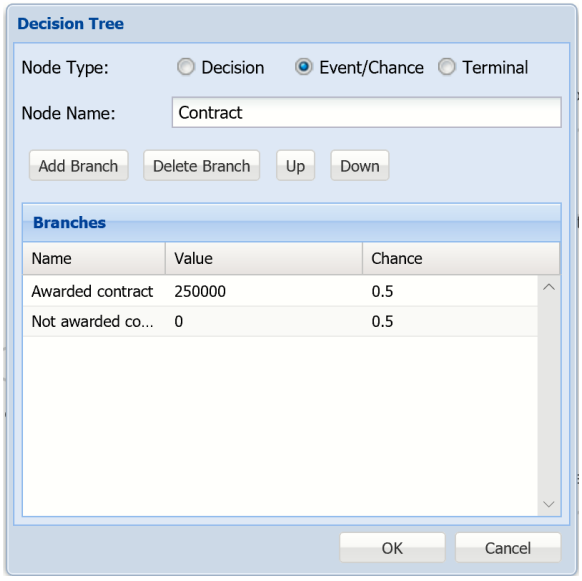
In this dialog, you can change the type of the node, the name of the node, and you can add, edit, reorder, or remove branches for this node. Each branch for a **decision node** has a **value** (the cost or payoff of taking that decision); each branch for an **event node** has a **value** and a **probability** (the cost or payoff, and the probability of occurrence, of that outcome).

In Analytic Solver Cloud

In Analytic Solver Cloud, clicking Add Node\Change Node also allows you to add\change a branch using the **Add Branch** and **Change Branch** options. To change a branch, you must first *select* it on the Excel worksheet. Branches are associated with the node to their left, and you can edit properties of the node and its branches here.

In this dialog, as in Analytic Solver Desktop, you can change the type of the node, the name of the node, and you can add, edit, reorder, or remove branches for this node. Each branch for a **decision node** has a **value** (the cost or payoff of taking that decision); each branch for an **event node** has a **value** and a

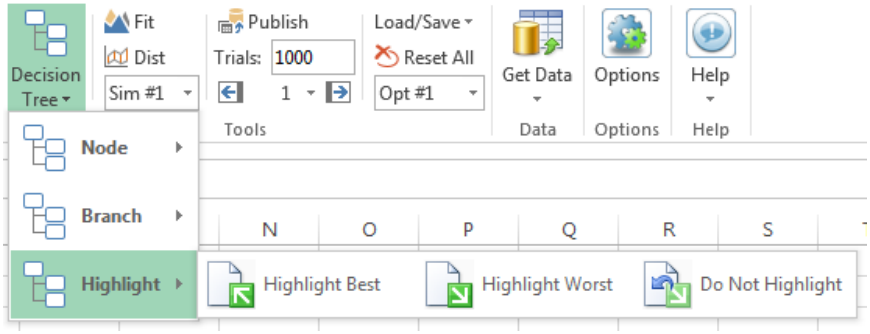
probability (the cost or payoff, and the probability of occurrence, of that outcome).



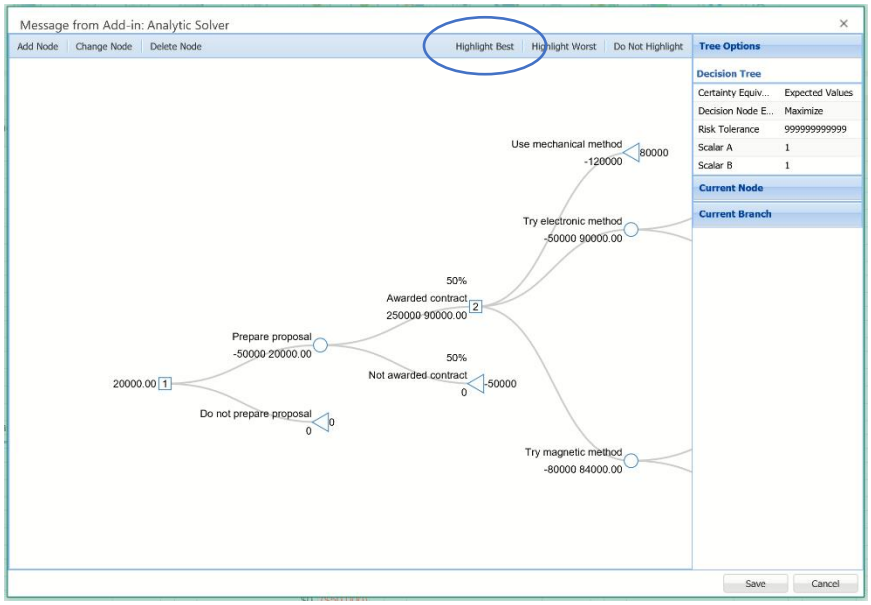
Highlighting a Decision Strategy

A *decision strategy* is a complete sequence of decisions that you can make through the decision tree. You can highlight the best or worst decision strategy by selecting **Highlight** in the Decision Tree dropdown list in Analytic Solver Desktop or by clicking **Highlight Best** in the Decision Tree dialog in Analytic Solver Cloud, as shown on the next page. If you are maximizing, the best strategy maximizes EV or CE, and the worst strategy minimizes EV or CE. If you are minimizing, the opposite applies.

Analytic Solver Desktop

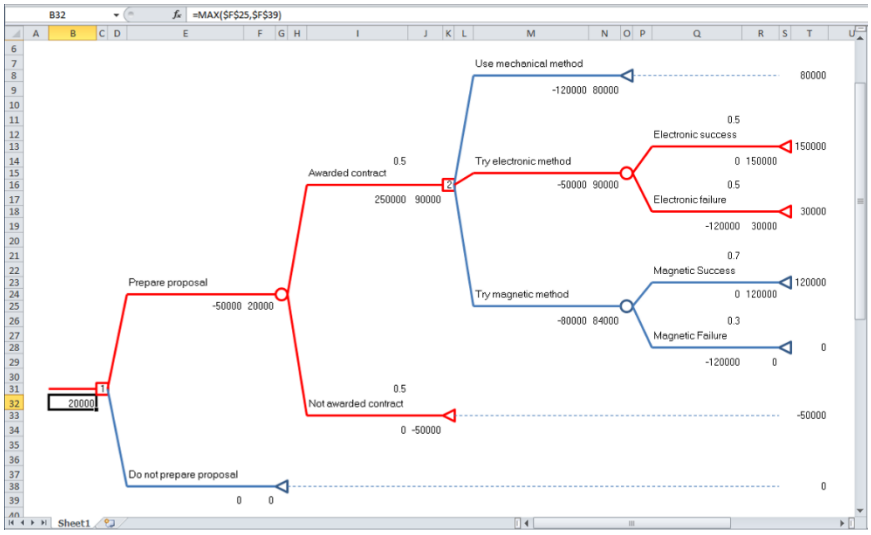


Analytic Solver Cloud



The next page shows the example decision tree shown earlier, with Excel worksheet gridlines turned off, and the best decision strategy highlighted.

Analytic Solver Desktop

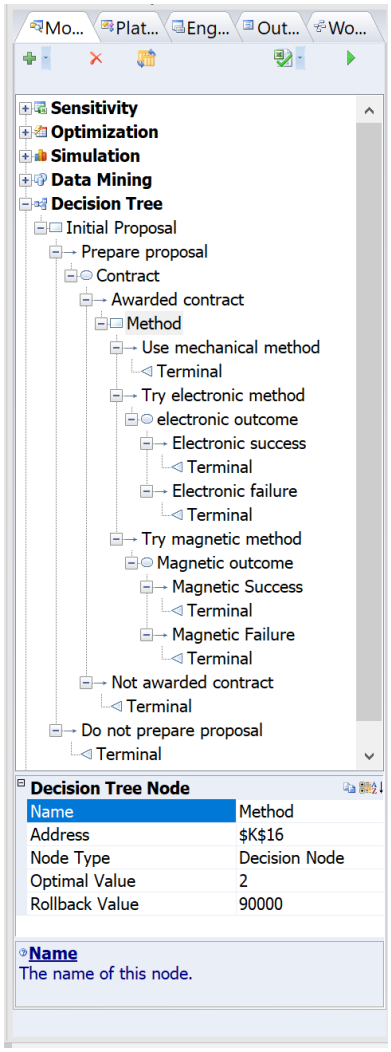


Decision Trees in the Task Pane

Model Tab in Analytic Solver Desktop

In Analytic Solver Desktop, decision trees may also be viewed and edited directly in the Task Pane Model tab, and choices for tree evaluation (see "Platform tab" below) can only be made in the Task Pane. When a node or branch is selected in the Task Pane outline, properties of that node or branch may be viewed and edited in the lower portion of the Task Pane, as shown on the next page. You can also **double-click a node** in the Model outline to display

the same Decision Tree dialog that appears when you add or change a node from the Ribbon.

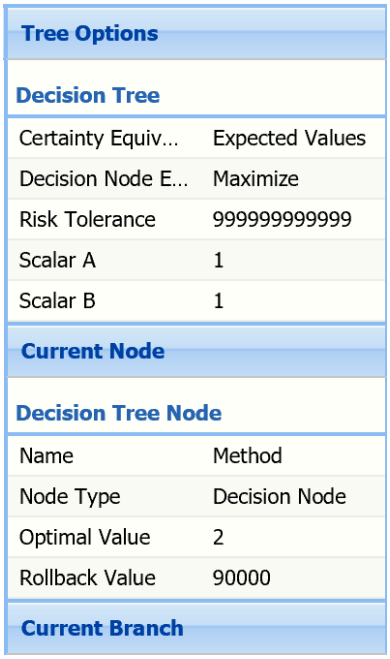


In this example, we've selected the decision node named Method, represented by the graphic symbol at cell K16 on the worksheet. The optimal choice at this node (given that we're maximizing expected value or EV) is branch #2, and the rollback value of the subtree rooted at this node is 90,000.

Note the small **Copy** icon in the upper right corner of the Decision Tree Node properties pane: You can click this icon to **copy a subtree** rooted at this node. When you've selected a Terminal node in the Model outline, you'll notice a small **Paste** icon in this same area: You can click this icon to **paste a subtree** at the position of the Terminal node.

Model Tab in Analytic Solver Cloud

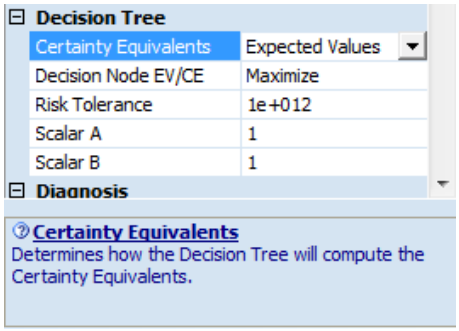
In Analytic Solver Cloud, decision trees may only be viewed and edited directly in the Decision Trees dialog, but choices for tree evaluation can be made either in the Decision Tree dialog or in the Task Pane on the Platform tab (see "Platform tab" below).



Platform Tab

By default, rollback values for a decision tree are computed assuming that you want to Maximize Expected Value or EV. You can change this by setting options in the Decision Tree section of the Task Pane Platform tab, as shown on the next page.

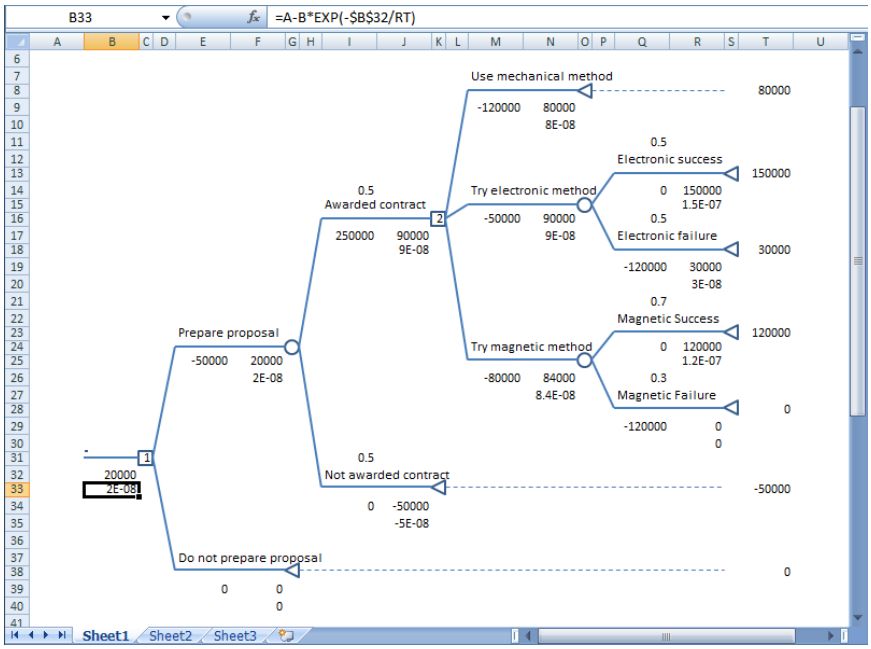
You can select **Maximize** or **Minimize** in the dropdown list for the Decision Node EV/CE option. For the Certainty Equivalents option, you can choose either **Expected Value** or **Exponential Utility Function**. The remaining three options come into play only when you choose Exponential Utility Function – they set parameters of this function.



For the **Maximize** option with exponential utility, the rollback formulas are U = A–B*EXP(X/RT) and CE = -LN((A-EU)/B)*RT, where X and EU are cell references. For the **Minimize** option with exponential utility, the formulas are U = A-B*EXP(X/RT) and CE = LN((A-EU)/B)*RT. RT is the value you specify for the **Risk Tolerance** option on the Platform tab, and A and B are the values of the **Scalar A** and **Scalar B** options on the Platform tab.

When you use an Exponential Utility Function, the utility (U =) and certainty equivalent (CE =) formulas are computed in extra cells on the worksheet, as shown on the next page. For example, B33 computes the **utility** of the decision

at B32; B32 contains =MAX(F25,F39) as before, to choose the decision with the maximum **certainty equivalent** value; F25 contains =-LN((A-$F$26)/B)*RT.



Multiple Discriminant Analysis

Discriminant analysis is a statistical technique for analyzing a data set, consisting of cases or observations of one or more variables, and classifying the cases into different groups. MDA is sometimes called discriminant factor analysis or canonical discriminant analysis. It has many applications in financial services and consumer marketing, among other fields.

Analytic Solver Data Mining and the Data Mining Cloud app include a powerful version of multiple discriminant analysis on the Data Mining tab on the Ribbon, through the menu option **Classify – Discriminant Analysis**, and described in depth in the Analytic Solver Data Mining User Guide.

But since a discriminant analysis facility historically was included with Risk Solver Platform (a predecessor to Analytic Solver), before Frontline acquired and integrated the XLMiner software (known today as Analytic Solver Data Mining), this facility is still available on the Analytic Solver Desktop tab, through the menu option **Reports – Discriminant Analysis – Discriminant Analysis**, and is documented here. Note: Discriminant Analysis is not supported in Analytic Solver Cloud or AnalyticSolver.com.

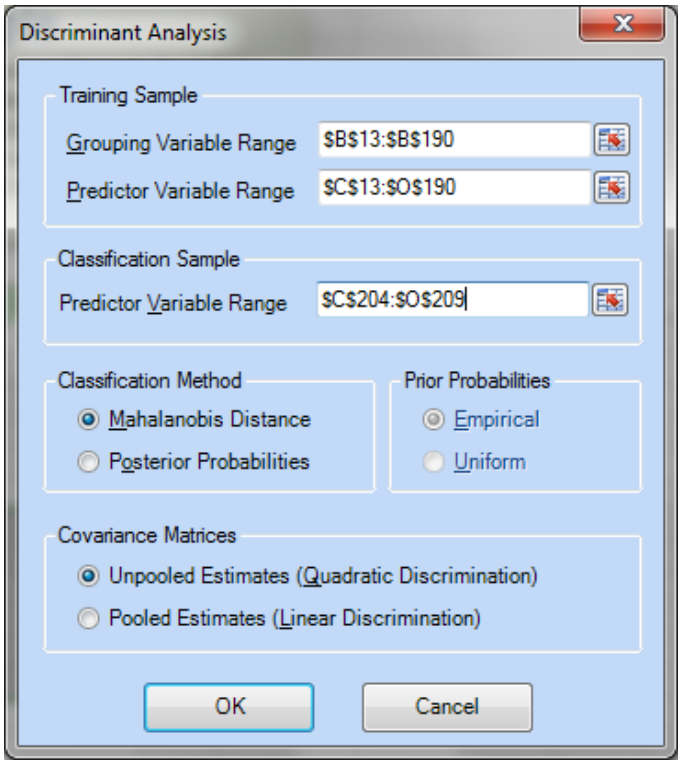
Discriminant Analysis Example

In the example described below, a winery maintains a dataset which includes 13 variables describing various properties of three different types of wines produced at their vineyard. The three different types of wines produced are classified as Type1, Type 2 and Type 3. The characteristics of each wine type include Alcohol content, Malic Acid content, Ash content, Ash Alkalinity content, Magnesium content, Total Phenols, Flavonoid content, etc. There are 59 observations for Type 1, 71 observations for Type 2, and 48 observations for

Type 3. The vineyard wants to develop a classification rule to help them screen new wine varieties into the three different wine types.

In the picture on the next page, we've selected **Reports – Discriminant Analysis – Discriminant Analysis** to display the Discriminant Analysis dialog.

For the Grouping Variable Range, we've selected cells B13:B190 which contain the categorical variables (1, 2 or 3) representing the three different types of wine and cells C13:O190 containing the remaining corresponding variable values for the Predictor Variable Range. For the Classification Sample, we've selected cells C204:O209 on the same worksheet, containing the values for the 13 different characteristic variables for six new varieties of wine. We are using the default choices for the Classification Method (Mahalanobis Distance), Prior Probabilities (Empirical), and Covariance Matrices (Unpooled Estimates).



Clicking OK in this dialog causes a new Discriminant Analysis report to be inserted into the workbook, as shown on the next page. The report shows how MDA determines 'centroids' for each of the three groups in the space of the predictor variables, and computes 'Mahalanobis distances' for each example of test scores from the group centroids.

At the top of the report, under Group Centroids, the centroids for the three groups have been calculated for each variable. X1 corresponds to the Alcohol variable, X2 corresponds to the Malic_Acid variable, X3 corresponds to the Ash variable, and so on.

Just down from Group Centroids is the Group Frequency table. This table lists the relative frequency of each wine by type (1, 2, or 3). The relative frequency is found by dividing the number of observations of each wine type by the total number of wines. For example, the Relative Frequency of Group 1 is 33.15% or

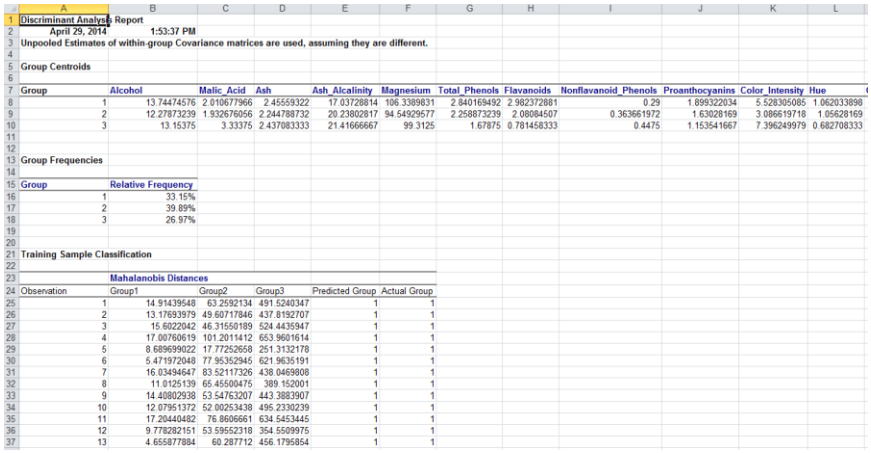
the number of observations of type (50) divided by the total number of observations (178).

The values listed in the Training Sample Classification Table for Group 1, Group 2, and Group 3 are the distance calculations from the individual observations to the group centroid or "center". The minimum value of the three groups determines the group assignment.

The 'Test Sample Classification' at the bottom of the report shows the predictions obtained by MDA for how the six new wine varieties will be typed. All have been assigned to Type 2.

Just above the 'Test Sample Classification' is a table, often called a 'confusion matrix,' that evaluates how well the classification rule would have handled the 178 historical cases. (The types of these 178 cases are all "known".)

The matrix shows that all 59 of the Group 1 observations would have been assigned to Group 1 correctly. All 71 of the Group 2 observations would have been assigned to Group 2 and all 48 of the Group three assignments would have been assigned to Group 3. The Totals in row 211 show that 178 out of 178, or 100% of the cases w correctly classified.



	A	B	C	D	E	F	G	H	I	J	K	L
1	Discriminant Analysis Report											
2	April 29, 2014	1:53:37 PM										
3	Unpooled Estimates of within-group Covariance matrices are used, assuming they are different.											
4												
5	Group Centroids											
6												
7	Group	Alcohol	Malic_Acid	Ash	Ash_Alcalinity	Magnesium	Total_Phenols	Flavanoids	Nonflavanoid_Phenols	Proanthocyanins	Color_Intensity	Hue
8	1	13.74474576	2.010677966	2.45559322	17.03728814	106.3389831	2.840169492	2.982372881	0.29	1.899322034	5.528305085	1.062033898
9	2	12.27873239	1.932676056	2.244788732	20.23802817	94.54929577	2.258873239	2.08084507	0.363661972	1.63028169	3.086619718	1.05628169
10	3	13.15375	3.33375	2.437083333	21.41666667	99.3125	1.67875	0.781458333	0.4475	1.153541667	7.396249979	0.682708333
11												
12												
13	Group Frequencies											
14												
15	Group	Relative Frequency										
16	1	33.15%										
17	2	39.89%										
18	3	26.97%										
19												
20												
21	Training Sample Classification											
22												
23		Mahalanobis Distances										
24	Observation	Group1	Group2	Group3	Predicted Group	Actual Group						
25	1	14.91439548	63.2592134	491.5240347	1	1						
26	2	13.17693979	49.60717846	437.8192707	1	1						
27	3	15.6022042	46.31550189	524.4435947	1	1						
28	4	17.00760619	101.2011412	653.9601614	1	1						
29	5	8.689699022	17.77252658	251.3132178	1	1						
30	6	5.471972048	77.95352945	621.9635191	1	1						
31	7	16.03494647	83.52117326	438.0469808	1	1						
32	8	11.0125139	65.45500475	389.152001	1	1						
33	9	14.40802938	53.54763207	443.3883907	1	1						
34	10	12.07951372	52.00253438	495.2330239	1	1						
35	11	17.20440482	76.8606661	634.5453445	1	1						
36	12	9.778282151	53.59552318	354.5509975	1	1						
37	13	4.655877884	60.287712	456.1795854	1	1						

187	163	151.5108002	47.86908863	10.65787146	3	3
188	164	130.7239025	28.02261494	4.853930741	3	3
189	165	298.5047588	127.9861802	9.813395417	3	3
190	166	226.1721237	71.00478082	13.11279348	3	3
191	167	277.4442442	178.5166146	14.08432047	3	3
192	168	305.3077705	156.8234863	12.80557438	3	3
193	169	215.1320784	111.3485718	10.72208931	3	3
194	170	202.3542767	128.6277453	13.31861083	3	3
195	171	160.1776543	35.99519886	11.79685799	3	3
196	172	369.4432504	143.9556536	15.13532178	3	3
197	173	323.7393973	145.474205	9.61647271	3	3
198	174	248.613381	104.8116238	9.204556732	3	3
199	175	183.9180917	81.23463901	4.245206505	3	3
200	176	281.9069341	156.7250782	13.87979825	3	3
201	177	270.0440022	122.8905606	11.78532656	3	3
202	178	328.6894574	164.8576027	10.08866347	3	3
203						
204						
205	**Classification Matrix**					
206						
207	**Actual / Predicted**	**Group1**	**Group2**	**Group3**	**Total**	**% correct**
208	Group1	59	0	0	59	100.00%
209	Group2	0	71	0	71	100.00%
210	Group3	0	0	48	48	100.00%
211	Total	59	71	48	178	100.00%
212						
213						
214	**Test Sample Classification**					
215						
216		**Mahalanobis Distances**				
217	Observation	Group1	Group2	Group3	Predicted Group	
218	1	145.8261836	39.05392542	59.05212675	2	
219	2	117.5568625	16.2641242	32.35067511	2	
220	3	142.5374781	94.71085006	352.3338449	2	
221	4	116.1107413	89.81575438	874.5137168	2	
222	5	67.44314748	46.51901833	540.0325431	2	
223	6	171.5445072	59.64767007	150.6589595	2	

Getting Results: Optimization

Introduction

This chapter explains how to obtain and interpret results from optimization in Analytic Solver Comprehensive and its subset optimization products: Analytic Solver Optimization, Analytic Solver Upgrade and Analytic Solver Basic when using either Analytic Solver Desktop or Cloud. We'll also discuss **what can go wrong**, and what to do about it, and also **how to get more** than a single optimal solution from your model.

Analytic Solver Optimization has many powerful optimization algorithms, and will fully exploit the power of your PC. But the *model that you create* may be relatively easy to optimize (if you use linear functions like SUM) or extremely difficult to optimize (if you use non-convex and non-smooth functions like LOOKUP). The results you get depend on the model you create.

In the following sections, we'll focus on immediate actions you can take when you get an unexpected result – but if you read the chapter "Mastering Conventional Optimization Concepts," you'll learn more about optimization models and solution methods, and better understand *why* the unexpected result appeared, and how to design your model to get the solutions you want.

What Can Go Wrong, and What to Do About It

When you click the **Optimize** button on the Ribbon, or the **green arrow** on the Task Pane to solve, you'll normally get one of these outcomes:

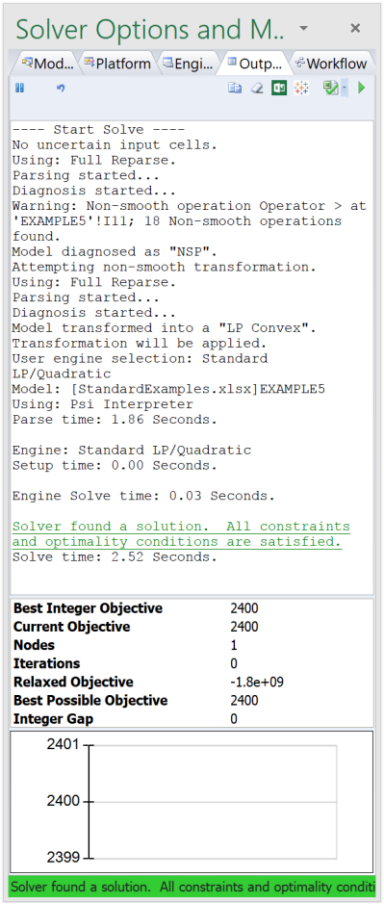
1. A solution that makes sense to you. This is normally accompanied by a Solver Result message in **green** at the bottom of the Task Pane. You can proceed to "When Things Go Right: Getting Further Results."
2. A Solver Result error message that you understand and can correct, in **red** at the bottom of the Task Pane. You can take corrective action.
3. A Solver Result error message that you *don't* understand, in **red** at the bottom of the Task Pane. You should **read the solution log** in the Output tab, **click the error message** and read Help about the message.
4. A *solution* that you *don't* understand, or that seems wrong. Again before doing anything else, you should **read the solution log** in the Output tab, **click the error message** to display Help, **run available reports** as described below, and **read the section** below "When the Solution Seems Wrong."
5. Solving runs for a very long time, and you don't get a solution or a Solver Result message until you press ESC or click Pause/Stop. You should **read the section** below "When Solving Takes a Long Time."

In rare cases, you might find Excel shutting down or "locking up" (so nothing happens when you click Pause on the Solver Task Pane). In this case please contact Frontline Systems Technical Support at (775) 831-0300 x4 or support@solver.com. Some Solver Result error messages ask you to contact Technical Support. If you can send us your model, this will be very helpful.

But experience shows that 99% of all technical support cases involve "pilot error" by the user, and that 90% of all such cases could be easily resolved by reading online Help or the User Guide. So we hope you'll keep reading, and that you'll take these steps before calling technical support!

Review Messages in the Output Tab

If using Analytic Solver Desktop, your first step should be to **review the messages** in the **solution log** in the Task Pane Output tab. Below is an example of the Output tab at the solution of EXAMPLE5 in **StandardExamples.xls** (described more fully in the chapter "Examples: Conventional Optimization"):



If you click the Copy icon, the contents of the solution log will be copied to the Windows Clipboard, where you can paste it into Microsoft Word, NotePad, or an **email message to Frontline Systems Technical Support**. Below is the complete solution log from the above example:

---- Start Solve ----
Using: Full Reparse.
Parsing started...
No uncertain input cells.
Diagnosis started...
Model diagnosed as "NSP".
Attempting Transformation.
Using: Full Reparse.
Parsing started...
Diagnosis started...

Model transformed into an LP. Transformation will be used.
User engine selection: Standard LP/Quadratic
Model: [OptimizationExamples.xls]EXAMPLE5
Using: Psi Interpreter
Parse time: 0.22 Seconds.

Engine: Standard LP/Quadratic
Setup time: 0.00 Seconds.

Engine Solve time: 0.20 Seconds.

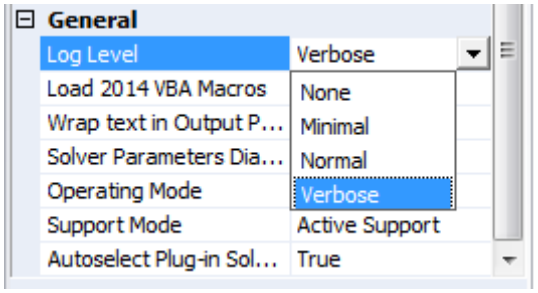
Solver found a solution. All constraints and optimality conditions are satisfied.
Solve time: 0.62 Seconds.

This was a *successful* solution – but in cases where you have a Solver Result *error message* that you don't understand, or a *solution* that you don't understand, the solution log can be quite helpful.

Note: Information related to the solving process in Analytic Solver Cloud is not available during parsing of the model. As a result, feedback is only available once the Solver Engine starts to solve the model.

More Detail in the Solution Log

You can obtain *more detailed* output in the solution log by setting the Task Pane Platform tab General group **Log Level** option to **Verbose** before you solve:



Below is a portion of the solution log (from the LP/Quadratic Solver) for the EXAMPLE5 model:

Integer solution of 3100 found by Feasibility Pump after 0 iterations and 0 nodes (0.01 seconds)
After 0 nodes, 1 on tree, 3100 best solution, best possible 2355.01 (0.18 seconds)
After 1 nodes, 2 on tree, 3100 best solution, best possible 2355.01 (0.18 seconds)
Integer solution of 2630 found by Unknown after 285 iterations and 2 nodes (0.19 seconds)
After 2 nodes, 2 on tree, 2630 best solution, best possible 2361.69 (0.19 seconds)
Integer solution of 2400 found after 294 iterations and 3 nodes (0.20 seconds)
After 3 nodes, 1 on tree, 2400 best solution, best possible 2361.69 (0.20 seconds)
Engine Solve time: 0.20 Seconds.

If you are having problems finding the solution you want or expect, this detailed log can sometimes be helpful.

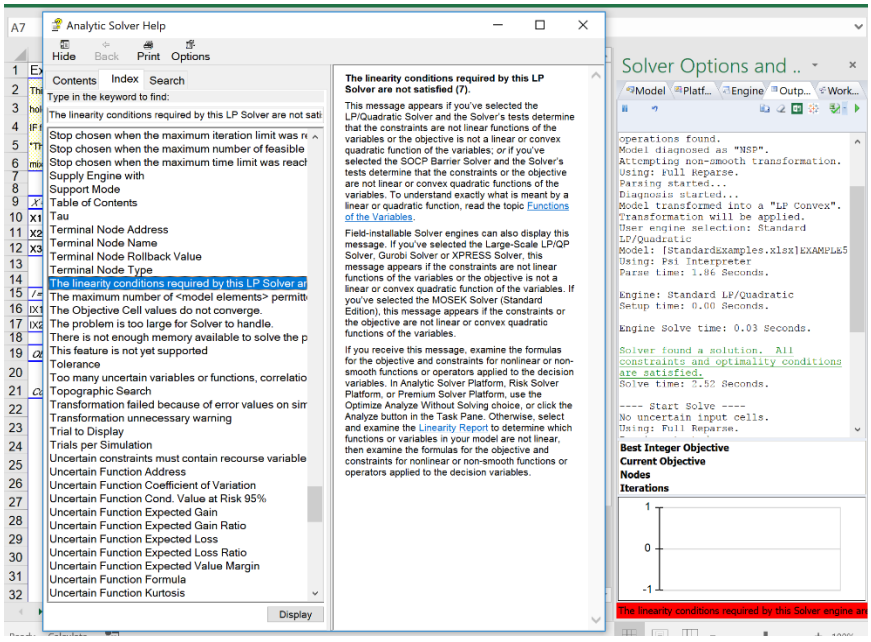
Note: This functionality is not supported in Analytic Solver Cloud.

Click the Solver Result Message for Help

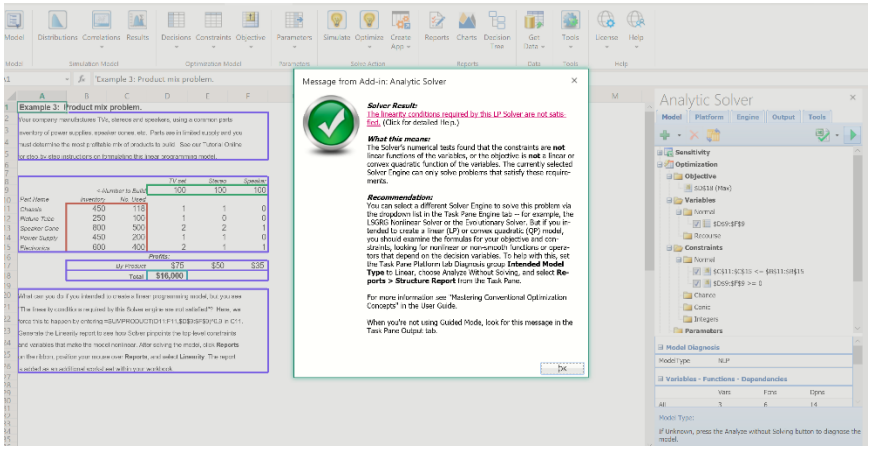
The Solver Result message is always **underlined** – it is a **hyperlink** to Help. If you aren't sure that you fully understand it, **click the link** to open online Help to a detailed discussion of the message.

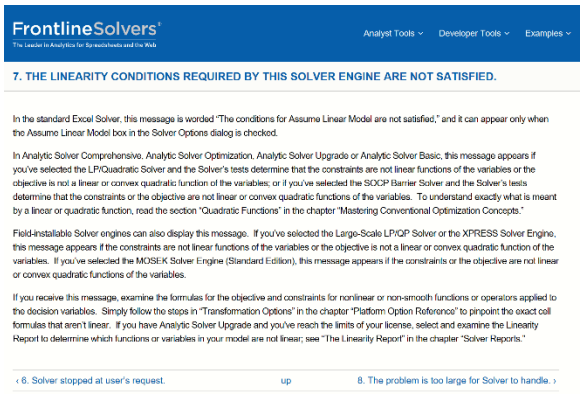
Below is an example of Help that appears in Analytic Solver Desktop when you solve EXAMPLE3 in **StandardExamples.xls**, and click on the Solver Result

error message in red, “The linearity conditions required by this Solver engine are not satisfied.” Notice the two hyperlinks in the Help text, to Functions of the Variables and the Linearity Report. If you click the latter link, the Help text below appears.



Below is an example of Help that appears in Analytic Solver Cloud when you solve the same example and then click the red hyperlink, "The linearity conditions required by this Solver engine are not satisfied."

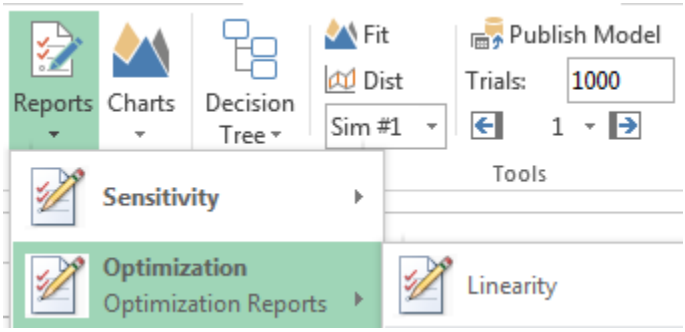




Given our experience that 90% of technical support cases could be easily resolved by **reading online Help** or the User Guide, you can save yourself, as well as Frontline Systems, time if you *do* read online Help first.

Choose Available Optimization Reports

The Help above suggests that we select the Linearity Report when we receive this Solver Result error message. As a general rule, it's good idea to **examine the available reports** and produce the reports that may help you understand what's wrong with your model. Just select **Reports – Optimization Reports** on the Ribbon – the reports in the gallery are updated each time you solve.



- The **Linearity Report** and the **Structure Report** can help when you encounter "The linearity conditions required by this Solver engine are not satisfied."
- The **Feasibility Report** and **Feasibility-Bound**s Report can help when you encounter "Solver could not find a feasible solution."
- The **Scaling Report** can help when you encounter either of these messages, or other unexpected messages or solution values. See the section below "Problems with Poorly Scaled Models."

See the section "An 'Accidentally' Nonlinear Model" in the chapter "Examples: Conventional Optimization" to see how the **Linearity Report**, and the **Structure Report** produced by the PSI Interpreter can help us pinpoint the nonlinear formulas in this model.

When Solving Takes a Long Time

When your model takes a long time to solve, the Task Pane Output tab can be helpful *during* the solution process – at a minimum, to reassure you that the

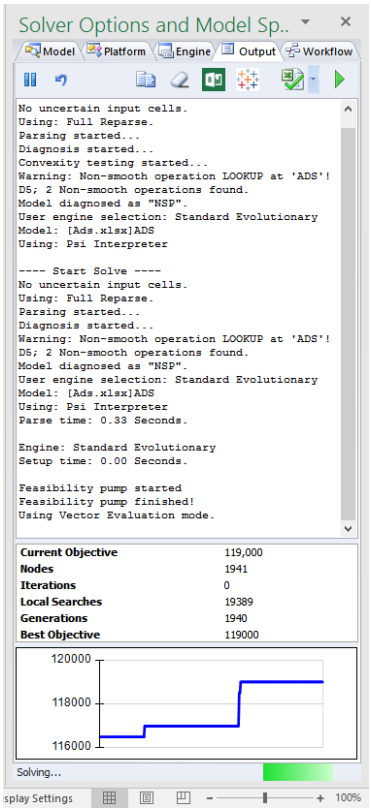
Solver is still making progress, and has not "hung up." If it is not already visible when you first start solving in Analytic Solver Desktop, the Output tab will **appear automatically** after a few seconds of solution time, as long as the Task Pane itself is visible.

The Output tab shows the objective of the best solution found so far, and for problems with integer constraints, the Best Integer Objective ("incumbent"), the Best Possible Objective ("best bound"), and the Integer Gap or percentage difference between these two objectives.

In Analytic Solver Cloud, the Task Pane Output tab will display a moving task pane to indicate the status of the model during the solution process.

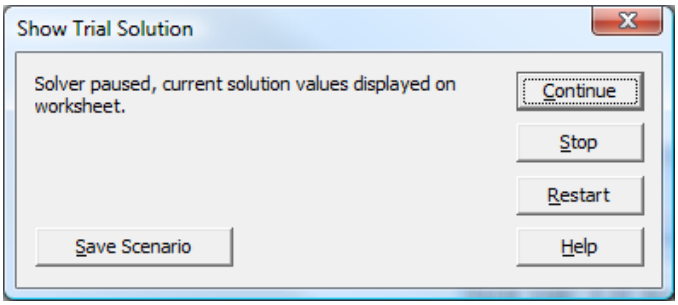
Running Chart of the Objective

The bottom part of the Output tab shows a running chart of the objective of the best solution found so far. On the next page is an example of the Output tab on a problem called **Ads.xlsx** that takes about 1 minutes to solve, with the Evolutionary Solver, on a modern 8 - core PC:



Interrupting the Solution Process

You can interrupt the solution process at any time, by **pressing the ESC key** in Analytic Solver Desktop, or by **clicking the** ⏸ **button** in either Desktop or Cloud, in the Task Pane Output tab. If your model is very large, you might have to hold down the ESC key for a second or two. Since the input focus may not be on the Task Pane when you click with the mouse, you might have to click the ⏸ button twice. A dialog like the one below will appear:



Click **Continue** if you want to continue solving; click **Stop** to cause the Solver to stop the solution process (this may take a few seconds) and display the message "Solver stopped at user's request." Clicking **Restart** may be useful with the Evolutionary Solver – see the Frontline Solvers Reference Guide.

Reasons Why Solving Takes a Long Time

There are several reasons why solving might take a long time:

1. Most often, you've used Excel formulas or functions that make your model non-smooth or non-convex, and much more difficult to solve. You might gain a lot from consulting assistance, or by reading the chapter "Mastering Conventional Optimization Concepts."
2. If **model diagnosis** or **problem setup** is slow (see timing messages in the Task Pane Output tab), you might be using array formulas, LOOKUP functions with large ranges as arguments, or long "chains" of formulas where each formula depends on an earlier formula.
3. You might be using a Solver Engine, or Engine option settings, that aren't appropriate for your problem. You can **check the box** "Automatically Select Engine" on the Task Pane Engine tab. **Click Engine options** to display Help on each option. You can gain further insight by reading "Optimization Problems and Solution Methods" in the chapter "Mastering Conventional Optimization Concepts."
4. Your model might be well formulated, but very large, or it might require non-smooth functions, or many integer variables. A more powerful plug-in Solver Engine may help considerably, and a faster processor, multi-core processor, or more memory can often help.

Adjusting Automatic Mode Options to Gain Speed

Be sure to read "Automatic Mode and Solution Time" in the chapter "Analytic Solver Overview." If you're using the **Automatic** setting (the ***default*** for new models) for any of the seven options described in this section, you can save time by pre-setting these options to the same values chosen automatically.

Model Design for Maximum Optimization Speed

Paying attention to your Excel worksheet layout and design, and avoiding certain practices, will help you get the most from the PSI Interpreter. Below is a brief list of Do's and Don'ts that will help you realize the best possible speed:

- **Do** build worksheets starting from the "upper left corner." **Don't** place cells or formulas at extreme row and column addresses all over the worksheet.

- **Do** build the model on a small number of worksheets. **Don't** include references on these worksheets to other worksheets that aren't required for the simulation model.
- **Do** use numeric and logical formulas and functions. **Don't** create string results in the middle of numeric calculations (see example below).
- **Do** use built-in Excel functions (including Analysis ToolPak functions) freely. **Don't** use third-party or user-written functions unless truly needed. Such functions must not have "side-effects" other than the value returned.
- **Do** use operators like + - * / ^ and functions like SUM, AVERAGE, MAX, MIN, AND, OR, NOT, IF, CHOOSE. **Don't** use INDIRECT, OFFSET, or TEXT, SEARCH, REPLACE, FIXED, DOLLAR, or ROMAN.
- If possible, **Don't** use array formulas, LOOKUP functions with large ranges as arguments, or long "chains" of formulas where each formula depends on an earlier formula (and hence on *all* earlier formulas). Each of these things can slow down analysis of your model considerably (by 10x in some cases).

A common practice that slows down the PSI Interpreter, and is easy to avoid, is illustrated by the following:

A1: =IF(B1>100,"Yes","No") and later A10: =IF(A1="Yes",A2,50)

You don't need "Yes" and "No" when Excel provides built-in values TRUE and FALSE. You could write =IF(B1>100,TRUE,FALSE), but this is simpler:

A1: =B1>100 and later A10: =IF(A1,A2,50)

The formula =B1>100 evaluates to either TRUE or FALSE. A1 holds this value and you can test it later in another formula.

When the Solution Seems Wrong

When the solution on the worksheet seems wrong, before doing anything else, you should **read the solution log** in the Output tab, **click the error message** to display Help, and **run available reports** as described above. We emphasize this, because very often when we are contacted in technical support, the user has not taken these basic steps.

Although software bugs are always possible, consider carefully the possibility that the solution found by the Solver is **correct for the model you've defined**, and that your expectation is wrong. This may mean that what your model actually says is different from what you intended. In the majority of cases we see in technical support, the user has an error in a formula or in the expression of a constraint that leads to the unexpected solution.

Problems with Poorly Scaled Models

Many unexpected Solver Result messages are due to a poorly scaled model. A *poorly scaled* model is one that computes values of the objective, constraints, or intermediate results that differ by several orders of magnitude. A classic example is a financial model that computes a dollar amount in millions or billions and a return or risk measure in fractions of a percent. Because of the finite precision of computer arithmetic, when these values of very different magnitudes (or others derived from them) are added, subtracted, or compared – in the user's model or in the Solver's own calculations – the result will be accurate to only a few significant digits. After many such steps, the Solver may detect or suffer from "numerical instability."

The effects of poor scaling in a large, complex optimization model can be among the most difficult problems to identify and resolve. It can cause Solver engines to return messages such as "Solver could not find a feasible solution," "Solver could not improve the current solution," or even "The linearity conditions required by this Solver engine are not satisfied," with results that are suboptimal or otherwise very different from your expectations. The effects may not be apparent to you, given the initial values of the variables, but when the Solver explores Trial Solutions with very large or small values for the variables, the effects will be greatly magnified.

Dealing with Poor Scaling

Most Solver engines include a **Use Automatic Scaling** option on the Task Pane Engine tab. When this option is set to True, the Solver rescales the values of the objective and constraint functions internally in order to minimize the effects of poor scaling. But this can only help with the Solver's own calculations – it can't help with poorly scaled results that arise *in the middle of your Excel formulas*.

The best way to avoid scaling problems is to carefully choose the "units" implicitly used in your model so that all computed results are within a few orders of magnitude of each other. For example, if you express dollar amounts in units of (say) millions, the actual numbers computed on your worksheet may range from perhaps 1 to 1,000.

If you're experiencing results that may be due to poor scaling, you can check your model for scaling problems that arise *in the middle of your Excel formulas* by selecting the Scaling Report after solving your model. If you're using Analytic Solver Upgrade, you'll have to go through each of your formulas and play "what-if" manually to identify such problems.

The Integer Tolerance Option

Users who solve problems with integer constraints using the standard Excel Solver occasionally report that "Solver claims it found an optimal solution, but I manually found an even better solution." What happens in such cases is that the Solver stops with the message "Solver found a solution" because it found a solution *within the range* of the true integer optimal solution *allowed by the Tolerance* option in the standard Solver's Options dialog. In similar cases, Analytic Solver displays a message "Solver found an integer solution within tolerance," to avoid confusion.

When you solve a problem with integer constraints, the solution process in almost all Solver engines is governed by the **Integer Tolerance** option on the Task Pane Engine tab. When this option value is non-zero – say 0.05, as in the standard Excel Solver – the Solver engine stops when it has found a solution satisfying the integer constraints whose objective is within 5% of the true integer optimal solution. Therefore, you may know of or be able to discover an integer solution that is better than the one found by the Solver.

To avoid this common problem, the *default* **Integer Tolerance** value in Analytic Solver Platform V9.0 and beyond is **0 or 0.001** (depending on the engine used) rather than 0.05. But this has an important consequence for solution time: The solution process for integer problems often finds a near-optimal solution (sometimes *the* optimal solution) relatively quickly, and then spends far more time exhaustively checking other possibilities to find (or verify that it has found) the very best integer solution.

To avoid this extra time, you can either set the Integer Tolerance to a non-zero value – say 0.025 or 0.05 – or you can watch the Task Pane Output tab during the solution process, which displays the current Integer Gap – the value against which the Integer Tolerance is compared. Here's an example from the solution of the EXAMPLE5 model shown earlier, where the Integer Gap was 1.6% just before the Solver "proved optimality" and reported the solution:

Best Integer Objective	2400
Current Objective	2400
Nodes	6
Iterations	0
Relaxed Objective	-5200
Best Possible Objective	2361.69
Integer Gap	0.0162228

You can make a real-time decision that the current solution is "good enough," and press ESC or click the Pause/Stop button, then click the Stop button in the Show Trial Solution dialog, to stop the Solver with the current solution.

When Things Go Right: Getting Further Results

When you *do* receive a solution that makes sense to you, and you have a Solver Result message in **green** at the bottom of the Task Pane, there are several ways you can get further results. We'll cover three possibilities:

1. **Obtaining dual values** from a linear or smooth nonlinear optimization problem.
2. **Obtaining multiple solutions** from an integer programming problem, or a global optimization problem.
3. Performing **multiple parameterized optimizations**, and capturing all the solutions in reports and charts.

Dual Values

When you formulate and solve a linear programming problem, or a smooth nonlinear optimization problem, the solution process also yields numbers, called *dual values*, for the decision variables and constraints that are "pressed to the limit" at the optimal solution. A dual value can tell you, for example, how much you could pay to acquire more units of a scarce resource that is fully utilized in the solution; it is sometimes called a *shadow price* or *marginal value*.

- The **dual value for a decision variable** is nonzero only when the variable's value is equal to its upper or lower bound at the optimal solution. This is called a *nonbasic* variable, and its value was driven to the bound during the optimization process. Moving the variable's value away from the bound will *worsen* the objective function's value; conversely, "loosening" the bound will *improve* the objective. The dual value measures the change in the objective function's value *per unit change* in the variable's value.
- The **dual value for a constraint** is nonzero only when the constraint is equal to its bound. This is called a *binding* constraint, and its value was driven to the bound during the optimization process. Moving the constraint left hand side's value away from the bound will *worsen* the objective function's value; conversely, "loosening" the bound will *improve* the objective. The dual value measures the change in the objective function's value *per unit change* in the constraint's bound.

In nonlinear optimization problems, the dual values are valid only at the *single point* of the optimal solution – if there is any curvature involved, the dual values begin to change as soon as you move away from the optimal solution. In linear programming problems, the dual values remain constant over a *range* of increases and decreases in the variables' objective coefficients and the constraints' right hand sides, respectively.

To obtain dual values in report form, simply select **Reports – Optimization – Sensitivity** from the Ribbon. An example Sensitivity Report appears below.

In Analytic Solver Desktop, you can also obtain dual values via the Analytic Solver Object-Oriented API, with simple references such as myProb.VarDecision.DualValue(i) or myProb.FcnConstraint.DualValue(i) in your VBA code. This is described in greater depth in the chapter "Automating Optimization in VBA."

On the next page is a Sensitivity Report for EXAMPLE1, the Product Mix model which is the first example in the chapter "Examples: Conventional Optimization." (Note: Number formatting has been expanded in cells E15 and E22 to show decimal values.) At the optimal solution, we use all 800 Speaker Cones and 600 Electronics units, but not all of the other components. We don't produce any Speakers – cell F9 is driven to its lower bound of 0. What do the dual values tell us about the two binding constraints, and the one "nonbasic" decision variable?

The dual value of 12.5 for Speaker Cones tells us that we could increase Total Profits by $12.50 for every additional Speaker Cone we can acquire, up to 100 more. Similarly, the dual value of 25 for Electronics units tells us we could use up to 50 more units and increase Total Profits by $25.00 for each extra unit.

The dual value of -2.5 for F9 tells us that, if we were forced to produce some Speakers, we would reduce Total Profits by $2.50 for each Speaker we made (because we'd give up production of another product that is more profitable).

Microsoft Excel 15.0 Sensitivity Report
Worksheet: [StandardExamples.xls]EXAMPLE1
Report Created: 5/14/2015 12:53:16 PM
Engine: Standard LP/Quadratic

Objective Cell (Max)

Cell	Name	Final Value
$D$18	Total Profits:	25000

Decision Variable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$D$9	Number to Build-> TV set	200	0	75	25.0000002	5.0000002
$E$9	Number to Build-> Stereo	200	0	50	25.0000001	12.5000001
$F$9	Number to Build-> Speaker	0	-2.5	35	2.5	1E+30

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$C$11	Chassis No. Used	400	0	450	1E+30	50
$C$12	Picture Tube No. Used	200	0	250	1E+30	50
$C$13	Speaker Cone No. Used	800	12.5	800	100	100
$C$14	Power Supply No. Used	400	0	450	1E+30	50
$C$15	Electronics No. Used	600	25	600	50	200

Multiple Solutions

When you solve an integer programming problem or a global optimization problem, the final solution you see on the Excel worksheet is typically the *best* of *several* candidate solutions that were found during the solution process. You can obtain and examine these other solutions; this can be useful, especially if you have other criteria, not captured in the formulation of the optimization model, for preferring one solution over another. For each candidate solution, you can examine the final values of the decision variables and the objective.

To obtain multiple solutions in report form, select **Reports – Optimization – Solutions** from the Ribbon.

- For **integer programming** problems, the report shows each 'incumbent' or feasible integer solution found by the Branch & Bound method during the solution process.
- For **global optimization** problems, the report shows each locally optimal solution found by the Multistart method.
- For **non-smooth optimization** problems solved with the Evolutionary Solver, the report shows key members of the final population of solutions.

For all types of problems, if only one candidate solution was found, the **Solutions choice will *not* appear** in the Reports – Optimization gallery. For example, advanced Solvers for integer programming problems may find optimal solutions at the root node of the Branch & Bound tree, without considering any other incumbent solutions. For integer programming problems solved with the LP/Quadratic or Large-Scale LP/QP Solver, the Engine tab Integer group PreProcessing option must be set to None in order to create a Solutions Report.

On the next page is an example of a Solutions Report created when the GRG Nonlinear Solver with Multistart was used to solve a model called SPACE2, a global optimization problem with many locally optimal solutions. (Given more time, the Solver would find an even better solution than the ones shown.)

Microsoft Excel 15.0 Solutions Report
Worksheet: [SPACE2.xlsx]SPACE
Report Created: 6/17/2014 3:08:27 PM
Result: Solver stopped at user's request. All constraints are satisfied.
Engine: Standard LSGRG Nonlinear
Number of Solutions: 464

Solutions:

Cell	Sol 1 (Obj = 0.745052)	Sol 2 (Obj = 1.54001)	Sol 3 (Obj = 2.18067)	Sol 4 (Obj = 2.18068)
$Q$4	0	0	0	0
$R$4	1	1.162078294	-4.140949271	-3.868312331
$Q$5	0.745051918	0	1.27364828	1.273951051
$R$5	-0.093539653	-3.672201275	-0.257571889	-0.256912259
$Q$6	0	1.540010025	0	0
$R$6	0.827136625	3.527571564	5.088091112	-6.28
$Q$7	0	0	0.907023763	0.906730628
$R$7	1.238990211	4.865344186	2.791229834	1.595919153
$Q$8	0	0	0	3.21002E-14
$R$8	1.166137728	-5.612806937	-6.110354592	5.616137672
$Q$9	0	0	0	0
$R$9	0.999682268	-4.141652944	2.160288458	3.143533378
$Q$10	0	0	0	0
$R$10	0.995379852	5.202512545	4.592909872	4.92518359
$Q$11	0	0	0	0
$R$11	1.000098558	1.413578737	-1.358593973	-5.950134205
$Q$12	0	0	0	0
$R$12	1.001361364	6.094590657	6.074434888	-3.758379802
$Q$13	0	0	0	0
$R$13	1.000809992	-0.751172593	1.891554759	1.72610483

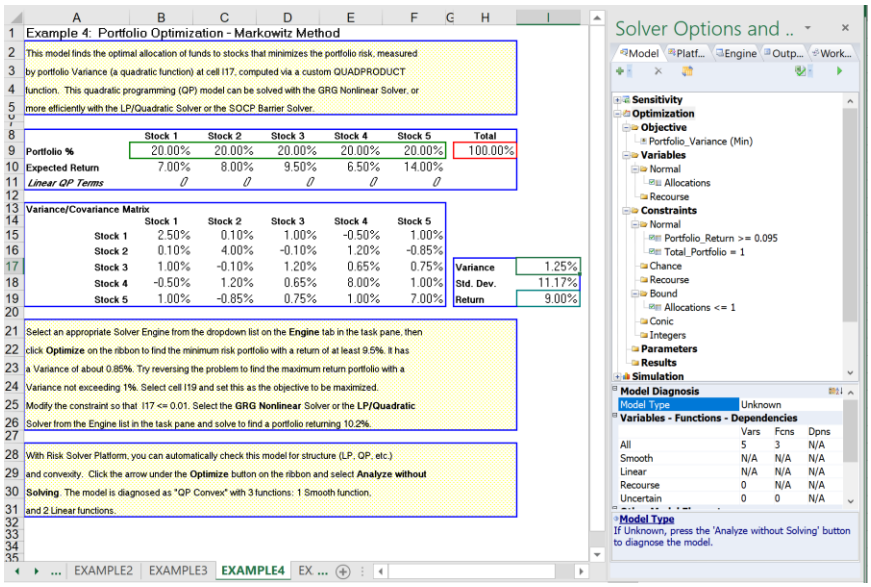
You can also obtain multiple solutions via the Analytic Solver Object-Oriented API, by accessing a property such as myProb.Solver.NumSolutions, setting the property myProb.Solver.SolutionIndex to choose a solution, then accessing the solution in the usual manner.

Multiple Parameterized Optimizations

Once you have a model where you're getting an optimal solution that makes sense for one set of inputs or parameters, it's often useful to vary one or more parameters across a range of values, and find the optimal solution for each individual parameter value. With Analytic Solver, you can easily define optimization parameters, run multiple optimizations and save the solutions to each optimization, and summarize the results in reports and charts.

The earlier chapter "Examples: Parameters and Sensitivity Analysis" gives an overview of the role of parameters for optimization, simulation, and sensitivity analysis, and the Frontline Solvers Reference Guide fully documents the features available for multiple parameterized optimization.

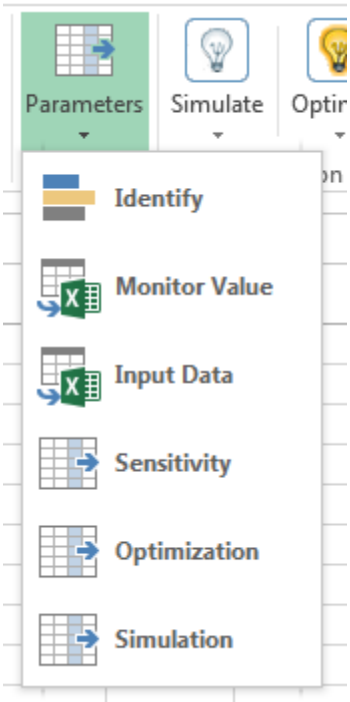
In this chapter, we'll illustrate what you can do with EXAMPLE4, the Markowitz portfolio optimization model in **StandardExamples.xls** described in the chapter "Examples: Conventional Optimization" under "Nonlinear Programming Examples." The model is pictured on the next page.



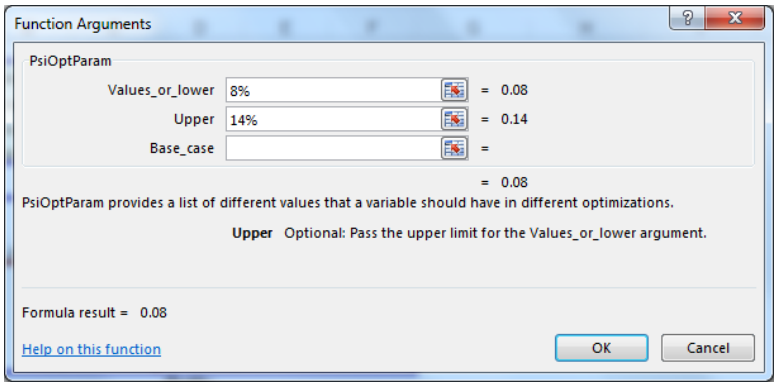
When we perform a single optimization with this model, we get an optimal allocation of funds to stocks that minimizes portfolio variance (a risk measure) while earning a portfolio rate of return of at least 9.5%, as shown in the Task Pane Model tab. This solution is a single point on the "efficient frontier;" we can find other points on this frontier by solving the problem for different levels of the required portfolio return.0

This is easy to do in Analytic Solver: We'll define a single optimization parameter, use it in the portfolio return constraint right hand side, and then run multiple (say 10) optimizations where the parameter is automatically varied from (say) 8% to 14%. Let's do this step by step.

To define an optimization parameter, select an empty cell – say **I20**, and choose **Parameters – Optimization** from the Ribbon, as shown below.

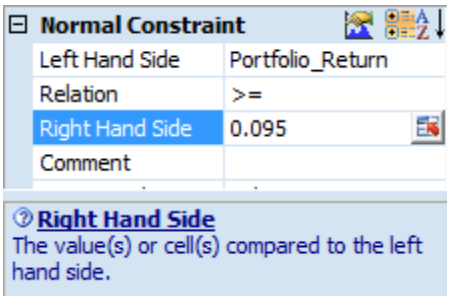


Analytic Solver displays a dialog where you can enter a lower and upper limit for the parameter value, or alternatively a list of values or a cell range:

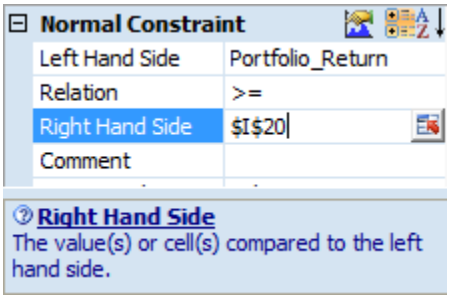


When you click OK, the formula **=PsiOptParam(0.08,0.14)** appears in cell I20.

Next, we'll use this parameter in the portfolio return constraint. To do this, we select the constraint 'Portfolio Return >= 0.095' in the Task Pane Model tab, and edit its properties in the lower part of the Task Pane.

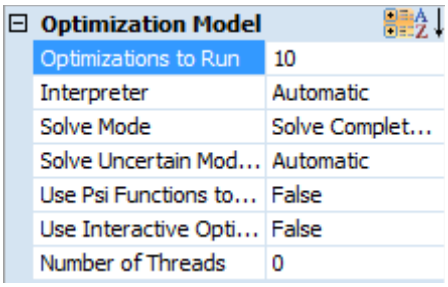


We click the cell selector icon to the right of the field containing 0.095, and then point and click to select cell I20. The properties of the constraint are updated to use cell I20 for the right hand side, as shown on the next page.



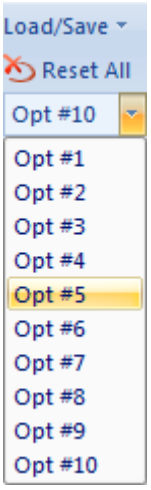
Note: Editing optimization parameters in the task pane is not supported in Analytic Solver Cloud. To change a constraint in the Cloud, simply double click the I19 >= 0.095 constraint in the task pane to open the Add Constraint dialog, then change 0.095 to I20.

Just one more step is required: We must specify how many optimizations we want to perform. On the Task Pane Platform tab, we set the very first option **Optimizations to Run** to 10, as shown on the next page.

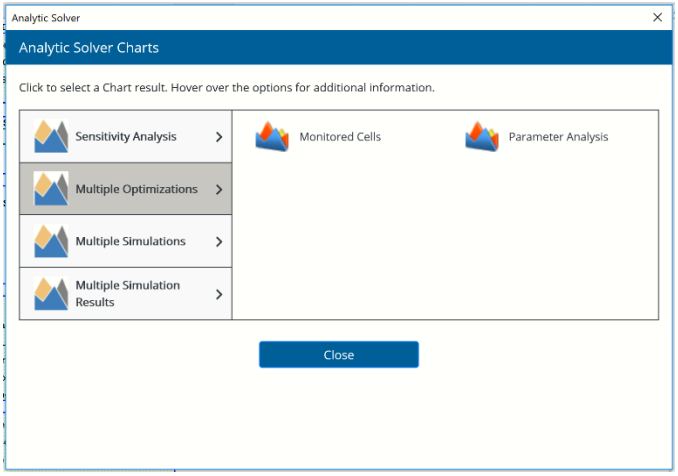


Now we simply click the **Optimize** button on the Ribbon, or the green right arrow on the Task Pane, to run all 10 optimizations. By default, Analytic Solver saves the optimal objective and decision variable values from all 10 optimizations; you can save other results, such as constraint values, by setting their Monitor property in the Task Pane to True.

Just after solving, Analytic Solver Optimization displays the results of the last optimization on the worksheet. But you can display the results of any of the other 9 optimizations by selecting from the **Opt # dropdown list** on the Ribbon:

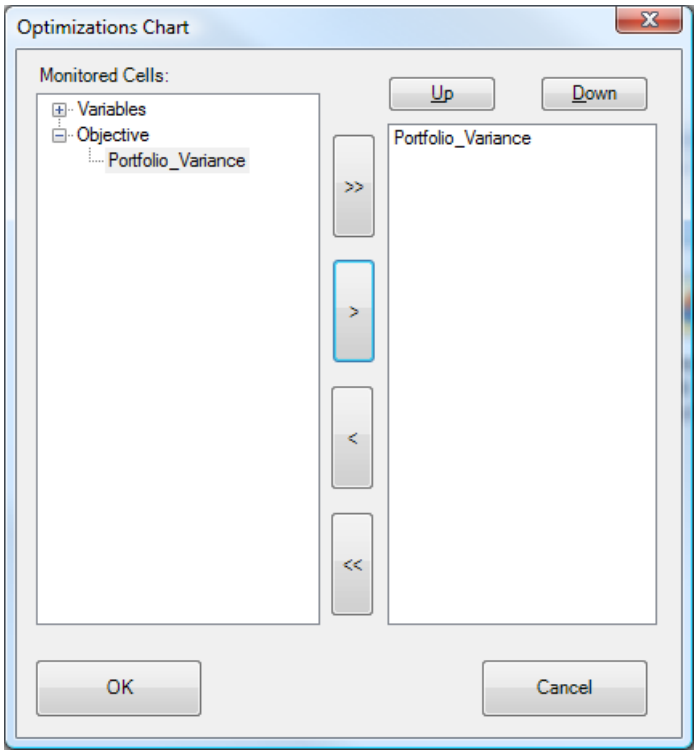


Analytic Solver has built-in facilities to create charts of multiple parameterized optimizations. Just select **Charts – Multiple Optimizations – Monitored Cells** from the Ribbon.

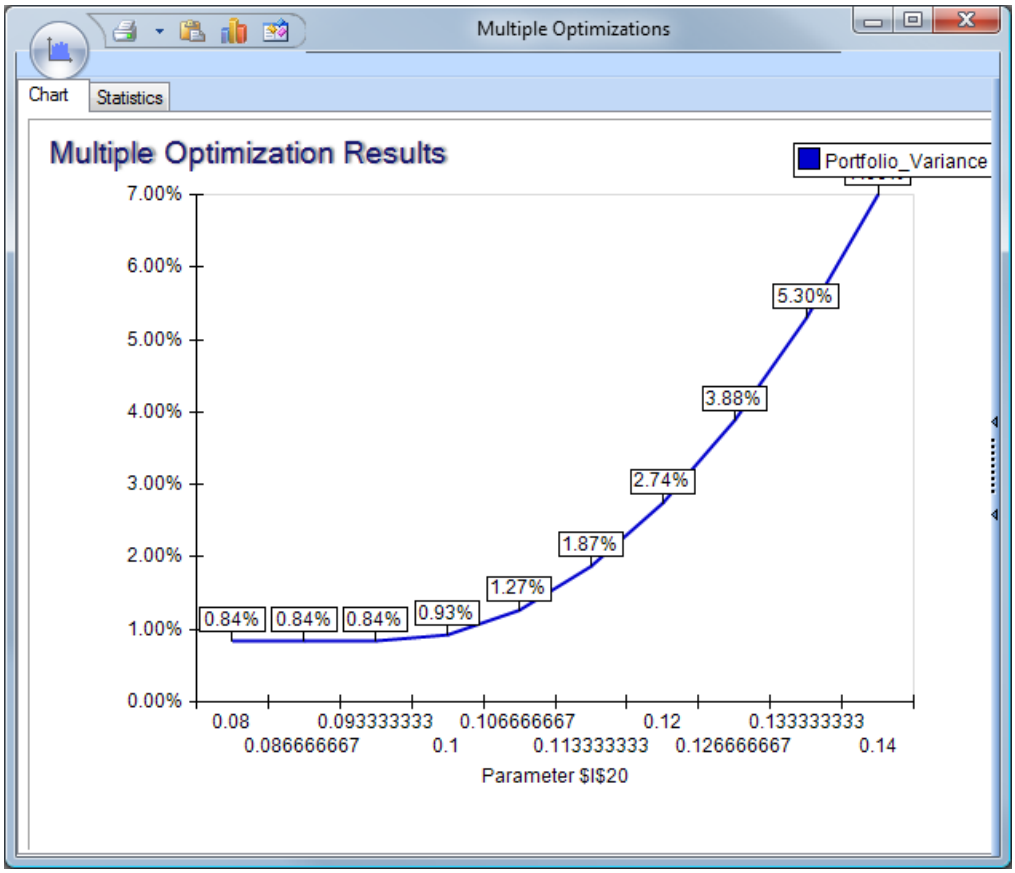


Select the optimization result you would like to chart: In this example, we want to plot the optimal objective (Portfolio Variance) across the 10

optimizations, where the Portfolio Return threshold is varied on each optimization.



When you click OK, Analytic Solver draws the chart, as shown below. That's a lot more useful results than a single optimal solution!


Multiple Optimizations
Chart
Statistics
Multiple Optimization Results
Portfolio_Variance
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
0.84%
0.84%
0.84%
0.93%
1.27%
1.87%
2.74%
3.88%
5.30%
0.08
0.086666667
0.093333333
0.1
0.106666667
0.113333333
0.12
0.126666667
0.133333333
0.14
Parameter $I$20

Getting Results: Simulation

Introduction

This chapter explains how to obtain and interpret results from simulation in Analytic Solver Comprehensive and its subset product Analytic Solver Simulation. We'll discuss **what can go wrong**, and what to do about it, and also **how to get maximum insight** from the results of a simulation.

Simulation is 'simpler' than optimization in the sense that it requires only (i) sampling of input values, (ii) calculation of your Excel model with these values, and (iii) collection of the results; no 'search for a best solution' is involved. A simulation can be performed on almost any model, using any Excel functions.

But the way you build your model does affect the *speed* of simulation, or the time required to get results. And the structure of your model will become even more important in the next chapter, when we consider optimization and models that include uncertainty.

In the following sections, we'll focus on immediate actions you can take when you get an unexpected result – but if you read the chapter "Mastering Simulation and Risk Analysis Concepts," you'll learn more about the Monte Carlo simulation process, and better understand how to design your model to get the best results in the least time.

What Can Go Wrong, and What to Do About It

When you click the **Simulate** button on the Ribbon, or the **green arrow** on the Task Pane to run a simulation, you'll normally get one of these outcomes:

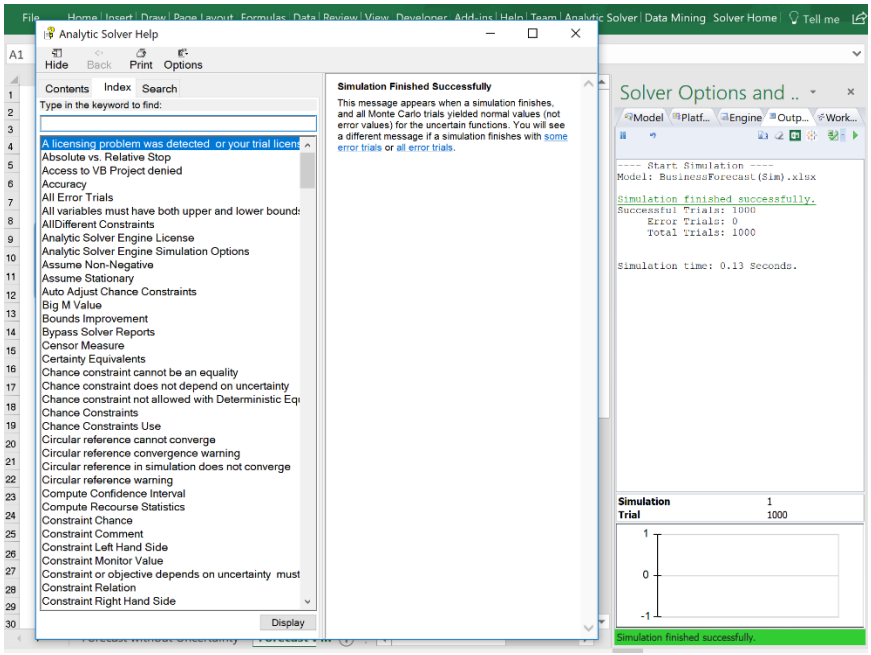
1. Results on the worksheet, and the message "Simulation finished successfully" in **green** at the bottom of the Task Pane. You can proceed to "When Things Go Right: Getting Further Results."
2. An error message that you understand and can correct, in **red** at the bottom of the Task Pane. You can take corrective action.
3. An error message that you *don't* understand, in **red** at the bottom of the Task Pane. You should **read the solution log** in the Output tab, **click the error message** and read Help about the message.
4. Results on the worksheet that you don't understand. Again, before doing anything else, you should **read the solution log** in the Output tab, **click the error message** to display Help, and **read the section** below "When Simulation Results Seem Wrong."
5. Simulation runs for a very long time, and you don't get results or a message in the Task Pane until you press ESC or click Pause/Stop. You should **read the section** "When Simulation Takes a Long Time."

In rare cases, you might find Excel shutting down or "locking up" (so nothing happens when you press and hold the ESC key for several seconds). In this case please contact Frontline Systems Technical Support at (775) 831-0300 x4 or support@solver.com. Some error messages ask you to contact Technical Support. If you can send us your model, this will be very helpful.

But experience shows that 99% of all technical support cases involve "pilot error" by the user, and that 90% of all such cases could be easily resolved by reading online Help or the User Guide. So we hope you'll keep reading, and that you'll take these steps before calling technical support!

Review Messages in the Output Tab

If using Analytic Solver Desktop, your first step should be to **review the messages** in the **solution log** in the Task Pane Output tab. Below is an example of the most common simulation error message, and Help that appears when you click the message:



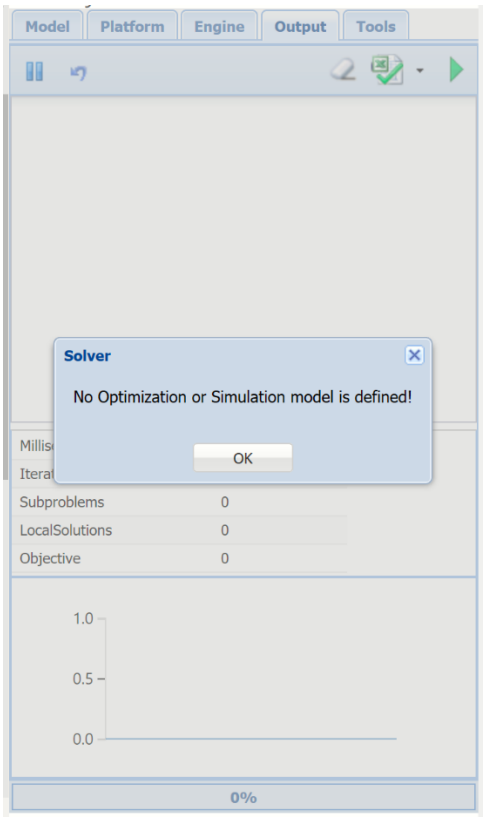
Note: Information related to the solving process in Analytic Solver Cloud is not available during parsing of the model. As a result, feedback is only available on the Output tab once the Solver Engine (for a simulation, Risk Solver Engine) starts to solve the model.

Click the Error Message for Help

Most simulation error messages are **underlined** – they are **hyperlinks** to online Help. If you aren't sure that you fully understand it, **click the link** to open Help to a detailed discussion of the message.

As the Help text explains in the example above, if your model doesn't define any simulation outputs, either via a PsiOutput() function that is added to the formula in an output cell or that refers to the output cell, or via a PSI Statistics function that refers to the output cell, there will be *no results* when you run a simulation. As corrective action, you simply need to define the formula cells for which you want results as simulation outputs.

Here is this same error in Analytic Solver Cloud.



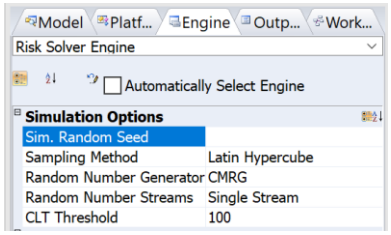
Hyperlinks are not supported in Analytic Solver Cloud.

Role of the Random Number Seed

The **seed**, or initial value, of the **random number generator** used in the simulation process determines whether your results are *exactly reproducible* when you re-run a simulation, or whether your results are *similar but not identical* because a different random sample was drawn.

By **default**, the seed for each simulation is set from the value of the system clock, which is **different** each time you run a simulation. If you set a seed value as explained below, the same seed value is used on each simulation, which means that the entire stream of random numbers drawn, and hence your simulation results, will be *exactly reproducible* on each simulation run.

To set the seed, use the Task Pane **Engine tab**. From the dropdown list at the top of the tab, select **Risk Solver Engine**, the software engine that actually performs a simulation. The options for Risk Solver Engine will be displayed:

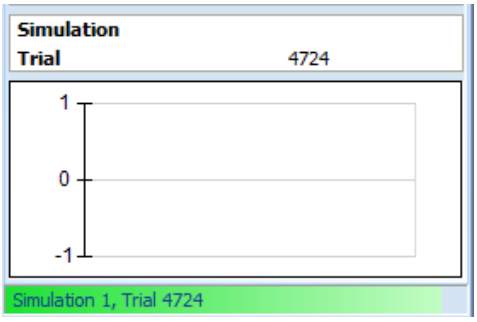


Enter a positive number for the option **Sim. Random Seed**. A value of 0 here means "use the value of the system clock as the seed on each simulation."

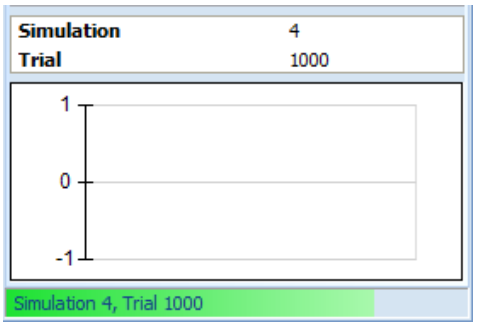
When Simulation Takes a Long Time

When a simulation takes a long time, or if you are running multiple parameterized simulations, the Task Pane Output tab shows you a progress indicator. If it is not already visible when you first start solving, the Output tab will **appear automatically** after a few seconds, as long as the Task Pane itself is visible.

If you are using Analytic Solver Desktop and have the Task Pane Platform tab Simulation group Interpreter option set to **Excel Interpreter**, the progress indicator will be updated during the Monte Carlo trials of a single simulation, as shown in the example below.

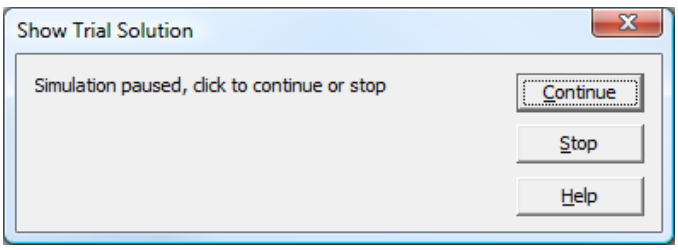


If you have the Interpreter option set to **Psi Interpreter**, the progress indicator usually ***won't*** be updated during the trials of a single simulation, because all of these trials are being executed in parallel. If you are running a multiple parameterized simulation, the progress indicator will be updated for each new simulation, as shown in the example below.



Interrupting the Simulation Process

You can interrupt the simulation process at any time, by **pressing the ESC key** in Analytic Solver Desktop, or by **clicking the** ⏸ **button** in the Task Pane Output tab in either app. If your model is very large, you might have to hold down the ESC key for a second or two. Since the input focus may not be on the Task Pane when you click with the mouse, you might have to click the ⏸ button twice. A dialog like the one below will appear:



Click **Stop** to stop the simulation or **Continue** if you want to continue.

Reasons Why Simulation Takes a Long Time

Analytic Solver Simulation is by far the fastest Monte Carlo simulation software for Excel on the market, and it takes full advantage of multi-core processors for even faster simulations. But it's still possible to create a model where a simulation takes a long time. There are several reasons for this:

1. If you have the Platform tab Simulation group Interpreter option set to **Excel Interpreter** in Analytic Solver Desktop, Excel is used to recalculate the worksheet on each Monte Carlo trial. This is usually an order of magnitude slower than the PSI Interpreter, though it requires significantly less memory. This functionality is not supported in Analytic Solver Cloud.
2. If you have Platform tab Simulation group Interpreter option set to **Psi Interpreter** (this is always the case in Analytic Solver Cloud), and the simulation is slow, you may be using certain Excel functions in ways that slow down the PSI Interpreter. See below for Do's and Don'ts to get the most from the PSI Interpreter.
3. Your model may simply be **very large**, with many complex formulas, references to other worksheets or workbooks, etc. that take a long time to evaluate. If your workbook includes sizable elements that aren't **essential to the simulation model** and its results, these extra elements may be slowing down the simulation process.

Time Versus Memory Tradeoffs in Analytic Solver Desktop

The PSI Interpreter is designed to take maximum advantage of available memory, and trade off memory against time. When Excel interprets =A1+A2*(A3-4), it uses memory for only four numbers – the values of A1, A2, A3 and the constant 4. But when PSI interprets this formula, it uses memory for 3,001 numbers – 1,000 each for A1, A2 and A3. If your PC has plenty of memory, PSI will help you take advantage of it. But if you are tight on memory, you may find that simulations slow down, because Windows will use 'virtual memory' and swap your data between main memory and your hard disk. You can add more memory -- DRAM chips for PCs and notebooks are an amazing value today. However, the best solution is simply to run your simulation model using Analytic Solver Cloud! Since the Cloud app runs on Microsoft's Azure App Service, memory is not an issue in the cloud!

Model Design for Maximum Simulation Speed

Paying attention to your Excel worksheet layout and design, and avoiding certain practices, will help you get the most from the PSI Interpreter. Below is a brief list of Do's and Don'ts that will help you realize the best possible speed:

- **Do** build worksheets starting from the "upper left corner." **Don't** place cells or formulas at extreme row and column addresses all over the worksheet.
- **Do** build the model on a small number of worksheets. **Don't** include references on these worksheets to other worksheets that aren't required for the simulation model.
- **Do** use numeric and logical formulas and functions. **Don't** create string results in the middle of numeric calculations (see example below).

- **Do** use built-in Excel functions (including Analysis ToolPak functions) freely. **Don't** use third-party or user-written functions unless truly needed. Such functions must not have "side-effects" other than the value returned.
- **Do** use operators like + - * / ^ and functions like SUM, AVERAGE, MAX, MIN, AND, OR, NOT, IF, CHOOSE. **Don't** use INDIRECT, OFFSET, or TEXT, SEARCH, REPLACE, FIXED, DOLLAR, or ROMAN.
- If possible, **Don't** use array formulas, LOOKUP functions with large ranges as arguments, or long "chains" of formulas where each formula depends on an earlier formula (and hence on *all* earlier formulas). Each of these things can slow down analysis of your model considerably (by 10x in some cases).

A common practice that slows down the PSI Interpreter, and is easy to avoid, is illustrated by the following:

A1: =IF(B1>100,"Yes","No") and later A10: =IF(A1="Yes",A2,50)

You don't need "Yes" and "No" when Excel provides built-in values TRUE and FALSE. You could write =IF(B1>100,TRUE,FALSE), but this is simpler:

A1: =B1>100 and later A10: =IF(A1,A2,50)

The formula =B1>100 evaluates to either TRUE or FALSE. A1 holds this value and you can test it later in another formula.

When Simulation Results Seem Wrong

When the simulation results seem wrong, before doing anything else, you should **read any messages** in the Output tab, and **click the message** to display Help as described above. We emphasize this, because very often when we are contacted in technical support, the user has not taken these basic steps. As *next* steps:

1. Make sure you understand how your formulas behave in an ordinary **Excel recalculation**. If you've "raced ahead" with a simulation model before doing this and you are using Analytic Solver Desktop, you can use the **Publish** button on the Ribbon to turn your simulation model back into a "what-if" model (by moving all PSI function calls into cell comments), and later click **Publish -- Unpublish** to restore the PSI functions that make up your simulation model.
2. Bear in mind that an uncertain function cell normally displays the calculated value for the **last** Monte Carlo trial of the **last** simulation run. It's usually more meaningful to look at the results returned by PSI Statistics functions, such as PsiMean() or PsiPercentile(), across all the trials of the simulation.
3. It can be very helpful to **cycle through the Monte Carlo trials** of a simulation, and examine the values of uncertain function cells, as well as intermediate formula cells on which they depend. Just use the **left and right arrows** on the Analytic Solver Desktop Ribbon or the up and down arrows on the Tools tab of the Solver task pane in Analytic Solver Cloud to change the **trial index**. You may find that your model calculates a result you did not expect for some values of the uncertain variables.
4. If you are using multiple simulations, check that the **Sim # index** on the Ribbon in Analytic Solver Desktop or on the Tools tab of the Solver task pane in Analytic Solver Cloud, or the **Sim # dropdown** in the Uncertain Function dialog title bar, are selecting the simulation you want, and that parameters (PsiSimParam() functions) are returning the values you expect for that simulation.

5. If you haven't already done so, double-click uncertain function cells and examine the **Frequency tab** chart and **Percentiles tab** numbers to see how the values of this function were distributed across Monte Carlo trials in the simulation. This will help explain the values of PSI Statistics functions.

Although software bugs are always possible, consider carefully the possibility that the simulation results are **correct for the model you've defined**, and that your expectation is wrong. We sometimes find in technical support that what your model actually says is different from what you intended.

When Things Go Right: Getting Further Results

When you have simulation results on the worksheet that make sense to you, and you have the message "Simulation finished successfully" in **green** at the bottom of the Task Pane, there are several ways you can get further results. We'll cover five possibilities:

1. **Documenting your results** in a Simulation Report.
2. **Using all the features** of the Uncertain Function dialog.
3. **Fitting an analytic distribution** to uncertain function results.
4. **Charting multiple uncertain functions**, typically over time.
5. Performing **multiple parameterized simulations**, and capturing the results on the worksheet or in charts.

Using the Simulation Report

One quick step you can take, when you have simulation results that you want to recall later, is to select **Reports – Simulation – Simulation** to produce a report worksheet, inserted into your workbook, like the one for the example model **BusinessForecastPsi.xls**, shown on the next page.

Microsoft Excel14.0 Simulation Report
Simulation Report [BusinessForecastPsi.xls]BusinessForecast
Report Created: 4/29/2014 2:03:41 PM
Simulation time: 0.031 seconds.

General Simulation Information

Simulation Options	Value
Simulations Run	1
Trials per Simulation	1000
Number of Error Trials	0
Current Simulation	1
Random Number Generator	CMRG
Sampling Method	Latin Hypercube
Random Number Stream	Single Stream
Simulation Seed	0
Interpreter Used	Automatic
Correlations Used	Yes

Model Information	Quantity
Uncertain Variables	2
Uncertain Functions	1
Correlated Variables	0

Global Bounds	Measure	Value
Lower Cutoff	None	-1E+30
Upper Cutoff	None	1E+30
Lower Censor	None	-1E+30
Upper Censor	None	1E+30

Uncertain Variable Summary Information

Cell	Name	Distribution	Mean	Std Dev	Minimum	Maximum	25th Percentile	50th Percentile	75th Percentile
$B$6	Unit cost	PsiTriangular(E11,E12,E13,PsiBaseCase(6.5))	6.5	0.40824829	5.5	7.5	6.207106781	6.5	6.792893219
$B$9		PsiIntUniform(1,3)	2	0.816496581	1	3	1	2	3

Uncertain Function Summary Information

Cell	Name	Formula	Mean	Std Dev	Minimum	Maximum	25th Percentile	50th Percentile	75th Percentile
$B$11	Net Profit	B4*(B5-B6)-B7	92354.41263	56534.64646	-61041.17952	210530.3128	58394.46491	102062.3714	132813.6987

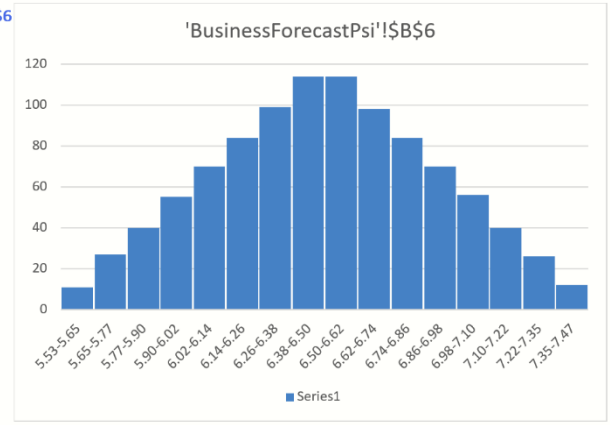
The Simulation Report in Analytic Solver Desktop documents the option settings used to perform the simulation and provides summary information about the uncertain variables and uncertain functions in your simulation model. You are much more likely to use simulation charts, or snapshots of your own worksheet layout when you are presenting reports to others, but this report can be quite useful when you want to refer later to the assumptions behind a simulation analysis.

This report has been completely redesigned in Analytic Solver Cloud. Select **Reports – Simulation – Simulation Report** to produce a report worksheet, inserted into your Excel Online or Desktop Excel workbook, like the one for the example model **BusinessForecast.xlsx**, as shown on the next page.

Data	
Status	Solver has completed the simulation.
Time	3/7/2019 2:02:13 PM
Number of Inputs	2
Number of Outputs	2
Number of Simulations	1
Number of Trials	1000
Executed Simulation	All

Inputs:

Cell:'BusinessForecastPsi'!$B$6



In Analytic Solver Cloud, this report displays the number of input and output functions in the simulation model, the number of simulations and the number of trials. The body of the report contains the distribution of values for all uncertain variables and functions along with the cell address, the mean, the standard deviation, the 5th and 95th percentiles of each.

Using the Uncertain Function Dialog

The Uncertain Function dialog has many features, described in the Frontline Solvers Reference Guide, that you can use to get enhanced results from your simulation. For an introduction to these features, refer back to "A First Simulation Example" in the chapter "Simulation and Risk Analysis," especially the sections starting with "Viewing the Full Range of Profit Outcomes." Here, we'll just reiterate the results available at your fingertips in the Uncertain Function dialog:

Dialog Tabs

- The **Frequency**, **Cumulative Frequency**, and **Reverse Cumulative Frequency** tabs provide three different views of the full range of outcomes

for an uncertain function. In Analytic Solver Desktop, you can click to display "crosshairs" with numerical values on these charts or add Lower and Upper bounds to see the estimated probability of a profit or loss.

- The Tornado chart on the **Sensitivity** tab quickly shows you which uncertain variables have the **greatest impact** on this uncertain function, across the full range of Monte Carlo trials. The **Scatter Plots** tab often reveals further insights about the behavior of this uncertain function versus each uncertain variable, or versus other uncertain functions.

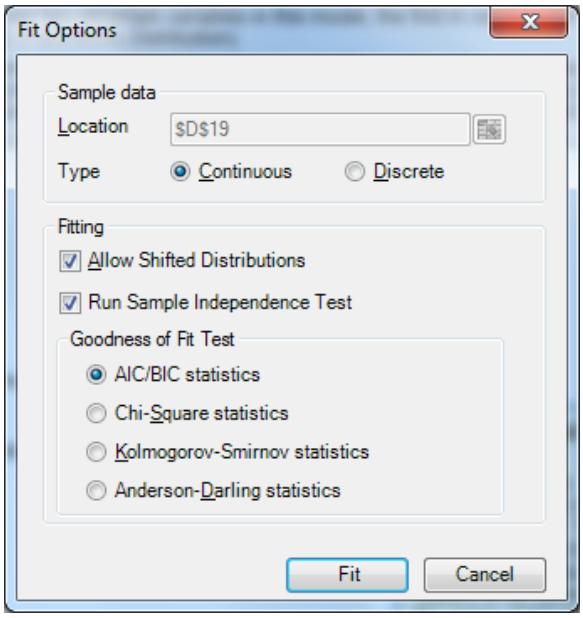
Panels and Toolbars

- Using the **right panel** of the dialog, you can access a drop down menu including **Statistics**, **Percentiles**, **Chart Type**, **Chart Options (Analytic Solver Desktop)**, **Axis Options (Analytic Solver Desktop)**, and **Markers (Analytic Solver Desktop)**. From the **Options dialog** (accessible from the Options button on the Analytic Solver Desktop Ribbon), on the **Charts** and **Markers** tabs, you can set default chart and marker settings for all of your charts.
- Using the **title toolbar icons** in Analytic Solver Desktop, you can save your settings, **print** the charts or numbers from any of the dialog tabs, or **copy** the charts or numbers to the Windows Clipboard, where they can be pasted into other applications. You can also **fit a distribution** (as shown below) to the simulation results or upload the simulation results to Microsoft's Power BI application or Tableau. (See the previous chapter, *Examples: Simulation and Risk Analysis*, for instructions on exporting model results to Power BI and Tableau.)
- Click the rightmost icon on the title toolbar in Analytic Solver Desktop to display the **3-D toolbar** that lets you – with a single click – shift between 2-D and 3-D, **shrink** or **magnify** the chart, or **move** or **rotate** the chart to a different perspective.

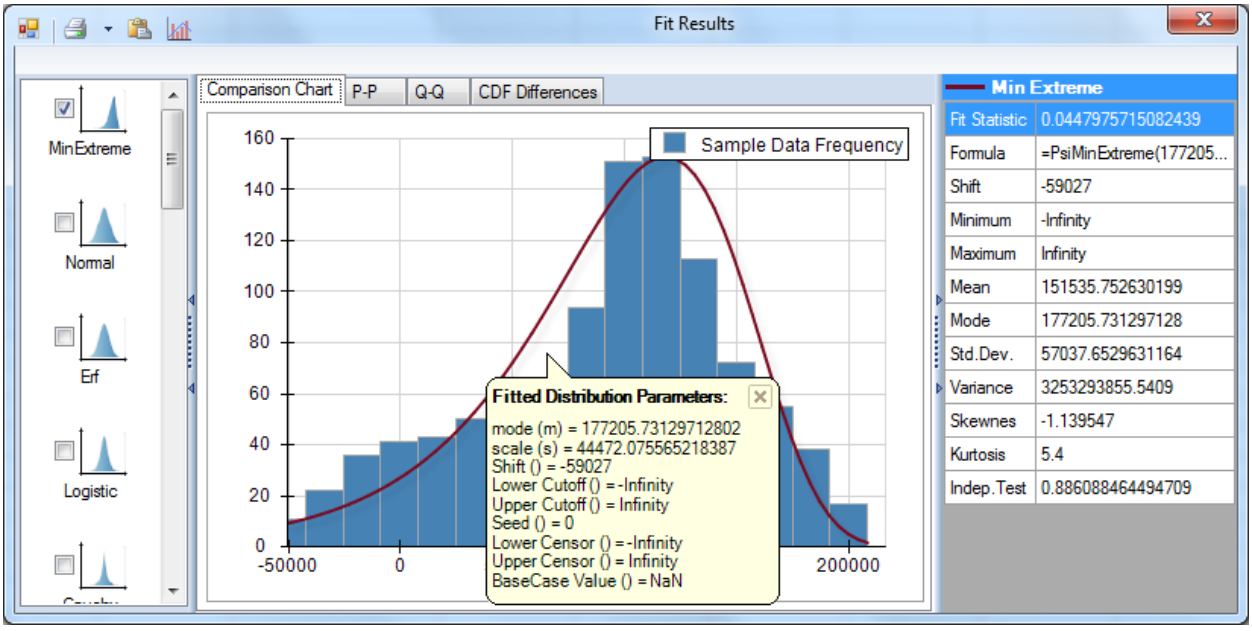
Fitting a Distribution to Simulation Results

One way to analyze your simulation results is to see whether the distribution of outcomes is similar to a well-known analytic distribution. Frontline Solver's Analytic Solver supports a wide range of analytic distributions, and can fit a distribution and its parameters to sample data. To fit your sample simulation results, click the icon on the Uncertain Function dialog title toolbar in Analytic Solver Desktop or click Tools – Fit on the Analytic Solver Cloud ribbon.

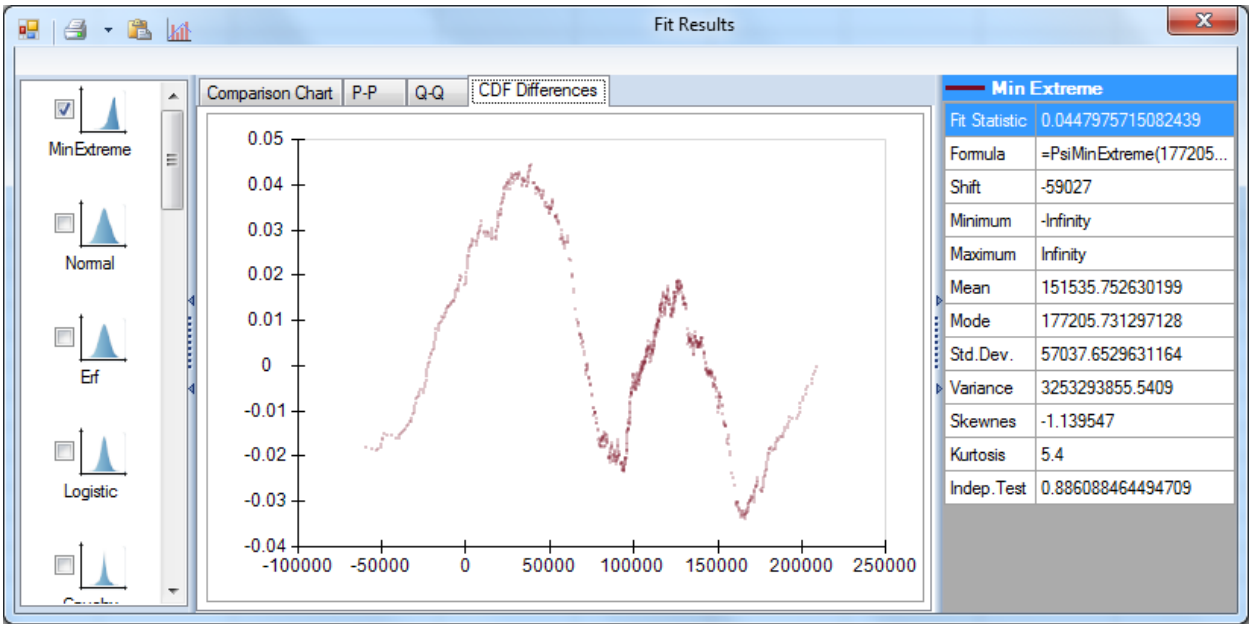
Click cell B11 on the BusinessForecastPsi tab within BusinessForecast.xlsx. When the Fit icon on the Analytic Solver Desktop Ribbon is clicked or Tools – Fit on the Analytic Solver Cloud ribbon, the **Fit Options** dialog appears.



If we accept the default settings and click the **Fit** button, in a few seconds, Analytic Solver fits a wide range of distributions to the sample data, ranks them in order of the selected goodness-of-fit criterion (AIC/BIC statistics by default, for more information see the Frontline Solvers Reference Guide), and displays the best-fitting distribution.



If you select the checkboxes adjacent to the additional distributions in the left panel, they will be superimposed on the frequency chart in the middle of the dialog. Other tabs of this dialog give you a visual picture of the fit, in the form of P-P and Q-Q charts, and a chart of CDF Differences, shown below.



The P-P tab displays the Probability-Probability chart. This graph is used to determine how well a specific distribution fits the observed data. This chart will be approximately linear (or lie on the y = x line) if the specified distribution is the correct choice.

Click the Q-Q tab to see the Quantile – Quantile chart. Again, if the two distributions being compared are a good fit, the plot will lie approximately on the y = x line.

The Cumulative Distribution Function Differences chart quantifies the difference between the empirical distribution function and the cumulative distribution function of the distribution.

You can also fit an analytic distribution to data that you obtain from another source, such as historical observations of the process you want to model. If you have this sample data on your Excel worksheet, you can simply select the cell range containing the data and click the **Fit** icon on the Analytic Solver Desktop Ribbon or Tools – Fit on the Analytic Solver Cloud ribbon. Using this tool, you can easily create an **uncertain variable** whose distribution models this data.

Note: When using Analytic Solver Cloud or AnalyticSolver.com, fitting a PsiMetalog function is supported only when using the PsiMetalogFit() function.

Fitting a Meta-Log Distribution

A meta-log distribution is an alternative distribution to a fitted distribution. The metalog distributions are a collection of continuous univariate probability distributions which can be used when cumulative distribution function data is available. For more information on this distribution, see the descriptions for PsiMetalog() in the Continuous Analytic Distribution subsection within the "Psi Function Reference" chapter that appears in the *Frontline Solvers Reference Guide*.

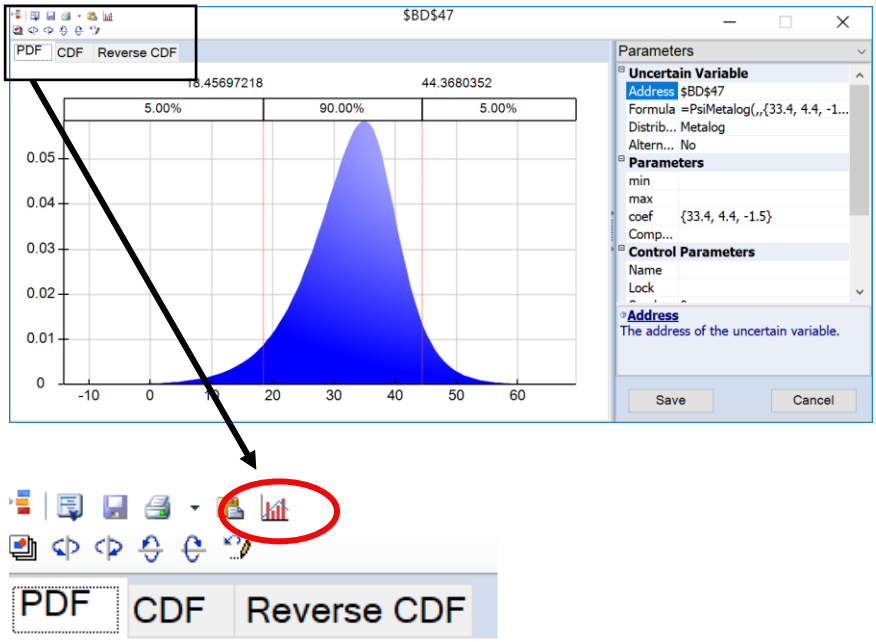
A general meta-log distribution is defined in a simulation model by using the Psi distribution, PsiMetalog(). This function has as arguments a vector of coefficients (coefficients) and optionally lower (min) and upper (max) bounds. The metalog distribution family is ***designed*** to be determined from historical

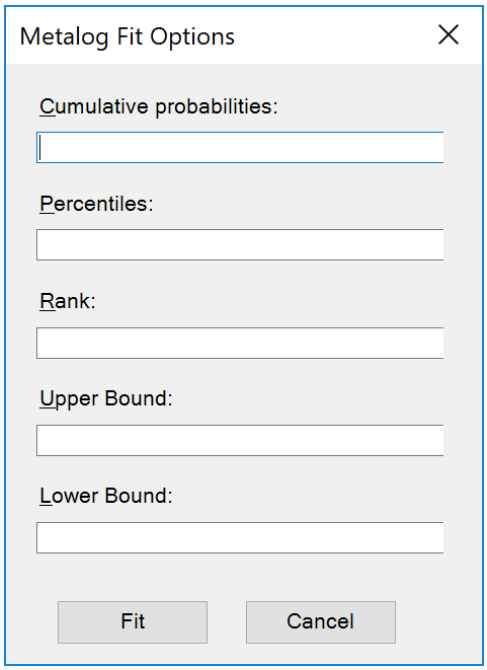
data, without requiring a distribution fitting process. They are computed from a set of historical data pairs {y, x}, where y is a cumulative probability and x is the corresponding percentile. The coefficients argument is either a range or an array of 2 to 10 numerical elements.

Fitting the PsiMetalog() function in Analytic Solver Desktop may be performed in two ways, by using the Psi function PsiMetalogFit() or by using the Metalog Fit Options dialog. Currently, this function may be used in Analytic Solver Cloud only by using the Psi function PsiMetalogFit().

To open this dialog on Analytic Solver Desktop, click on a blank Excel cell, then click the Fit Distribution icon on the PsiMetalog() uncertain variable dialog.

Note: In Analytic Solver Cloud, the PsiMetalogFit return a Dynamic Array. To use this function in the Cloud, you need only enter the Psi function in one cell as a normal function, i.e., not as a control array. The contents of the Dynamic Array will "spill" down the column. If a nonblank cell is "blocking" the contents of the Dynamic Array, PsiMetalogFit will return #SPILL until such time as the blockage is removed. When used in the Cloud apps, the first argument, *numCoef*, is a scalar, the number of coefficients to produce.





Argument Descriptions

- Cumulative Probabilities - Excel range containing the historical cumulative probabilities (y values)
- Percentiles – Select the Excel range containing the percentile values (x values)
- Rank – If omitted, the rank is equal to 3. The value entered for Rank must be greater than or equal to 2 and less than or equal to 10. In

addition, this value should be less or equal to the number of historical pairs given in the Cumulative probability and Percentiles arguments.

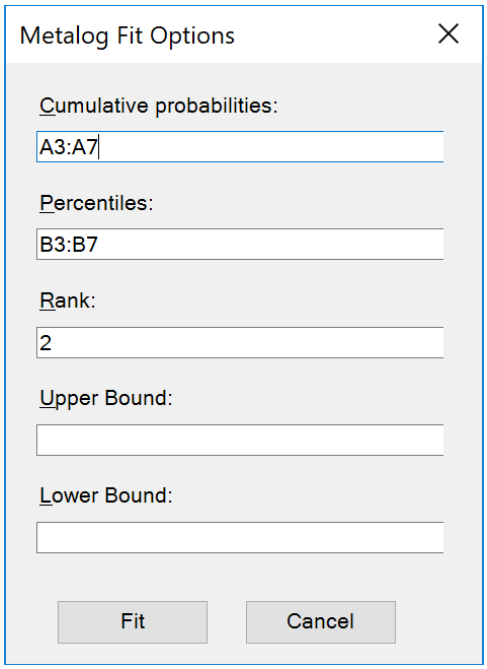
- Upper Bound – The function may be limited on the right by the upper bound. If omitted, positive infinity is used for the upper bound.
- Lower Bound – The function may be limited on the left by the lower bound. If omitted, negative infinity isused for the lower bound.

Click Fit in Analytic Solver Desktop to fit the Meta-log distribution. (Click Cancel to close the dialog without performing the distribution fitting.) Analytic Solver replaces the distribution currently in the Uncertain Variable dialog with the PsiMetalog() distribution parameters. If you click the Save button or close the dialog by clicking the "X" in the upper right hand corner in the title bar of this dialog, the PSIMetalog() distribution function with the fitted parameters is written to the current cell.

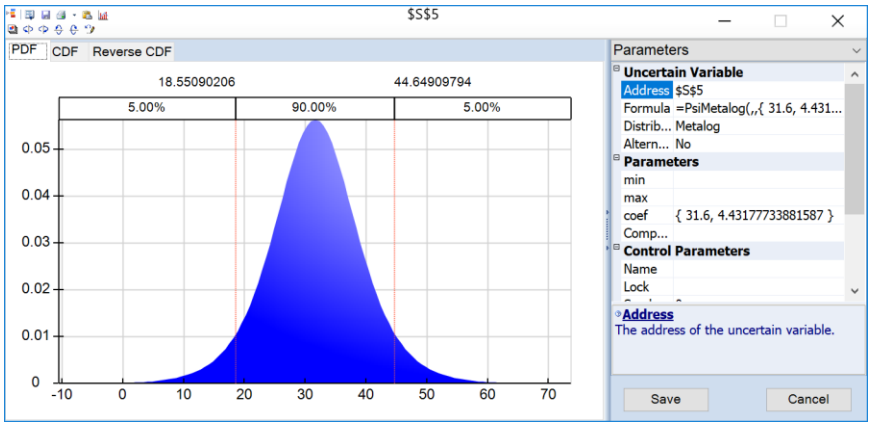
For example, given the following input parameters.

	A	B
1	input parameters	
2	**y**	**x**
3	0.010	10.0
4	0.100	22.0
5	0.500	33.0
6	0.900	43.0
7	0.990	50.0

The arguments in the Metalog Fit Options dialog would be as follows. Note that since the Upper and Lower Bound fields are empty, the fitted distribution will be unbounded. Distributions may be bounded on both sides, semi-bounded (bounded on one side) or unbouded. Note: Rank is equal to 2 which falls between the rank argument lower bound, which is equal to 2, and the number of historical pairs passed for Cumulative probability and Percentiles, 5.



After clicking Fit, the uncertain variable dialog changes to the following.



Click Save to close the uncertain variable dialog and save the fitted parameters to the Excel cell. To inspect the coefficients obtained by the fitting, see the resultant PsiMetalog() function that was saved to this cell. In this example, the coefficients obtained were 31.6 and 4.431777.

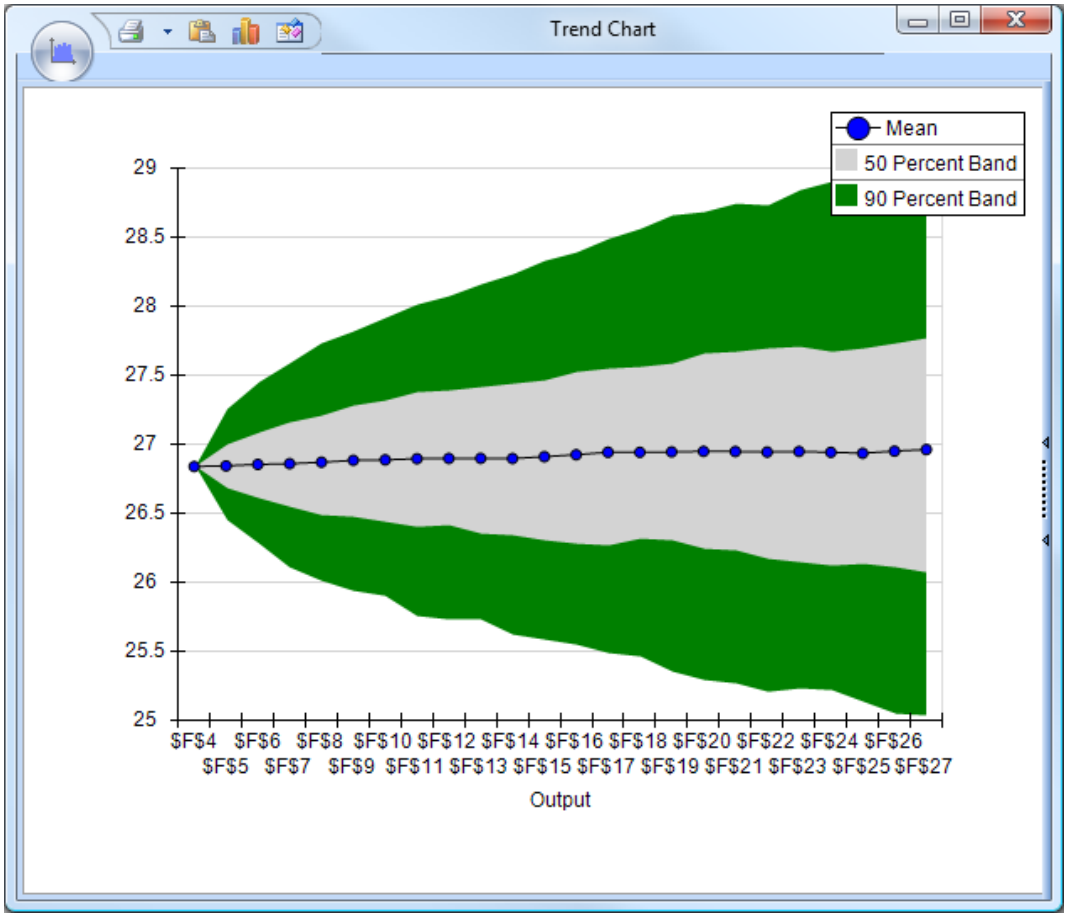
```
=PsiMetalog(,,{31.6,4.43177733881587})
```

Charting Multiple Uncertain Functions

In some simulation models, you will have a series of uncertain functions that represent the evolution of some process over time. The individual cells might represent sales or inventory levels, interest rates or exchange rates, or some other uncertain factor. You want to understand how this uncertain function changes over time, taking into account its *uncertainty*.

Analytic Solver Comprehensive has a general facility for creating charts of multiple simulation results, including Overlay, Trend, and Box-Whisker charts. Below, we've used this facility to visualize the evolution of a stock price over

time, using the example model GBMSimpleModel.xls, which simulates stock prices using a Geometric Brownian Motion model. When we perform a simulation, select **Charts – Multiple Simulation Results – Trend**, and select the first 24 uncertain functions for inclusion in the chart, we get a Trend Chart like the one below:



Here we can see a slow upward drift of the mean value of the stock price, and also its volatility around the mean, depicted here with the 25th and 75th, and the 10th and 90th percentiles.

Multiple Parameterized Simulations

Once you have results from a single simulation, you normally want to explore "what if" scenarios, where you change some parameter that is under your control and run simulations to observe the effects of the uncertain variables that are *not* under your control.

Using Interactive Simulation in Analytic Solver Desktop

Analytic Solver Simulation offers a powerful facility to do this through Interactive Simulation: You can simply click the Simulate button on the Analytic Solver Cloud Ribbon to enter Interactive mode, then change a number on your worksheet and instantly see new simulation results. This is illustrated in "A First Simulation Example" in the earlier chapter "Simulation and Risk Analysis." Analytic Solver is fast enough to make this sort of "what-if" analysis practical.

Using Multiple Simulations

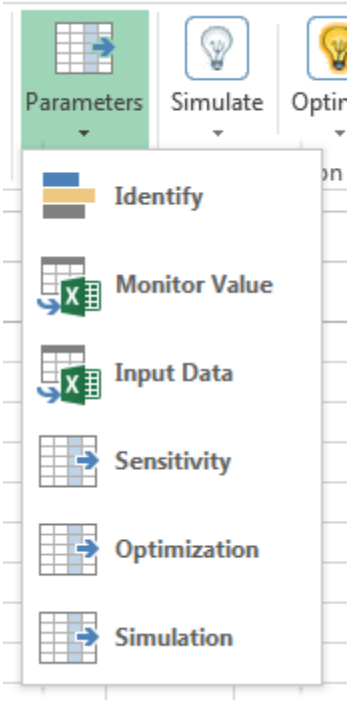
But after exploring the model and its results through Interactive Simulation, you'll likely want to automate the "what-if" process, and more systematically evaluate the effects of changing some parameter or parameters under your control on the simulation results. Analytic Solver makes this easy, with multiple parameterized simulations. This is illustrated in "An Airline Revenue Management Model" in the chapter "Simulation and Risk Analysis."

Setting Up Multiple Parameterized Simulations

Two simple steps are required to set up a multiple parameterized simulation:

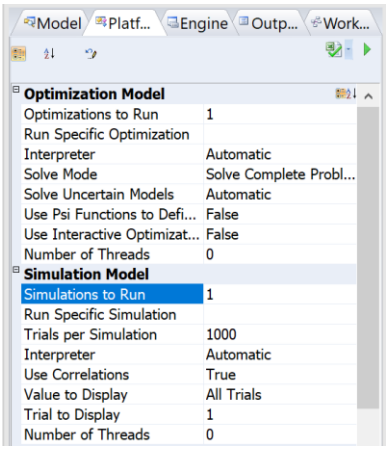
1. Define one or more **simulation parameters**, and use them in your model.
2. Set the **number of simulations** option to a value greater than 1, and run the simulation.

To define a simulation parameter, simply select **Parameters – Simulation** from the Ribbon:



Analytic Solver Simulation displays a dialog box, where you can enter a lower limit and upper limit for the parameter value, or a specific list of values that you would like the parameter to take on successive simulations. If you specify a lower and upper limit, then when you set the **number of simulations**, the parameter will take on equally-spaced values from the lower to the upper limit.

To set the number of simulations, simply edit the option in the Task Pane Platform tab Simulation group option **Simulations to Run**:



When you next click the **green arrow** in the Task Pane, or choose **Simulate – Run Once** from the Analytic Solver Desktop Ribbon, all 10 (in this example) simulations will be run, automatically varying each simulation parameter over its range or list of values, and all the results will be collected and stored. (If you click the Simulate icon in Analytic Solver Desktop to activate *Interactive Simulation*, all 10 simulations will be run each time you make a change on the worksheet.)

Viewing Results of Multiple Simulations

After running multiple parameterized simulations, you can view the results on the worksheet, or in the Uncertain Function dialog, by selecting the simulation of interest from the **Sim #** dropdown. You can create reports and charts of results that span all or some of the simulations. We highly recommend that you read "An Airline Revenue Management Model" in the earlier chapter "Simulation and Risk Analysis," which illustrates how this is done – creating a Trend Chart and a Box-Whisker Chart across all 10 simulations in this model.

Once you become familiar with multiple parameterized simulations, you'll likely want to use them in nearly every simulation analysis you do. They're a natural way to get further results from the effort you've put into a simulation model, and communicate those results to colleagues or clients.

Time Series Forecasting

Starting with version 2014-R2, Analytic Solver Data Mining includes the ability to forecast a future point in a time series in one of your spreadsheet formulas (without using the Score button on the Ribbon) using a PsiForecast() function in conjunction with a model created using ARIMA or one of our smoothing methods (Exponential, Double Exponential, Moving Average, or Holt Winters).

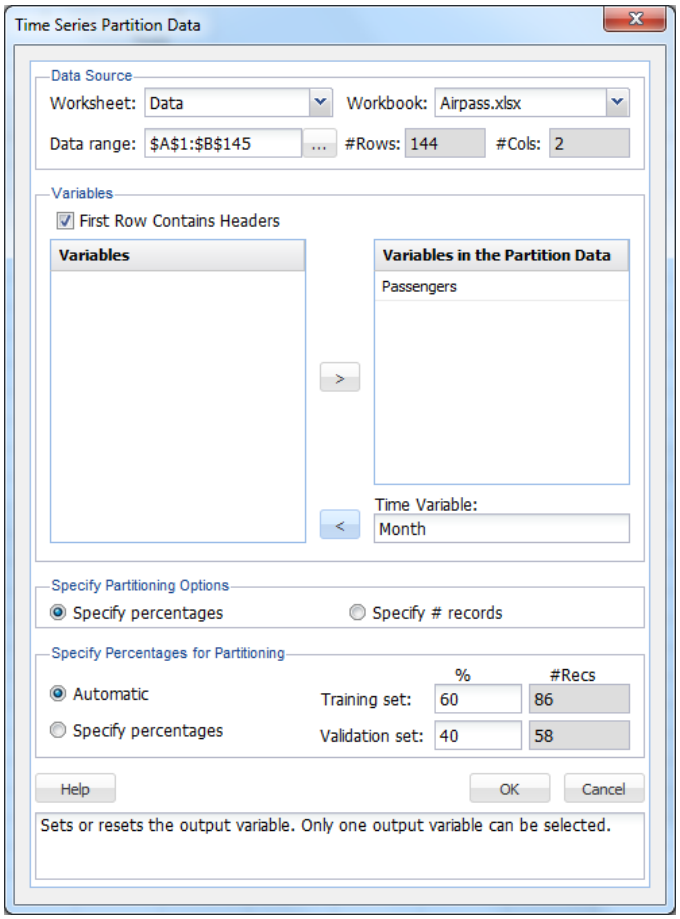
PsiForecast() is similar to the previous PSIForecastXXX functions supported in V2014, 2015, and 2016: it will compute future-looking forecasts based on the fitted model, using the provided new time series observations as initial points. The number of forecasts is determined by the number of selected cells in array-formula entry. The result of PsiForecast() can be deterministic, if the Simulate argument is FALSE, or non-deterministic, if the Simulate argument is TRUE– in which case the forecasts are adjusted with random normally distributed errors, defined by the forecasts' statistics.

Open the Airpass.xlsx example dataset by clicking Help – Examples on the Data Mining ribbon, then clicking Forecasting/Data Mining Examples. This example

dataset includes International Airline Passenger Information by month for years 1949 – 1960. Since the number of airline passengers increases during certain times of the year, for example Spring, Summer, and in the month of December, we can say that this dataset includes "seasonality".

First, we will partition this dataset into two datasets: a training dataset and a validation dataset. We'll use the training dataset to create the ARIMA model and then we'll apply the model to the validation dataset to forecast six future data points, or one half year of data.

Click Partition in the Time Series section of the Data Mining ribbon to open the Time Series Partition Data dialog. Select Passengers for the Variables in the Partition Data and Month for the Time Variable.



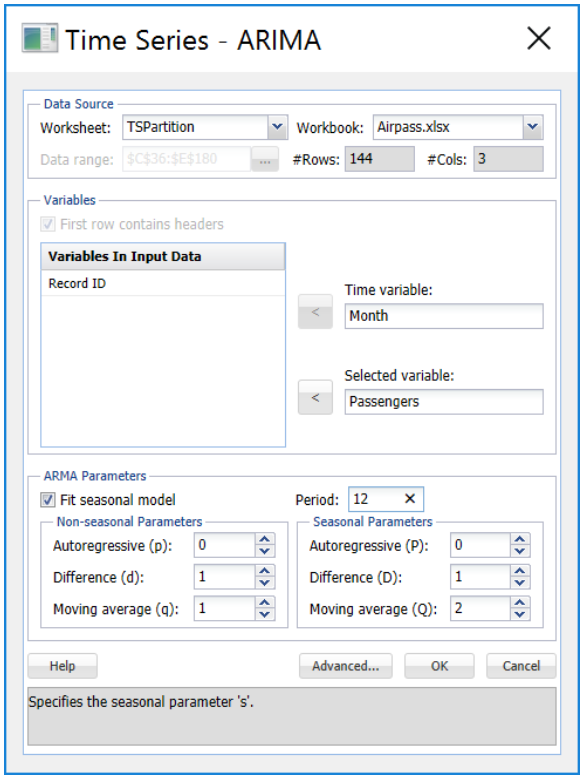
Click **OK** to accept the defaults for Specify Partitioning Options and Specify Percentages for Partitioning. Recall that when a time series dataset is partitioned, the dataset is partitioned sequentially. Therefore, 60% or the first 86 records, will be assigned to the training dataset and the remaining 40%, or 58 records, will be assigned to the validation dataset. (For more information on partitioning a time series dataset, see the previous chapter Exploring a Time Series Dataset.)

The TSPartition worksheet will be inserted into the Model tab of the Analytic Solver task pane under Transformations – Time Series Partition. Recall the steps needed to produce the forecast. Click ARIMA -- ARIMA to open the ARIMA dialog. Month has been pre selected as the Time variable. Select Passengers as the Selected variable.

This example will use a SARIMA model, or Seasonal Autoregressive Integrated Moving Average model, to predict the next six datapoints in the dataset. (For more information on this type of time series model, please see the earlier chapter, "Exploring a Time Series Dataset.") A seasonal ARIMA model requires 7 parameters, 3 nonseasonal (autoregressive (p), integrated (d), and moving average (q)), 3 seasonal (autoregressive (P), integrated (D), and moving average (Q)), and period. Each parameter must be a non-negative integer.

Selecting appropriate values for p, d, q, P, D, Q and period is beyond the scope of this User Guide. Consequently, this example will use a well documented SARIMA model with parameters p = 0, d = 1, q = 1, P = 0, D = 1, Q = 2 and period (P) = 12. Please refer to the classic time series analysis text **Time Series Analysis: Forecasting and Control** written by George Box and Gwilym Jenkins for more information on parameter selection.

Select Fit seasonal model and enter 12 for Period since it takes a full 12 months for the seasonal pattern to repeat. Set the Non-seasonal Parameters as Autoregressive (p) = 0, Difference (d) = 1, Moving Average (q) = 1 and the Seasonal Parameters as Autoregressive (P) = 0, Difference (D) = 1, and Moving Average (Q) = 2.



Click **OK** to create the SARIMA model.

ARIMA_Output will be inserted into the Model tab of the XLMiner task pane under Reports – ARIMA. This output contains the Training Error Measures and Fitted Model Statistics. (For more information on this report, please see the chapter Exploring a Time Series Dataset within the Analytic Solver Data Mining Reference Guide.) ARIMA_Stored contains the stored model parameters.

Now we'll use this ARIMA model to predict new data points in the validation dataset using the PsiForecast() function. (*Note: The first forecasted point will be more accurate than the second, the second forecasted point more accurate than the third and so on.)* The PsiForecast() function will be interactive in the

sense that if any of the input values (values passed in the 2nd argument) change, the forecast will be recomputed.

In later versions of desktop Excel, the PsiForecast() function returns a Dynamic Array. To use this function in the Cloud, you need only enter the Psi function in one cell as a normal function, i.e., not as a control array. The contents of the Dynamic Array will "spill" down the column. If a nonblank cell is "blocking" the contents of the Dynamic Array, the Psi Data Mining function will return #SPILL until such time as the blockage is removed. In Excel versions that do not support Dynamic Arrays, PsiForecast() must be entered as an Excel array.

The PsiForecastARIMA function takes five arguments: Model, Input Data, Simulate, Num_forecasts, and Header. Select a blank cell on the Data worksheet and enter **=PsiForecast(**. If using a version of Excel that does not support Dynamic Arrays, select B146:B152 on the Data worksheet, then enter **=PsiForecast(.**

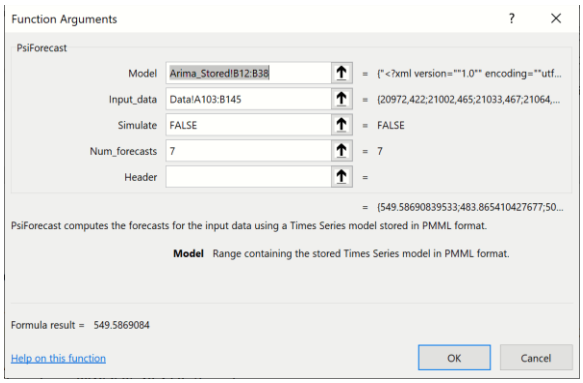
The first argument, *Model*, is the range of cells used by Analytic Solver Data Mining to store the ARIMA model on the *ARIMA_Stored* worksheet. This data range will change as the forecast method changes. Select or enter **ARIMA_Stored!B12:B38,** for this argument.

The second argument, *Input_Data*, is the range containing the initial starting points from the validation data set. The minimum number of initial points that should be specified for a seasonal ARIMA model is the larger of p + d + s * (P + D) and q + s * Q. In this example, p + d + s * (P + D) is equal to 13 (0 + 1 + 12 * (0 + 1) and q + s * Q is equal to 13 (1 + 12 * 1), therefore the minimum number of initial starting points required is 13 (MAX (13, 13)). If you provide fewer than the minimum required number of starting points, PsiForecast() will return a column of zeros. (See the table below for the minimum number of initial starting points required by each Forecasting method included in Analytic Solver Data Mining.) The maximum number of starting points is the number of points in the validation dataset. All points supplied in the second argument will be used in the forecast. Select or enter **Data!A1:B145,** for this argument.

Pass True or False for the third argument. Passing False will result in a static forecast that will only update if a cell passed in the 2nd argument is changed. If True is passed for this argument, a random error will be included in the forecasted points. See the Time Series Simulation example below for more information on passing True for this argument. In this case, Pass **False)** for this argument.

Your formula should now be the following:
=PsiForecast(ARIMA_Stored!B12:B38,Data!A1:B145, False). If using a version of Excel that does not support Dynamic Arrays, press **CTRL** + **SHIFT** + **ENTER** to enter this formula as an array in all seven cells (B146:B152).

It's also possible to enter this formula using the Insert Function dialog by clicking Formulas – Insert Function, select PSI Data Mining for Category, then PsiForecastARIMA.



The results from this function are displayed below.

Enter True for the Header argument to insert a heading above the forecasted values.

Notice that the formula is entered into cell B146 and the contents of the PsiForecast() Dynamic Array "spill" down into cells B147:B152.

	A	B
141	Aug-60	606
142	Sep-60	508
143	Oct-60	461
144	Nov-60	390
145	Dec-60	432
146		Forecast: 17899
147		468.082984
148		443.90313
149		444.106104
150		428.416324
151		424.563033
152		413.37003
153		

If any values change in the ranges ARIMA_Stored!B12:B38 or Data!B2:B145, the forecast will be recomputed; but if the input argument values stay the same, the PsiForecast() function will always return the same forecast values. As mentioned above, the first forecasted value in cell B146 is the most accurate predicted point. Accuracy declines as the number of forecasted points increases.

See the Frontline Solvers Reference Guide for specifications on PsiForecast().

Time Series Simulation

Analytic Solver Data Mining includes the ability to perform a time series simulation, where future points in a time series are forecast on each Monte Carlo trial, using a model created via ARIMA or one of our smoothing methods (Exponential, Double Exponential, Moving Average, or Holt Winters).

To run a time series simulation, we must pass “True” as the third argument to PsiForecast(). When the third argument is set to True, Analytic Solver will add a random (positive or negative) “epsilon” value to each forecasted point. Each time a simulation is run, 1000 trial “epsilon” values are generated using the PsiNormal distribution with parameters mean and standard deviation computed

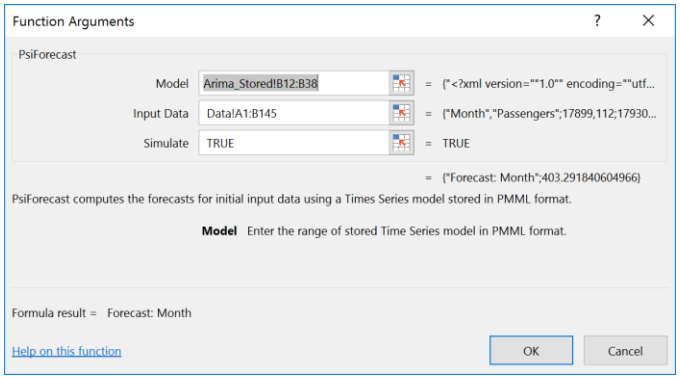
by the PsiForecast() function. You can view the output of this simulation in the same way as you would view "normal" simulation results in Analytic Solver Comprohensive, Analytic Solver Simulation, Analytic Solver Upgrade, or Analytic Solver Basic, simply by creating a PsiOutput() function and then double clicking the Output cell to view the Simulation Results dialog.

Select a blank cell, or Data!C146:C152 if using a version of Excel that does not support Dynamic Arrays, then click Formulas – Insert Function to display the Function Argument dialog.

As discussed previously, the first argument, ARIMA_Stored!B12:B38, is the range of cells used by Analytic Solver to store the ARIMA model on the *ARIMA_Stored* worksheet.

For the second argument the range containing the initial points in the series must be greater than the minimum number of initial points for a static forecast. For a seasonal ARIMA model when Simulate = True, the minimum number of initial points must be greater than Max((p + d + s * (P + D), (q + s * Q). In this example, p + d + s * (P + D) is equal to 13 (0 + 1 + 12 * (0 + 1) and q + s * Q is equal to 13 (1 + 12 * 1), therefore the minimum number of initial starting points required is 13 (Minimum #Initial Points > MAX (13, 13)). However, when PsiForecastARIMA() is called with Simulate = True, it is recommended to add an additional number of datapoints, equal to the #Periods, to the minimum number required. In this instance the number of initial points will be 25: 13 (minimum # of points) + 12 (# of points for Period in the Time Series - ARIMA dialog). If you provide fewer than the minimum required number of starting points (13 in this example) PsiForecastARIMA() will return #VALUE. (See the table below for the minimum number of initial starting points required by each forecast method in Analytic Solver.) All points supplied in the second argument will be used in the forecast. Select or enter **Data!A1:B145,** for this argument.

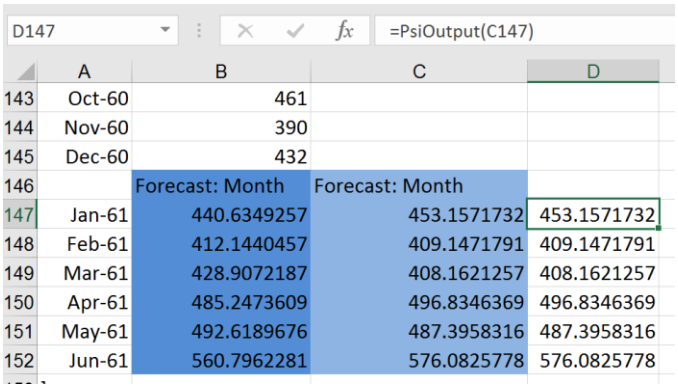
Passing TRUE for the third argument indicates to Analytic Solver Data Mining that you plan to use this function call in a Monte Carlo simulation, so it should add a random epsilon value (different on each Monte Carlo trial) to each forecasted point.



In versions of Excel supporting Dynamic Arrays, this formula is entered into cell C146 and the contents of the PsiForecast() Dynamic Array "spills" down into cells C147:C152. If versions of Excel that do not support Dynamic Arrays, the formula must be entered as an Excel array.

To view the results of the simulation including frequency and sensitivity charts, statistics, and percentiles for the full range of trial values, we must first create an output cell. Select cell C147, then click Analytic Solver – Results – Referred Cell. Select cell D147 (or any blank cell on the spreadsheet) to enter the

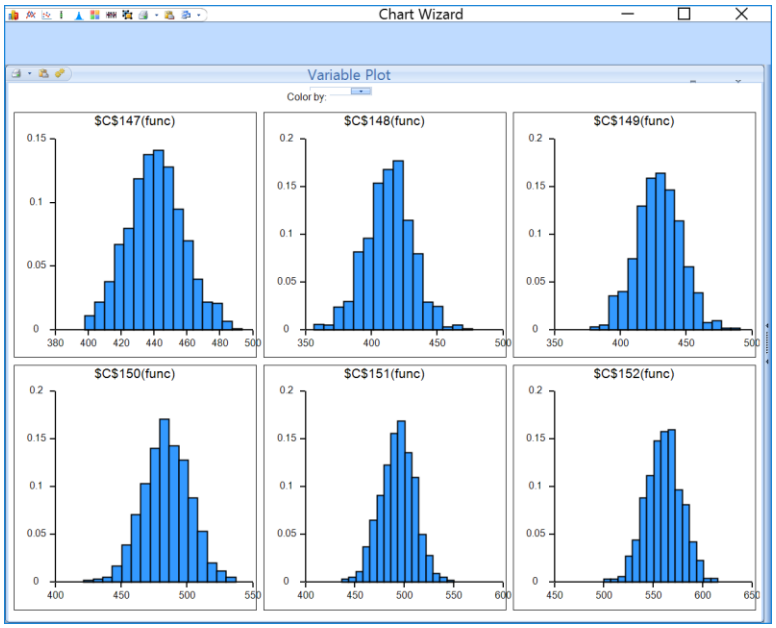
PsiOutput formula. Copy this formula from cell D147 down to cell D152. Therefore D147 = PsiOutput(C147), D148 = PsiOutput(C148), and so on.



	A	B	C	D
143	Oct-60	461		
144	Nov-60	390		
145	Dec-60	432		
146		Forecast: Month	Forecast: Month	
147	Jan-61	440.6349257	453.1571732	453.1571732
148	Feb-61	412.1440457	409.1471791	409.1471791
149	Mar-61	428.9072187	408.1621257	408.1621257
150	Apr-61	485.2473609	496.8346369	496.8346369
151	May-61	492.6189676	487.3958316	487.3958316
152	Jun-61	560.7962281	576.0825778	576.0825778

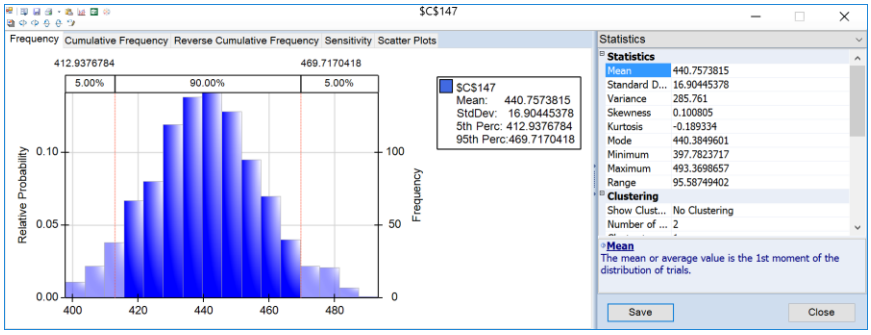
Click the down arrow on the Simulate icon and select Run Once. Instantly, Analytic Solver will perform a simulation with 1,000 Monte Carlo simulation trials (the default number). Since this is the first time a simulation has been performed, the following dialog opens. Subsequent simulations will not produce this report. However, it is possible to reopen the individual frequency charts by double clicking each of the output cells (B147:B152).

Important Note: For Users who are familiar with simulation models in Analytic Solver Simulation, you'll notice that the time series simulation model that we just created now includes 6 uncertain functions, B147:B152, which are the cells containing our PsiForecast() functions. For more information on simulation with Analytic Solver, please see the Frontline Solvers User Guide chapter, "Examples: Simulation and Risk Analysis".



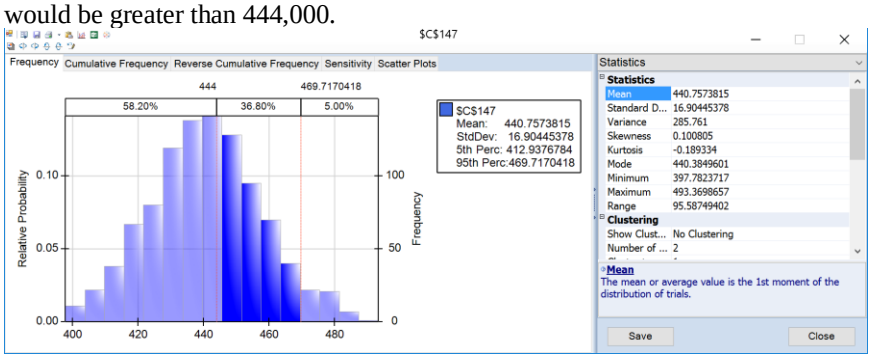
This dialog displays frequency charts for each of the six cells containing the forecasted data points. Double click the chart for cell C147 (top left) to open the Simulation Results dialog for the PsiForecast() function in cell C147. From here

you can view frequency and sensitivity charts, statistics and percentiles for each forecasted point.

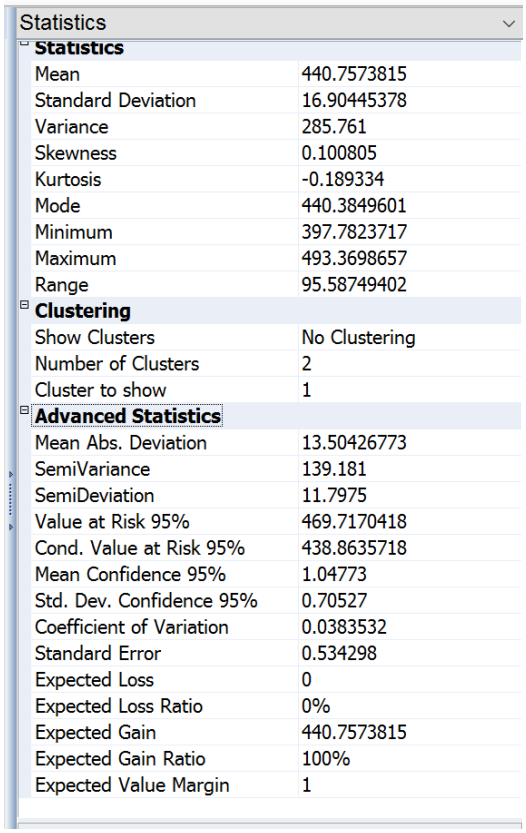


The frequency chart displays the distribution of all 1000 trial values for cell C147 with and observed mean 440.76 and standard deviation of 16.90 shown in the Chart Statistics. Select Simulate – Run Once a few more times (or click the green "play" button on the Solver Pane Model tab). Each time you do, another 1,000 Monte Carlo trials are run, and a slightly different mean will be displayed.

Enter 444 for the Lower Cutoff in the Chart Statistics section of the right panel, A vertical bar appears over the Frequency chart to display the frequency with which the forecasted value was greater than this value during the simulation. You can use this as an *estimate* of the probability that the actual value will be less than the forecasted value. In this case there was a 58.20% chance that the number of international airline passengers would be less than 444,000 in January 1961 and a 41.80% chance that the number of passengers would be greater than 444,000.



Looking to the right, you'll find the Statistics pane, which includes summary statistics for the full range of forecasted outcomes. We can see that the minimum forecasted value during this simulation was 397.78, and the maximum forecasted value was 493.37. Value at Risk 95% shows that 95% of the time, the number of international airline passengers was 469.72 or less in January 1961, in this simulation. The Conditional Value at Risk 95% value indicates that the average number of passengers we would have seen (up to the 95% percentile) was 438.86. For more information on Analytic Solver Platform's full range of features, see the Frontline Solvers User Guide chapter, "Examples: Simulation and Risk Analysis".



Statistics	
Statistics	
Mean	440.7573815
Standard Deviation	16.90445378
Variance	285.761
Skewness	0.100805
Kurtosis	-0.189334
Mode	440.3849601
Minimum	397.7823717
Maximum	493.3698657
Range	95.58749402
Clustering	
Show Clusters	No Clustering
Number of Clusters	2
Cluster to show	1
Advanced Statistics	
Mean Abs. Deviation	13.50426773
SemiVariance	139.181
SemiDeviation	11.7975
Value at Risk 95%	469.7170418
Cond. Value at Risk 95%	438.8635718
Mean Confidence 95%	1.04773
Std. Dev. Confidence 95%	0.70527
Coefficient of Variation	0.0383532
Standard Error	0.534298
Expected Loss	0
Expected Loss Ratio	0%
Expected Gain	440.7573815
Expected Gain Ratio	100%
Expected Value Margin	1

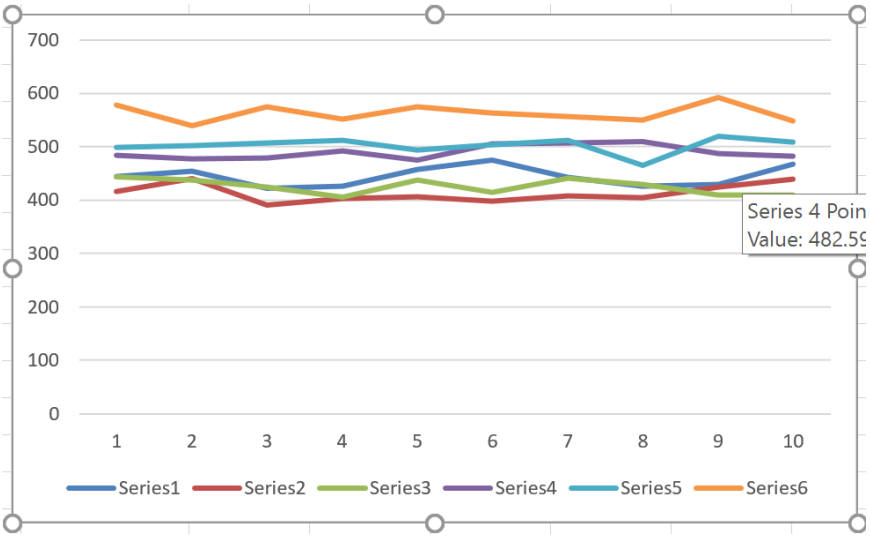
Select cells E147:E156 and then enter the formula, =PsiData(C147) If using a version of Excel that does not support Dynamic Arrays, press CTRL + SHIFT + ENTER to array enter the formula into all 10 cells. Repeat the same steps to array enter "=PsiData(C148)" in cells F147:F156, "=PsiData(C149)" in cells G147:G156, "=PsiData(C150)" in cells H147:H156, "PsiData(C151)" in cells I147:I156, and "=PsiData(C152)" in cells J147:J156. Then click Simulate – Run Once to run a simulation.

The ten Excel cells in these columns will update with trial values for each of the PsiForecast() functions in column C. For example, cells E147:N147 will contain the first 10 trial values for the PsiForecast() function in cell C147, Cells E147:N147 will contain the first 10 trial values for cell C148 and so on. (For more information on the PsiData() function, please see the Excel Solvers Reference Guide chapter, "Psi Function Reference.")

Note: In Analytic Solver Cloud and in later versions of desktop Excel, the PsiData() function returns a Dynamic Array. To use this function in the Cloud, you need only enter the Psi function in one cell as a normal function, i.e., not as a control array. The contents of the Dynamic Array will "spill" down the column. If a nonblank cell is "blocking" the contents of the Dynamic Array, PsiData() will return #SPILL until such time as the blockage is removed. Use the optional *numTrials* argument to specify the number of trials returned in the Dynamic Array. If not present, all trials will be returned.

If we create an Excel chart of these values, you'll see a chart similar to the one below where each of Series1 through Series6 represents a different Monte Carlo trial. The random "epsilon" value added to each forecast value accounts for (all of) the variation among the lines. If the third argument were FALSE or omitted,

all of the lines would overlap, assuming that the table or parameters and the starting values were not changing.



The remaining Forecasting methods can be used in the same way using PsiForecast() with information from their respective Stored Model sheets.

Forecasting Algorithm	Stored Model Sheet	Minimum # of Initial Points when Simulate = False	Minimum # of Initial Points when Simulate = True
Non- Seasonal ARIMA	ARIMA_Stored	Max(p + d, q)	Max(p + d, q)
Seasonal ARIMA	ARIMA_Stored	Max((p + d + s *(P + D), (q + s * Q)	1 + Max((p + d + s *(P + D), (q + s * Q)**
Exponential Smoothing	Expo_Stored	1	1
Double Exponential Smoothing	DoubleExpo_Stored	1	1
Moving Average Smoothing	MovingAvg_Stored	# of Intervals	# of Intervals
Holt Winters Smoothing	MulHoltWinters_Stored AddHoltWinters_Stored NoTrendHoltWinters_Stored	2 * #Periods	2 * #Periods

**Adding a number of data points equal to the Number of Periods (as shown on the Time Series – ARIMA dialog) to the Minimum # of Initial Points when Simulate = True is recommended when calling PsiForecast() with Simulate = True.

Excel 2016 Forecast Functions

Users of Analytic Solver Comprehensive, Analytic Solver Simulation and Analytic Solver Basic will notice two Psi Forecast functions:

PsiForecastLinear() and PsiForecastETS(). These two functions were introduced to coincide with the new Excel 2016 Forecast functions: Forecast.Linear and Forecast.ETS.

PsiForecastLinear predicts future values for a time series data set (containing known or historical data) using linear regression. PsiForecastETS uses exponential smoothing to predict future values in a time series dataset with the option to either automatically detect seasonality in the data set or pass a seasonality period. Passing False as the last argument to either function will result in a static forecast. If True is passed for this argument, a random error will be included in the forecasted points.

Note: When comparing the results of the Psi functions with the Excel functions, you may see slightly different calculated forecast values depending on whether the Psi Interpreter or Excel Interpreter is selected on the Task Pane Platform tab. When the Psi Interpreter is used, a slightly different (but arguably better) methodology is used to compute these forecast functions. When the Excel Interpreter is selected, Microsoft Excel is used to calculate the worksheet, and thus Excel's methodology will be used.

To illustrate an example of how to use these two functions, we'll reuse the Airpass time series dataset. Click back to the Data tab within Airpass.xlsx. Recall that the Airpass time series dataset contains international airline passenger data from January 1949 to December 1960. Using this historical data, we will forecast the number of passengers in 1961.

PsiForecastLinear() performs linear regression of known_y values with known_x time variables to forecast the value at time, X. This function takes the following arguments.

`PsiForecastLinear(X, known_ys, known_xs[, simulate])`

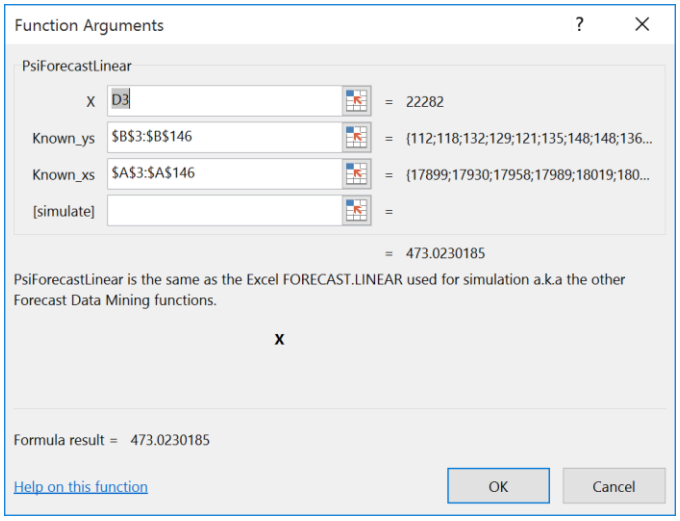
- `X`: The target date. A data point for which you want the predicted value. A data point may be date/time or numeric.
- `known_ys`: An Excel range containing the independent variables in the given dataset.
- `known_xs`: An Excel range containing the time variables in the given dataset.
- `simulate`: (Optional) Pass True or False for the third argument. Passing False (the default) will result in a static forecast that will only update if a cell passed in the known_ys argument is changed. If True is passed for this argument, a random error will be included in the forecasted points.

Click a blank cell on the worksheet, say cell E3, then in Analytic Solver Desktop click **Formulas – Insert Function** on the Ribbon to display the Function Argument dialog. In Analytic Solver Cloud, you'll need to type the formula directly into cell E3.

Select **PsiData Mining** form the *Category* drop-down menu, then scroll down to **PsiForcastLinear** and click **OK**. The *Function Arguments* dialog opens.

- `X`: Select cell Data!E3 for the `target` argument.
- `Known_ys`: Select or enter B3:B146. These are the independent y values. Be sure to anchor this range of cells (as shown in the screenshot below) so that we can easily copy the formula.

- `Known_ys`: Select or type A3:A146 for the third argument, `known_xs`. Again, anchoring this Excel range now allows easy copying and pasting later.
- `Simulate`: Pass **False** for this argument. See the Time Series Simulation example below for more information on passing True for this argument.



Click **OK** to enter the formula into the Excel cell, then copy and paste this formula into cells E4:E14.

	A	B	C	D	E
1					
2	Month	Passengers		Future Dates	PsiForecastLinear
3	Jan-49	112		Jan-61	471.3943104
4	Feb-49	118		Feb-61	475.7290965
5	Mar-49	132		Mar-61	478.1732961
6	Apr-49	129		Apr-61	480.8793742
7	May-49	121		May-61	483.4981594
8	Jun-49	135		Jun-61	486.2042375
9	Jul-49	148		Jul-61	488.8230227
10	Aug-49	148		Aug-61	491.5291008
11	Sep-49	136		Sep-61	494.2351789
12	Oct-49	119		Oct-61	496.8539641
13	Nov-49	104		Nov-61	499.5600422
14	Dec-49	118		Dec-61	502.1788274

If any values change in the ranges Data!A3:A146 or Data!B3:B146, the forecast will be recomputed; however, if the input argument values remain the same, PsiForecastLinear() will always return the same forecast values. As mentioned above, the first forecasted value in cell E3 is the most accurate predicted point. Accuracy declines as the number of forecasted points increases.

We can create a similar forecast using PsiForecastETS(). PsiForecastETS() performs Exponential Triple Smoothing on known values to forecast future values at time, target. The fourth argument, seasonality, is optional. If not given, seasonality is automatically detected from the the data. If given, automatic seasonality detection is turned off, and the given seasonality period is enforced. This function takes the following arguments.

```
PsiForecastETS(target_date, values, timeline[,
seasonality][, data_completion][, aggregation][,
simulate])
```

- `target_date`: A data point for which you want the predicted value. A data point may be date/time or numeric. If a target date is given that appears before the start of the timeline in the dataset, PsiForecastETS will return #NUM (i.e., if 1940 is passed for X).
- `values`: An Excel range containing the historical values in the given data set.
- `timeline`: An Excel range containing the time variables in the given data set. Both functions require the historical data to be structured using a constant interval between data points. Since the Airpass data set presents monthly passenger data, the forecast must also predict the number of passengers by month.
- `seasonality`: (Optional) This argument indicates the length of the seasonal pattern. The following values are accepted as valid inputs. All other values will return a #NUM error.

  0: Signifies no seasonality exists in the data. The result is a linear prediction.

  1: (Default Value) Triggers Solver to automatically detect seasonality within the data.

  1 < N < 8,760: Positive integer values greater than 1 but less than 8,760, will can be entered as the seasonality period.
- `data_completion`: (Optional) This argument specifies how to handle missing values. The default value of 1 replaces missing values by interpolation. If 0 is passed, missing values will be replaced with 0's.
- `aggregation`: (Optional) PsiForecastETS can aggregate multiple points with the same time stamp. Pass an integer value from 0 to 6 to indicate which method should be used.

  0: (Default) Average

  1: SUM

  2: COUNT

  3: COUNTA

  4: MIN

  5: MAX

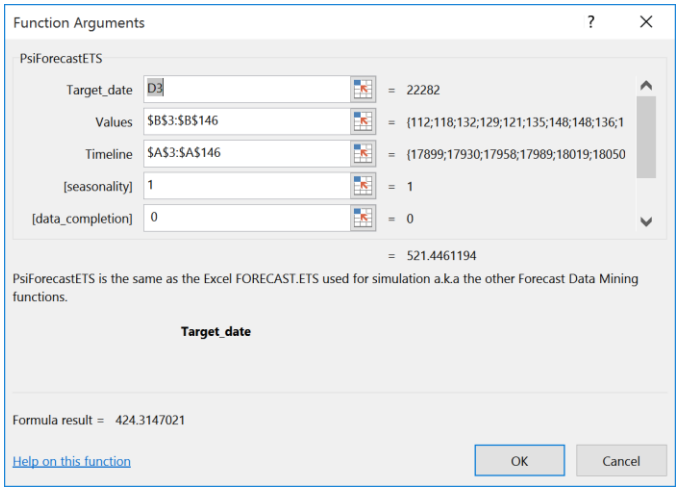
  6: MEDIAN
- `simulate`: (Optional) Pass True or False for the third argument. Passing False (the default) will result is a static forecast that will only update if a cell passed in the second argument is changed. If True is passed for this argument, a random error will be added to each forecasted point.

On the Excel ribbon, click **Formulas – Insert Function** to display the *Function Argument* dialog.

Select **PsiData Mining** form the *Category* drop-down menu, then scroll down to **PsiForcastETS** and click **OK**.

- `Target_date`: Select cell Data!E3.

- `Values`: Select or enter B3:B146. These are the independent y values. Anchoring the cell range (as shown in the screenshot below) will allow us to easily cut and paste the formula later.
- `Timeline`: Enter the dates January 1961 – December 1961 in cells D3:D11 for timeline. These are our `target` dates or the dates that we want to predict. These are our time variables. Anchoring the cell range, as shown in the screenshot below, will allow us to easily cut and paste the formula.
- `Seasonality`: Enter 1 for this argument to automatically detect the seasonality within the data.
- `data_completion`: Enter 0 for this argument to substitue any empty value with 0.
- `aggregation`: Enter 0 for this argument to aggregate multiple points with the same date using AVERAGE.
- `Simulate`: Passing TRUE for the third argument indicates to XLMiner that you plan to use this function call in a Monte Carlo simulation. Therefore, a random epsilon value (different on each Monte Carlo trial) will be added to each forecasted point.



Click **OK** to enter the formula into the Excel cell. This formula can easily be copied to cells E4:E14.

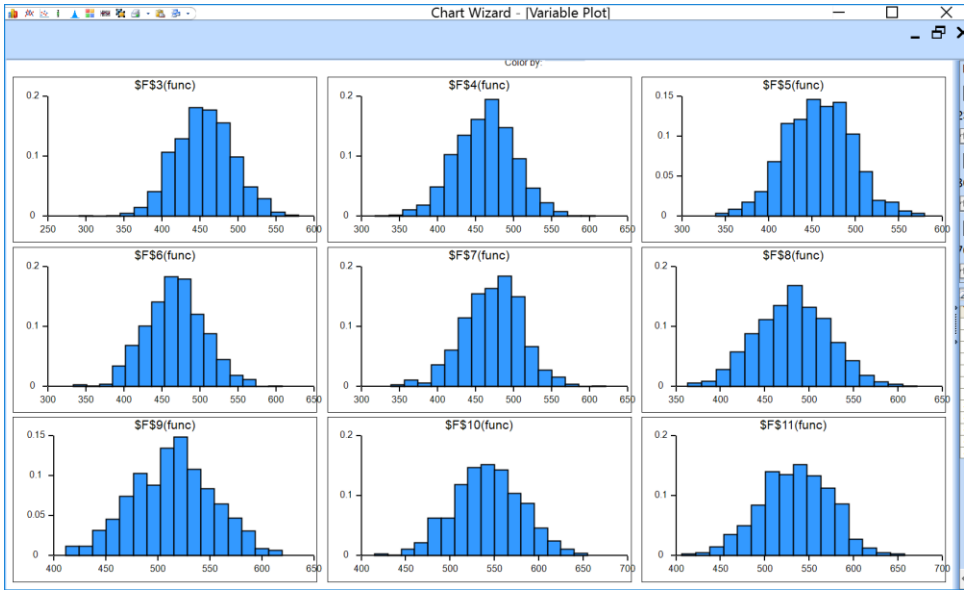
	A	B	C	D	E	F
1						PsiForecastET
2	Month	Passengers		Future Dates	PsiForecastLinear	Automatic Seasonality Detection
3	Jan-49	112		Jan-61	467.7264315	450.9100631
4	Feb-49	118		Feb-61	475.7290965	476.9380729
5	Mar-49	132		Mar-61	478.1732961	460.112461
6	Apr-49	129		Apr-61	480.8793742	491.7549692
7	May-49	121		May-61	483.4981594	482.2688644
8	Jun-49	135		Jun-61	486.2042375	433.3969442
9	Jul-49	148		Jul-61	488.8230227	514.7938906
10	Aug-49	148		Aug-61	491.5291008	577.1929713
11	Sep-49	136		Sep-61	494.2351789	516.4226707
12	Oct-49	119		Oct-61	496.8539641	501.8959522
13	Nov-49	104		Nov-61	499.5600422	459.7185426
14	Dec-49	118		Dec-61	502.1788274	430.0349623

As with the PsiForecast Data Mining functions, to view the results of the simulation, including frequency and sensitivity charts, statistics, and percentiles

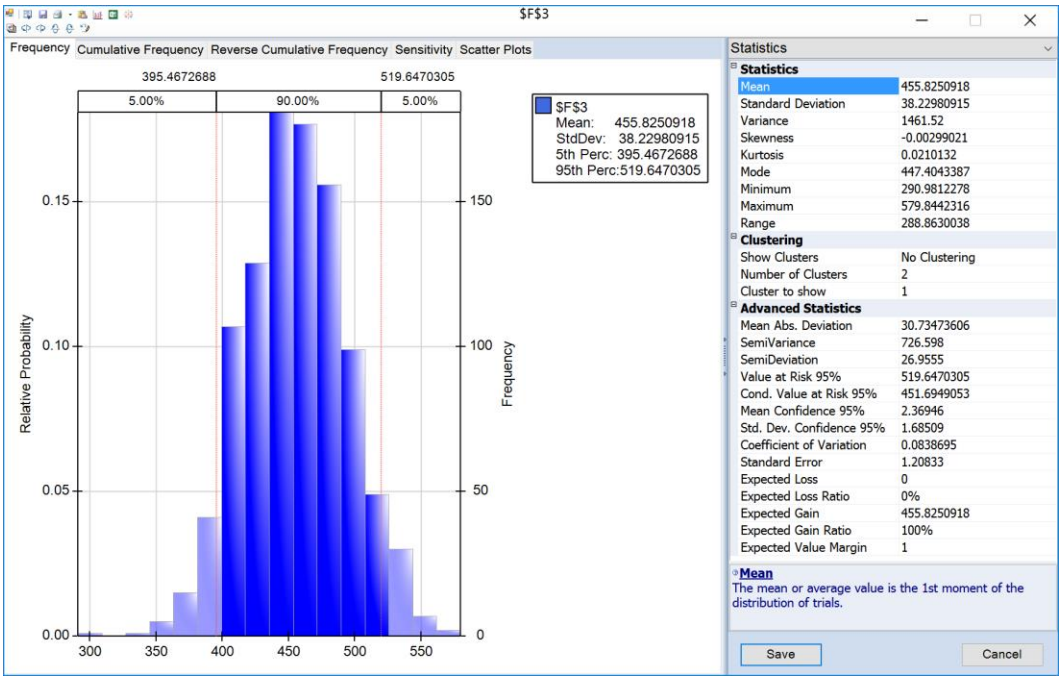
for the full range of trial values, we must first create an output cell. Select cell F3, then click **Analytic Solver Platform – Results – Referred Cell** on the Excel ribbon. Select cell F17 (or any blank cell on the spreadsheet) to enter the PsiOutput formula. Copy this formula from cell F17 down to cell F28. Therefore F17 = PsiOutput(F3), F18 = PsiOutput(F4), and so on.

Click the down arrow on the Simulate icon on the Analytic Solver Platform ribbon and select Run Once. Instantly, Analytic Solver Simulation performs a simulation with 1,000 Monte Carlo simulation trials (the default number). Since this is the first time a simulation has been performed, the following dialog opens. Subsequent simulations will not produce this report. However, it is possible to reopen the individual frequency charts by double-clicking each of the output cells (F17:F28).

Important Note: For users who are familiar with simulation models in Analytic Solver, you will notice that the time series simulation model that we just created now includes 12 uncertain functions (F17:F28) which are the cells containing our PsiForecastETS() functions.



The dialog above displays frequency charts for the first nine, of the total 12, uncertain function cells containing the forecasted data points. Double-click the chart for cell F3 (top-left) to open the *Simulation Results* dialog displaying PsiForecastETS() function in cell F3. From here, you can view frequency and sensitivity charts, statistics and percentiles for each forecasted point.



The frequency chart displays the distribution of all 1000 trial values for cell F3 with an observed mean 455.825 and standard deviation of 38.23 shown in the Chart Statistics.

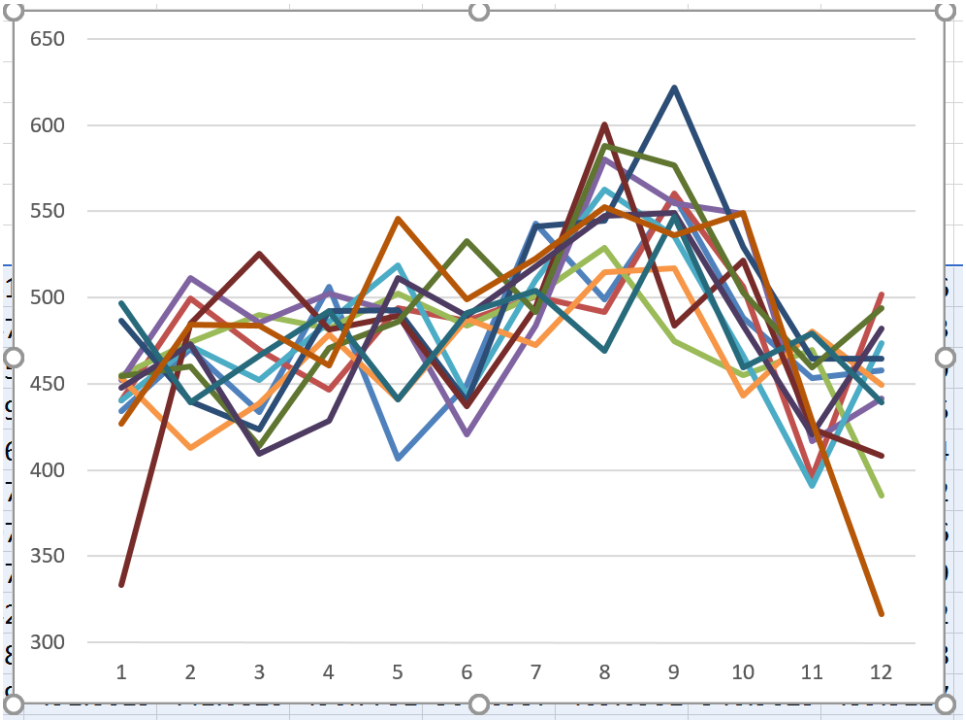
On the right of the dialog, you'll find the Statistics pane, which includes summary statistics for the full range of forecasted outcomes. We can see that the minimum forecasted value during this simulation was 290.98, and the maximum forecasted value was 579.84. In this simulation, Value at Risk 95% shows that 95% of the time, the number of international airline passengers was 519.65 or less in January 1961. The Conditional Value at Risk 95% value indicates that the average number of passengers we would have seen (up to the 95% percentile) was 451.69. For more information on Analytic Solver Platform's full range of features, see the chapter, "Examples: Simulation and Risk Analysis".

As in the previous section, we will graph the first few trial values (out of a total of 1000) for each forecasted point. Select cells G17:G28, then enter the formula, =PsiData(F17), then press CTRL + SHIFT + ENTER to array enter the formula into all 12 cells. Repeat the same steps to array enter "=PsiData(F18)" in cells H17:H28, "=PsiData(F19)" in cells I17:I28, and so one. On the Analytic Solver Platform ribbon, click **Simulate – Run Once** to run a simulation.

The 12 Excel cells in these columns will update with trial values for each of the PsiForecastETS() functions in cells F3:F14. Cells G17:G28 will contain the first 12 trial values for the PsiForecastETS() function in cell F3, cells G17:G28 will contain the first 12 trial values for cell F4, and so on. (For more information on the PsiData() function, please see the Excel Solvers Reference Guide chapter, "Psi Function Reference.")

If we create an Excel chart of these values, you will see a chart similar to the one below where each of Series 1 through Series 12 represents a different Monte Carlo trial. The random "epsilon" value added to each forecast value accounts for (all of) the variation among the lines. If the third argument were FALSE or

omitted, all of the lines would overlap, assuming that the table or parameters and the starting values were not changing.



Getting Results: Stochastic Optimization

Introduction

This chapter explains how to obtain and interpret results from stochastic optimization (optimization of models with uncertainty) in Analytic Solver Comprehensive or Analytic Solver Simulation with Analytic Solver Optimization. We'll discuss **what can go wrong**, and what to do about it, and also **how to get more** than a single optimal solution from your model.

Analytic Solver Comprensive has powerful algorithms for automatically transforming and solving optimization models with uncertainty. But since a stochastic optimization model includes **decision variables**, **uncertain variables**, and **constraints** and an **objective** that may depend on both, there are "more things that can go wrong." Indeed, everything you've read in the previous two chapters, "Getting Results: Optimization" and "Getting Results: Simulation" will apply to stochastic optimization – plus there are a variety of special result messages and error messages that apply *only* to stochastic optimization models.

The good news is that everything you've learned so far about conventional optimization and Monte Carlo simulation *does* apply to stochastic optimization in Analytic Solver Comprehensive. Unlike most other software packages, Analytic Solver Comprehensive has one consistent user interface, set of terms, and model elements for all types of simulation and optimization models.

In the following sections, we'll focus on immediate actions you can take when you get an unexpected result – but if you read the chapter "Mastering Stochastic Optimization Concepts," you'll learn far more about stochastic optimization models and solution methods, and better understand *why* the unexpected result appeared, and how to design your model to get the solutions you want.

What Can Go Wrong, and What to Do About It

When you click the **Optimize** button on the Ribbon, or the **green arrow** on the Task Pane to solve, you'll normally get one of these outcomes:

1. A solution that makes sense to you. This is normally accompanied by a Solver Result message in **green** at the bottom of the Task Pane. You can proceed to "When Things Go Right: Getting Further Results."
2. A Solver Result error message that you understand and can correct, in **red** at the bottom of the Task Pane. You can take corrective action.
3. A Solver Result error message that you *don't* understand, in **red** at the bottom of the Task Pane. You should **read the solution log** in the Output tab (in Analytic Solver Desktop), **click the error message** and read Help about the message.
4. A *solution* that you *don't* understand, or that seems wrong. Again before doing anything else, you should **read the solution log** in the

Output tab (in Analytic Solver Desktop), **click the error message** to display Help, **run available reports** as described below, and **read the section** below "When the Solution Seems Wrong."

5. Solving runs for a very long time, and you don't get a solution or a Solver Result message until you press ESC or click Pause/Stop. You should **read the section** below "When Solving Takes a Long Time."

In rare cases, you might find Excel shutting down or "locking up" (so nothing happens when you press and hold the ESC key for several seconds in Analytic Solver Desktop or the Pause button in Analytic Solver Cloud). In this case please contact Frontline Systems Technical Support at (775) 831-0300 x4 or support@solver.com. Some Solver Result error messages ask you to contact Technical Support. If you can send us your model, this will be very helpful.

But experience shows that 99% of all technical support cases involve "pilot error" by the user, and that 90% of all such cases could be easily resolved by reading online Help or the User Guide. So we hope you'll keep reading, and that you'll take these steps before calling technical support!

Review Messages in the Output Tab

If using Analytic Solver Desktop, your first step should be to **review the messages** in the **solution log** in the Task Pane Output tab. This is **especially important** when you're solving a stochastic optimization model, to ensure that you understand the solution method that Analytic Solver Comprehensive used, and how your model was transformed and solved.

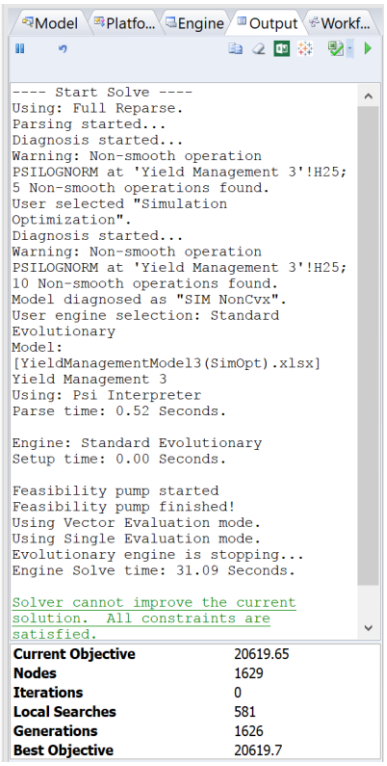
A Model Solved with Simulation Optimization

On the next page is an example of the Output tab at the solution of the example model **YieldManagementModel3.xls** (described more fully in the chapter "Examples: Simulation and Risk Analysis").

If you are using Analytic Solver Desktop, you can click the Copy icon to copy the contents of the solution log to the Windows Clipboard, where you can paste it into Microsoft Word, NotePad, or an **email message to Frontline Systems Technical Support**. Also, on the next page is the complete solution log from the Gas Company Chance model (before clicking the button to automatically improve the solution).

Note what happened during the solution process: Analytic Solver Comprehensive found that a Stochastic Transformation could not be applied to this model, because it has a *decision-dependent uncertainty* (the number of no-shows at cell C7 depends on the number of tickets sold, our decision variable, at C11). See the chapter "Mastering Stochastic Optimization Concepts" for more information on this important property of your model.

Analytic Solver diagnosed the model as "SIM NonCvx," and solved it using ***simulation optimization*** – the most general, but least scalable stochastic optimization method in Analytic Solver Comprehensive. It used the GRG Nonlinear Solver Engine (selected by the user) for optimization, and on every trial solution explored by the GRG Solver, it automatically performed a simulation.



---- Start Solve ----
Using: Full Reparse.
Parsing started...
Diagnosis started...
Warning: Non-smooth operation PSILOGNORM at 'Yield Management 3'!H25; 5 Non-smooth operations found.
User selected "Simulation Optimization".
Diagnosis started...
Warning: Non-smooth operation PSILOGNORM at 'Yield Management 3'!H25; 10 Non-smooth operations found.
Model diagnosed as "SIM NonCvx".
User engine selection: Standard GRG Nonlinear
Model: [YieldManagementModel3(SimOpt).xls]Yield Management 3
Using: Psi Interpreter
Parse time: 0.30 Seconds.

Engine: Standard GRG Nonlinear
Setup time: 0.00 Seconds.

Engine Solve time: 0.22 Seconds.

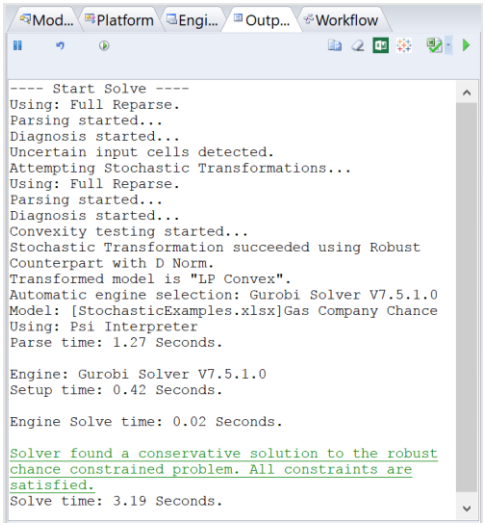
Solver found a solution. All constraints and optimality conditions are satisfied.
Solve time: 0.76 Seconds.

Note: Information such as what is shown above is not available in the Cloud app since the RASON Server does not rely any information back to the app until the model is handed over to the Solver engine.

Let's contrast what happened above with another example, where there are no decision-dependent uncertainties, and the underlying optimization model is a linear programming problem, but there is a *chance constraint*.

A Model Solved with Robust Optimization

Below is an example of the Output tab in Analytic Solver Desktop at the solution of the Gas Company Chance model in **StochasticExamples.xls** (described more fully in the chapter "Examples: Stochastic Optimization").



Again, if you click the Copy icon, the contents of the solution log will be copied to the Windows Clipboard, where you can paste it into Microsoft Word, NotePad, or an **email message to Frontline Systems Technical Support**. Below is the solution log from the Gas Company Chance model (before clicking the button to automatically improve the solution).

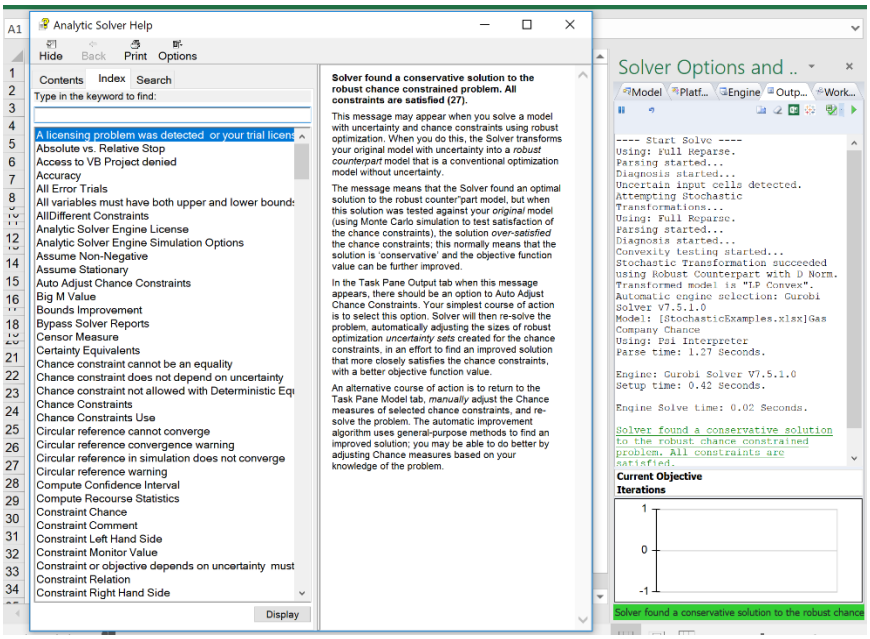
---- Start Solve ----
Using: Full Reparse.
Parsing started...
Uncertain input cells detected.
User requested Robust Counterpart.
Diagnosis started...
Convexity testing started...
Stochastic Transformation succeeded using Robust Counterpart with D Norm.
Transformed model is "LP Convex".
Model: [StochasticExamples.xls]Gas Company Chance
Using: Psi Interpreter
Parse time: 1.19 Seconds.
Engine: Standard LP/Quadratic
Setup time: 0.02 Seconds.
Engine Solve time: 0.00 Seconds.

Solver found a conservative solution to the robust chance constrained problem. All constraints are satisfied.
Solve time: 1.36 Seconds.

Click the Solver Result Message for Help

The Solver Result message in Analytic Solver Desktop is always **underlined** – it is a **hyperlink** to Help. If you aren't sure that you fully understand it, **click the link** to open online Help to a detailed discussion of the message.

Below is an example of Help that appears when you solve the Gas Company Chance model, and click on the Solver Result error message in green, "Solver found a conservative solution to the robust chance constrained problem. All constraints are satisfied."



Notice that the Help topic points out the option to **Auto Adjust Chance Constraints**. This is one key to better solutions when robust optimization is used, as in this example. Clicking the icon at the top of the Task Pane yields an improved solution, and the following solution log:

---- Start Solve ----
Model: [StochasticExamples.xls]Gas Company Chance
Using: Psi Interpreter
Using: Full Reparse.
Parsing started...
Diagnosis started...
Parse time: 0.19 Seconds.
Engine: Standard LP/Quadratic
Setup time: 0.00 Seconds.
Engine Solve time: 0.00 Seconds.
(*above lines appear 7 times*)

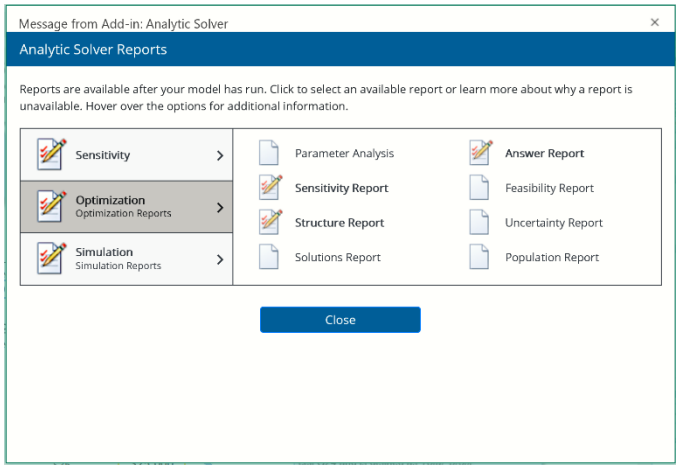
Solver has converged to the current solution of the robust chance constrained problem. All constraints are satisfied.
Solve time: 0.39 Seconds.

This was a *successful* solution – but in cases where you have a Solver Result *error message* that you don't understand, or a *solution* that you don't understand, the solution log can be even more helpful.

Note: If you are using Analytic Solver Cloud, set Operating Mode (Help – Operating Mode) to either Guided Mode or Auto Help Mode to find detailed information on the Solver result messages.

Choose Available Optimization Reports

As for conventional optimization, the available reports can help you understand the properties of a solution found by Analytic Solver. Just select **Reports – Optimization Reports** on the Ribbon – the available reports in the gallery are updated each time you solve.



Below is an Answer Report obtained for the Gas Company Chance model when we first received the Solver Result message "Solver found a conservative solution to the robust chance constrained problem. All constraints are satisfied." Note: This report is only generated in Analytic Solver Cloud when uncertain exceptions exist.

Microsoft Excel 14.0 Answer Report
Worksheet: [StochasticExamples.xls]Gas Company Chance
Report Created: 4/29/2014 2:41:33 PM
Result: Solver found a conservative solution to the robust chance constrained problem. All constr
Engine: Standard LP/Quadratic
Solution Time: 00 Seconds
Iterations: 0
Subproblems: 0
Incumbent Solutions: 0

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$C$25	Minimize Total Cost	1669.436556	1508.896962

Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
$D$14	Gas to Buy and Resell - year 1	100	100	Normal
$D$15	Gas to Buy and Store - year 1	100.0	0.0	Normal
$D$18	Gas to Buy and Resell - year 2	100	169.4943271	Normal

Constraints

Cell	Name	Cell Value	Formula	Status	Slac
$C$22	Meet Demand - year 1	0	$C$22=0	Binding	
$C$23	Meet Demand - year 2	47.3	$Var_{0.95}($C$23)>=0$	99.5% satisfied	32.5347
$D$14	Gas to Buy and Resell - year 1	100	$D$14>=0	Not Binding	
$D$15	Gas to Buy and Store - year 1	0.0	$D$15>=0	Binding	
$D$18	Gas to Buy and Resell - year 2	169.4943271	$D$18>=0	Not Binding	169.494

Note especially row 26, which reports the status of the chance constraint $VaR_{0.95}($C$23) >=0$: We asked for satisfaction of this constraint **95%** of the time, but at this solution the constraint is being satisfied **99.5%** of the time. This is a strong hint that the solution is conservative, and can be improved.

The Uncertainty Report for this model shows us the subset of the constraints and objective that depend on uncertainty. (*Note*: Since this model is automatically *transformed* to its robust counterpart, which has *no* uncertainty, you must set the Task Pane Platform tab Optimization Model group **Solve Uncertain Models** option to Simulation Optimization, then choose **Analyze Original Problem** to produce this report.)

Note: This report is not available in Analytic Solver Cloud.

Microsoft Excel 14.0 Uncertainty Report
Worksheet: [StochasticExamples.xls]Gas Company Chance
Report Created: 4/29/2014 2:43:55 PM
Model Type: Stochastic LP Use Of Uncertainty: No Uncertainties

Statistics

	Variables	Functions	Dependents
All	3	3	6
Recourse	0	0	0
Uncertain	1	2	2

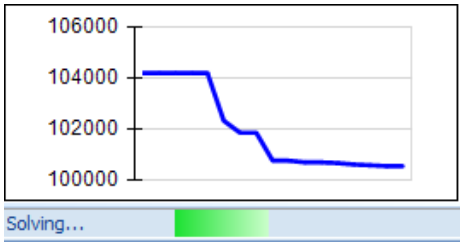
				Exception 1		Exception 2		Exception 3	
Cell	Name	Cell Value	Formula	Uncertainty	Formula	Uncertainty	Formula	Uncertainty	Formula
$C$23	Meet Demand - year 2	47.27462922	=D15+D18-C8	$D$5	$D$5				
$C$25	Minimize Total Cost	1465.162659	=(D14*C4) + (C5*D18) + (D15*(C4+C6))	$D$5	$D$5				

When Solving Takes a Long Time

When your model takes a long time to solve, the Task Pane Output tab can be helpful *during* the solution process – at a minimum, to reassure you that the Solver is still making progress, and has not "hung up." If it is not already visible when you first start solving, the Output tab will **appear automatically** after a few seconds of solution time, as long as the Task Pane itself is visible.

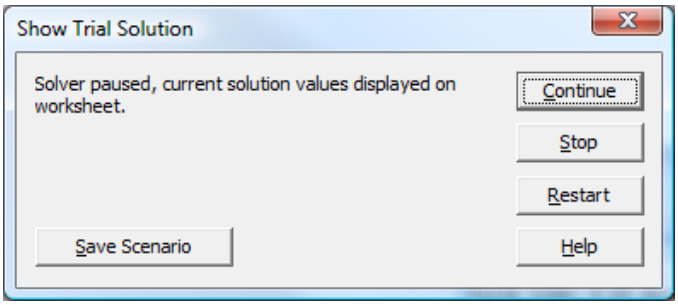
Running Chart of the Objective

The bottom part of the Output tab shows a running chart of the objective of the best solution found so far. This is most often useful for simulation optimization models, which may take some time to solve. Below is an example (staffing for a call center, not included among the installed example files):



Interrupting the Solution Process

You can interrupt the solution process at any time, by **pressing the ESC key** in Analytic Solver Desktop, or by **clicking the** ⏸ **button** in either Analytic Solver Desktop or the Cloud app, in the Task Pane Output tab. If your model is very large and you are using Analytic Solver Desktop, you might have to hold down the ESC key for a second or two. Since the input focus may not be on the Task Pane when you click with the mouse, you might have to click the ⏸ button twice. A dialog like the one on the next page will appear.



Click **Continue** if you want to continue solving; click **Stop** to cause the Solver to stop the solution process (this may take a few seconds) and display the message "Solver stopped at user's request." Clicking **Restart** may be useful with the Evolutionary Solver – see the Frontline Solvers Reference Guide.

Reasons Why Solving Takes a Long Time

There are several reasons why solving a stochastic optimization model might take a long time. To better understand why, read the chapter "Mastering Stochastic Optimization Concepts."

1. If your model doesn't meet the requirements for the stochastic programming or robust optimization solution methods, then the slowest method – **simulation optimization** – must be used. Since this requires an optimizer (such as the Evolutionary Solver) that will explore many Trial Solutions, and a *new simulation* must be performed for *every* Trial Solution, this method can take a lot of computing time.
2. If you are using Analytic Solver Desktop and you have the Platform tab Simulation group Interpreter option set to **Excel Interpreter**, Excel is used to recalculate the worksheet on each Monte Carlo trial. This is usually an **order of magnitude slower** than the PSI Interpreter, though it requires significantly less memory.
3. If **model diagnosis** or **problem setup** is slow (see timing messages in the Task Pane Output tab), you might be using array formulas, LOOKUP functions with large ranges as arguments, or long "chains" of formulas where each formula depends on an earlier formula, which can slow down the **PSI Interpreter**. See the analysis in the chapter "Getting Results: Optimization."
4. Your model might be well formulated, but very large, or it might require non-smooth functions, or many integer variables. A faster processor, multi-core processor, or more memory may help.

When the Solution Seems Wrong

When your optimization results seem wrong, before doing anything else, you should **read any messages** in the Output tab, and **click the message** to display Help as described above. We emphasize this, because very often when we are contacted in technical support, the user has not taken these basic steps.

Bear in mind that the uncertain function cells in your optimization model normally display the calculated value for the **last** Monte Carlo trial of the **last** simulation run. (All of Analytic Solver's solution methods – stochastic programming, robust optimization, and simulation optimization – perform at least one simulation). It can be very helpful to **cycle through the Monte Carlo**

trials, and examine the values of uncertain function cells, as well as intermediate formula cells on which they depend. Just use the **left and right arrows** on the Ribbon to change the trial index. You may find that your model calculates a result you did not expect for some values of the uncertain variables.

Although software bugs are always possible, consider carefully the possibility that the simulation results are **correct for the model you've defined**, and that your expectation is wrong. We sometimes find in technical support that what your model actually says is different from what you intended.

When Things Go Right: Getting Further Results

When you *do* receive a solution that makes sense to you, and you have a Solver Result message in **green** at the bottom of the Task Pane for your stochastic optimization model, you have available **all the optimization and simulation reports and charts** that apply to your model and solution. Since a simulation is performed for every stochastic optimization model, you can **double-click** the uncertain function cells in your model (in Analytic Solver Desktop) or on the Model tab of the Solver Task Pane (in Desktop or the Cloud) to display the Uncertain Function dialog, and obtain many different views of the uncertainty in your model:

Dialog Tabs

- The **Frequency**, **Cumulative Frequency**, and **Reverse Cumulative Frequency** tabs provide three different views of the full range of outcomes for an uncertain function. In Analytic Solver Desktop, you can click to display "crosshairs" with numerical values on these charts, or add Lower and Upper bounds to see the estimated probability of a profit or loss, for example.
- The Tornado chart on the **Sensitivity** tab quickly shows you which uncertain variables have the **greatest impact** on this uncertain function, across the full range of Monte Carlo trials. The **Scatter Plots** tab often reveals further insights about the behavior of this uncertain function versus each uncertain variable, or versus other uncertain functions.
- The **Statistics** and **Percentiles** tabs give you a full range of numerical results for this uncertain function, across the full range of Monte Carlo trials. Using PSI Statistics functions, you can place any of these values into a worksheet cell.

Panels and Toolbars

Analytic Solver Desktop includes rich charting abilities that are currently not available in Anlaytic Solver Cloud, but are coming soon. The suggestions below all pertain to Analytic Solver Desktop.

- Using the **right panel** of the dialog, you can change the chart type and color in both Analytic Solver Desktop and Cloud apps. In Analytic Solver Desktop you can additionally add titles, legends, gridlines, or chart markers. From the **Options dialog** (accessible from the Options button on the Analytic Solver Desktop Ribbon), on the **Charts** and **Markers** tabs, you can set default chart and marker settings for all of your charts.
- Using the **title toolbar icons** in Analytic Solver Desktop, you can save your settings, **print** the charts or numbers from any of the dialog tabs, or **copy** the charts or numbers to the Windows Clipboard, where they can be pasted

into other applications. You can also **fit a distribution** to the simulation results or export your results to either Power BI or Tableau.

- In Analytic Solver Desktop, click the leftmost icon on the second row to display the **3-D toolbar** that lets you – with a single click – shift between 2-D and 3-D, **shrink** or **magnify** the chart, or **move** or **rotate** the chart to a different perspective.

Dimensional Modeling

Introduction

Dimensional Modeling is a fundamental new capability in Analytic Solver Comprehensive when using Analytic Solver Desktop. It introduces new concepts such as **dimensions** and **cubes**, and provides all the tools you need to build and solve models using these concepts. If you're used to spreadsheet modeling, Dimensional Modeling will require some learning and practice. But when you want to construct *larger* models for common business situations where there are multiple products, projects or investments, multiple customer types, geographic regions, or time periods, multiple sources and destinations, dimensional modeling can turn a very complex, hard-to-maintain spreadsheet problem into a simple, well-structured, easily maintained and expandable model.

Note: Dimensional modeling is not currently supported in Analytic Solver Cloud.

If you've used **Pivot Tables** or **PowerPivot** in Excel, or if you've used a multidimensional database, data warehouse or business intelligence tool, the concepts behind Dimensional Modeling will probably be familiar. But these tools primarily deal with multidimensional *data*, generally reflecting the past. Dimensional Modeling makes it easy to construct multidimensional *models*, mostly composed of formulas, that you can use in planning for the future.

Unlike other tools, in Analytic Solver you can **use everything you know about Excel formulas** in Dimensional Modeling. For example, if cell A1 contains a number and cells B2 and C3 contains =PsiCube() functions, a formula like =A1+B2*C3 in a cell will yield a "cube result," multiplying and adding the appropriate values along several dimensions. You can also define B2 and C3 based on Pivot Tables containing input data, and easily obtain a Pivot Table that displays the results of like =A1+B2*C3.

Very often, a successful model is **expanded** to include more products, regions, time periods, etc. This is *much easier* to do with a Dimensional Model than with a traditional spreadsheet model. Formulas like =A1+B2*C3 need not change at all when you add elements (more cell or database values) to the existing dimensions. You can even add new *dimensions* to B2 and C3, or turn A1 from a single cell to a cube, and =A1+B2*C3 will automatically calculate results across the additional dimensions.

Dimensional Modeling in Optimization and Simulation

Dimensional Modeling can be used to create multidimensional "what if" models – a very powerful capability by itself. But you can also use it to create better structured, more compact and easily readable optimization and simulation models. For example, blocks of constraints that once required large ranges of repetitive formulas can now be entered in one or a few cells, drastically reducing the number of formulas. Similarly, in a simulation model, blocks of uncertain functions that once required large numbers of repetitive formula cells can be reduced to one or a few cells. You can define as many "structural dimensions" as you like, and use up to 8 of them at one time, in any PsiCube() function or calculated "cube intermediate result" in a formula.

Dimensional Modeling and Parametric Analysis

Dimensional Modeling also offers a powerful extension of Analytic Solver's capabilities for multiple parameterized optimization and simulation (described in the earlier chapters "Examples: Parameters and Sensitivity Analysis," "Getting Results: Optimization" and "Getting Results: Simulation"). It enables you to perform sensitivity analysis, or run many optimizations or simulations, varying parameters *across multiple dimensions* on each run, and capture all the results – optionally in Pivot Tables and Pivot Charts.

Without Dimensional Modeling, you define parameters for sensitivity analysis, optimization and simulation, using PsiSenParam(), PsiOptParam() and PsiSimParam() functions, respectively. These parameters function like simple "cubes" defined over just *one* dimension – the "run index" 1, 2, 3, etc. You run multiple calculations, optimizations or simulations, where all the parameters of a given type "move together" through their arrays of values.

With Dimensional Modeling, you can define as many "parametric dimensions" as you like, and create cubes of parameter values that are defined over *one or more* dimensions. You can then perform sensitivity analysis or run multiple optimizations or simulations, where any subset of your parametric dimensions are "active" (the others are "locked"), and get results for *all combinations* of the parameter values you've defined.

Just as you can **expand** a model by adding a structural dimension and generalize one or more cubes over the new dimension, without changing your formulas, you can add a parametric dimension, use it in one or more cubes, and expand your sensitivity analysis, optimization or simulation runs to include more scenarios, without changing any formulas.

Visualizing Dimensional Modeling Results

As mentioned earlier, you can define cubes based on Pivot Tables containing input data, and easily create new Pivot Tables that displays results of formulas like =A1+B2*C3. But creating a Pivot Table does require several steps, as well as "real estate" on your spreadsheet. If you want to inspect the results of intermediate calculations, you might need a separate table area for each "cube formula" cell in your model.

Analytic Solver makes this much easier. Just *double-click* on any cube formula to see a pop-up window that behaves like an "instant Pivot Table," allowing you to 'drag and drop' both structural and parametric dimensions across the columns and rows, and reorganize and display the data or calculated results. You'll see a number of examples of these pop-up windows in this chapter. For final results and reporting, you can use Pivot Tables and Charts.

Dimensions and Cubes

Let's define the concepts in Dimensional Modeling more formally. You can define two types of ***dimensions***, Structural and Parametric, and use them in calculation/sensitivity analysis, optimization and simulation models. You give a name (such as "Region") for the dimension, and you provide names/labels or numbers for the elements of the dimension – for example "North," "South," "East" and "West." Note that a dimension doesn't define the data itself – it defines a *structure*, relevant for your business situation, for the data.

Cubes are multi-dimensional arrays that hold the data. Other names used in data warehouse and business intelligence systems, are *measures* and/or *fact tables.*

A cube has an element (data value) for each combination of elements of the dimensions you specify when defining the cube. For example, you might create a cube named "Sales," defined over the "Regions" dimension, with four numeric values representing sales in the North, South, East and West regions. The structure of a cube is very much like a Pivot Table, and you can create a cube by placing a PsiPivotCube() function in a cell, referencing an existing Pivot Table.

A single cube holds a single "measure" or type of value. For example, a person has many attributes such as height, weight, hair color, and eye color. You might define a dimension "Person" with elements such as "John", "Mary" and "Susan." But since a cube holds a single attribute or measure, you'd need four different cubes, each defined over the "Person" dimension, to hold the values of height, weight, hair color, and eye color.

There are three main steps involved in creating a Dimensional Model. Step 1 is to define at least one **dimension**, either parametric or structural. Step 2 is to define at least one (usually several) **cubes**. Step 3 is to define at least one **output** cell – for example, the objective cell in an optimization model – with a formula that depends on a cube. Often, you'll have outputs that *are* cubes and contain many – even thousands of – result values.

An Example Dimensional Model

This chapter will use the Product Mix example, introduced at the beginning of the chapter "Examples: Conventional Optimization," to illustrate Dimensional Modeling concepts, and the menu choices and Psi functions you can use to build a Dimensional Model step by step. The example is very simple, with just two structural dimensions – Products and Parts. This will make it easier to fully grasp the concepts and step-by-step operations, but since you can usually "lay out" two-dimensional data in regular spreadsheet columns and rows, Dimensional Modeling might seem like "overkill" for this simple example. The advantages of Dimensional Modeling will be apparent when you are modeling a more realistic business situation with many dimensions.

Click **Help -- Examples** on the Analytic Solver ribbon, to open the Frontline Example Models Overview workbook. Click the Optimization Examples button, or select the Optimization tab, and scroll down to find and click **Structural Dimensions** from the list. When this workbook opens, click the *Product Mix Original* tab, which displays a conventional version of the Product Mix model.

	A	B	C	D	E	F	G	H
11								
12			Production Decisions					
13			TV	Stereo	Speakers			
14		*Number to Build:*	0	0	0			
15								
16			Part Requirements by Product				Part Inventory Levels	
17		Part Name	LCD TV	Stereo	Speakers		Used	Available
18		Chassis	*1*	*1*	0		0	450
19		*Screen*	*1*	*0*	0		0	250
20		*Speaker*	2	2	1		0	800
21		*Power Supply*	1	1	0		0	450
22		*Electronics*	2	1	1		0	600
23								
24		*Profit per unit*	$75	$50	$35		$0	

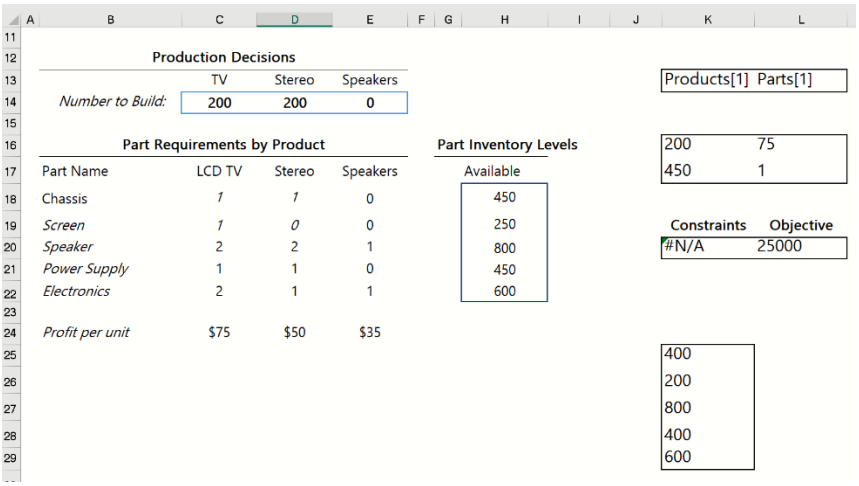
This example solves the problem of how many TVs, Stereos, and Speakers a company should manufacture. It has three **decision variables** (C14:E14) that correspond to the number of TVs, Stereos, and Speakers that the company will manufacture. The profit margins for each product are known. The gross margin (cell C24) for a TV is $75. The gross margin for stereos (cell D24) is $50 and the gross margin for speakers (cell E24) is $35.

Five different parts are used in the manufacturing process of these three products. The parts needed to build a TV are: 1 chassis, 1 picture tube, 2 speaker cones, 1 power supply, and 2 electronic kits. To build a stereo requires 1 chassis, 2 speaker cones, 1 power supply, and 1 electronic kit. Finally, speakers require 1 speaker cone and 1 electronic kit.

The **constraints** are simply that the number of parts used to build each product (calculated in cells G18:G22) cannot exceed the inventory (found in cells H18:H22). A non-negativity bound has also been added to the variables (C14:E14 >= 0) as it would be impossible to manufacture a negative amount of products. Since the company wants to maximize profit, we ask ASP to maximize the value of the **objective** (cell G24), the total gross profit.

You can view the complete model in the Task Pane Model tab. **Solve the model** by clicking the green arrow in the Model tab. ASP will run an optimization to find a solution of 200 TVs (cell C14), 200 Stereo (cell E14) and 0 speakers (cell E14). This solution gives a final objective of $25,000 in cell G24.

Now let's inspect a model of this same problem setup using Dimensional Modeling: Click the *Dimensional Modeling* tab.



Cells K13 and L13 define the Products and Parts dimensions. Cells K16:L17 define four cubes, using the PsiCube() function. Cells K20 and L20 contain cube formulas that calculate the constraints and objective, using the PsiReduce() function. Cells K25:K29 contain an Excel array formula{ =PsiCubeData(K20)} to display the values of the left hand sides of the constraints on the spreadsheet; but if you simply **double-click cell K17**, you'll see the same values in a pop-up window that functions like an "instant Pivot Table."

Notice that the **Task Pane Model tab** outline (not pictured here) lists the Dimensions and Cubes in the model, as well as the Variables, Constraints,

Objective and other model elements. To keep things simple for users who aren't using Dimensional Modeling, these outline elements appear *only* when you have functions such as PsiDim() and PsiCube() in cells on your worksheet.

The **decision variables** are still in cells C14:E14. Try changing one of these cells to a new value such as 100. You'll see that the worksheet **recalculates** just like a normal Excel model, even though it is composed of dimensions and cubes.

Dimensional optimization models continue to use a separate cell for each decision variable – whereas they might have thousands of constraints in a single cell. Keeping decision variables in individual cells makes it easy to capture final solution values, save them in your workbook, and use Excel to recalculate the spreadsheet later. Cube formulas appear to Excel as ordinary formulas (with single values) using user-defined functions such as PsiCube() and PsiReduce(); the actual multidimensional calculations are performed "behind the scenes" by the PSI Interpreter.

Solve the model by clicking the green arrow in the Model tab, just as you did on the Original sheet. You'll see the same optimal solution appear in cells C14:E14.

The following sections will take you step by step through the process of building a Dimensional Model like the one above. You can use the Analytic Solver menu choices, grouped under the Model button, to define dimensions, cubes and results, or you can type functions such as PsiCube() and PsiReduce() directly into cells, without using the GUI at all.

Using Dimensional Modeling in Optimization

Keep in mind the following three steps when using Dimensional Modeling:

1. Define a Dimension.

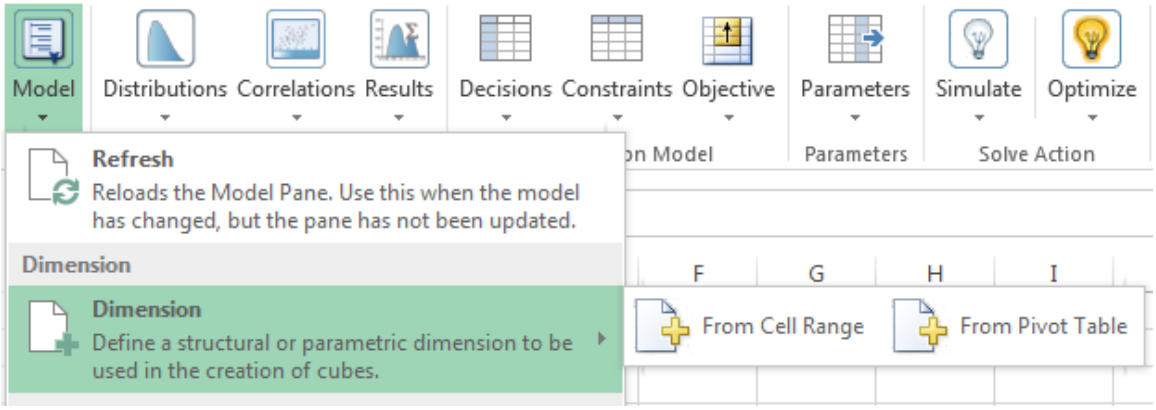
2. Define a Cube.

3. Define a Cube Output cell. (This step is optional).

Defining a Dimension

Two dimensions have been created in cells K13 and L13, Products and Parts, respectively. The Products dimension (cell K13) contains three items or elements: TVs, Stereos, and Speakers. The Parts dimension (cell L13) contains five items or elements: Chassis, LCD Screens, Speakers, Power Supply, and Electronics.

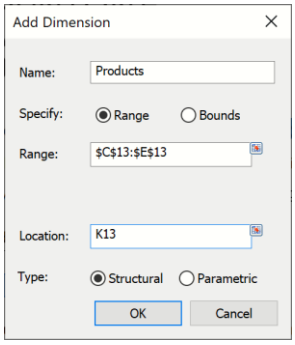
To create a dimension, you may either type the PsiDim() function call directly into a cell, or use the Model menu, shown below, to insert the PsiDim() formula into the active (selected) cell.



To use the Model menu, click **Model – Dimension – From Cell Range**. The Add Dimension dialog appears.

Enter a name of your choice for the *Name* field. In this case, we have used **Products**. Select *Range* and enter the Excel cell range that contains the product names. One could also enter an integer here, say "11", which would result in the creation of a dimension with 11 elements. Select *Bounds* to enter a lower and upper bound. These bounds can be entered directly into the lower and upper bound fields or cell addresses can be used. For example, if bounds of 1 and 10 are entered directly or cell addresses of cells containing 1 and 10 are entered into the *Lower* and *Upper* fields, a dimension with 10 (upper - lower + 1) elements will be created. (In this case, there will be no names associated with the elements other than indices from 1 to n.)

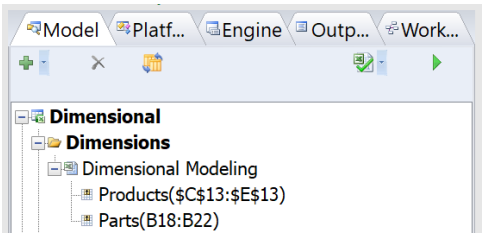
Enter the range address of **C13:E13** which hold the product names: TVs, Stereos, and Speakers. Specify the cell address or defined cell name for *Location*, this example uses **K10**. Finally, select **Structural** to create a Structural dimension. (See below for instructions on how to create a Parametric Dimension.) Click **OK** to add the formula "=PsiDim("Products",C13:E13)" to cell K13, Repeat these steps in cell L10 using the *Name* **Parts** and *Range* **B18:B22**.



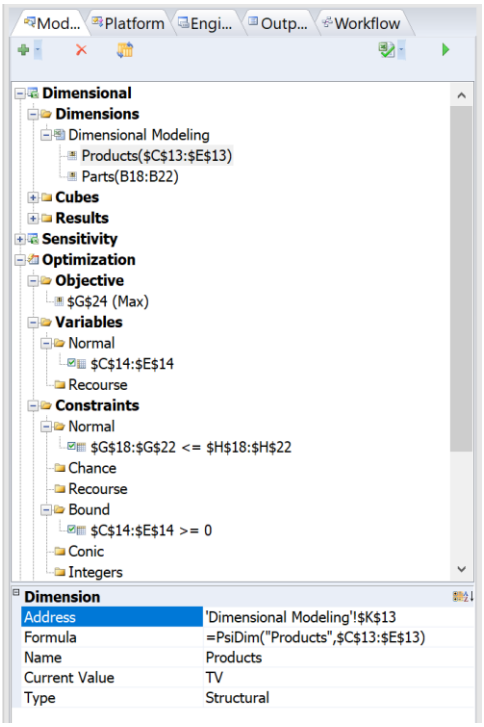
For more information on the *PsiDim()* function, please see the Frontline Solvers Reference Guide.

Let's take a look at the Model tab on the Solver Task Pane. You should now have two dimensions listed under the *Sheet1* worksheet, Products and Parts. The Products dimension has three elements: TVs, Stereos, and Speakers. The Parts

dimension has five elements: Chassis, Screen, Speaker, Power Supply and Electronics.



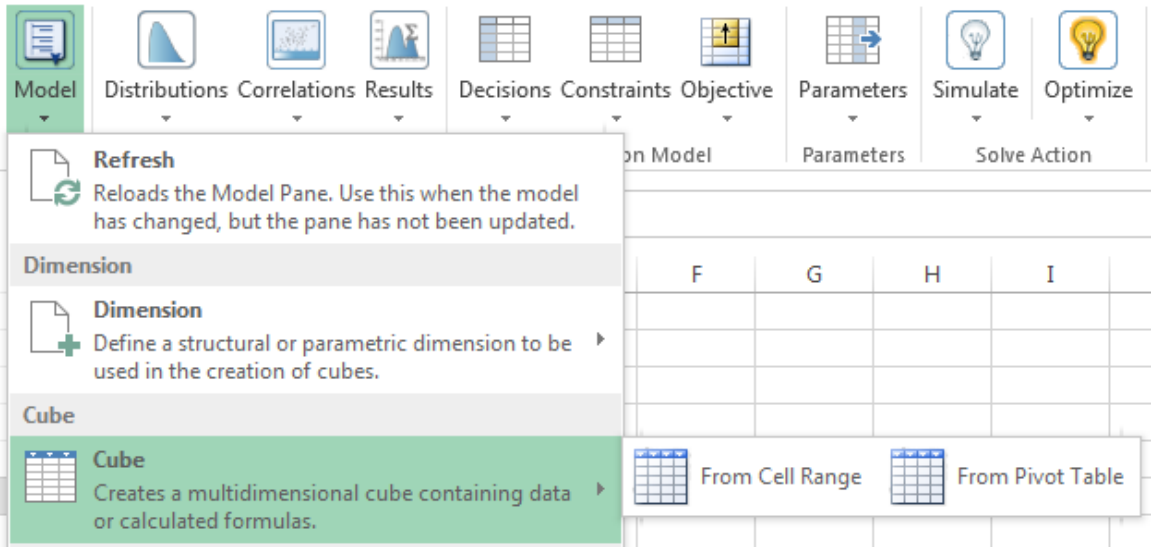
Select the Products dimension.



Several options will appear at the bottom of the task pane under Dimension (as shown in the screenshot above). Here you can view the cell where the dimension is located (cell K13), the formula, the name of the dimension and the type of dimension (structural or parametric). These fields are all read-only. Current Value, however, controls the values displayed in the cell containing the cube. For example, select Speakers for Current Value. Values in cells K16, K17, L16, and L17 will change to reflect values for Speakers. For example, K13 will change to Products[3] to indicate that the third element of the Products dimension has been selected. K16 will change to 0 (the value of cell C13), K17 will change to 450 (the value of cell H18), L16 will change to 35 (the value of cell E24), and cell L17 will change to 0 to reflect that 0 chassis are used in the production of speakers.

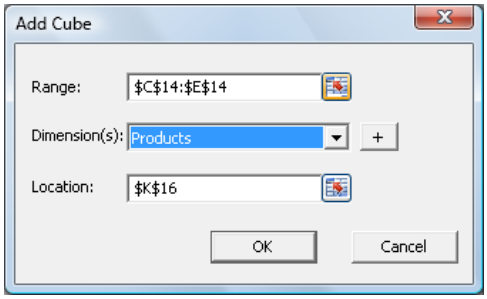
Defining a Cube

Four Cubes have been created in cells K16 (which holds the variable cells), L16 (which holds the Profit values for each product), K17 (which holds the constraint right hand sides), and L17 (which holds the amount of parts used per product). To create a cube, you may either type the *PsiCube*() formula into a cell or use the Model menu, shown below, to insert the formula into the selected cell.



To use the Model menu, click **Model – Cube – From Cell Range**. The *Add Cube* dialog appears.

Enter an Excel cell range for *Range*, in this instance, select cells **C14:E14**, the variable values. Select **Products** from the *Dimension* drop down menu. To add more than one dimension to the cube, click "+" button. Select a blank cell for *Location* – this example uses cell K16. Click **OK** to create the cube. The following formula will be entered into cell K16, =PsiCube($C$14:$E$14,"Products"). (This formula may also be entered directly.)



The first argument of any cube is the cell address of the data. In the cube located in cell K16, the first argument is C14:E14 (the variable cells). The second thru ninth arguments are the dimensions for which the data will be calculated. (At least one dimension is required.) This 1-dimensional cube, calculated over the Products dimension, holds the data in cells C14:E14 which

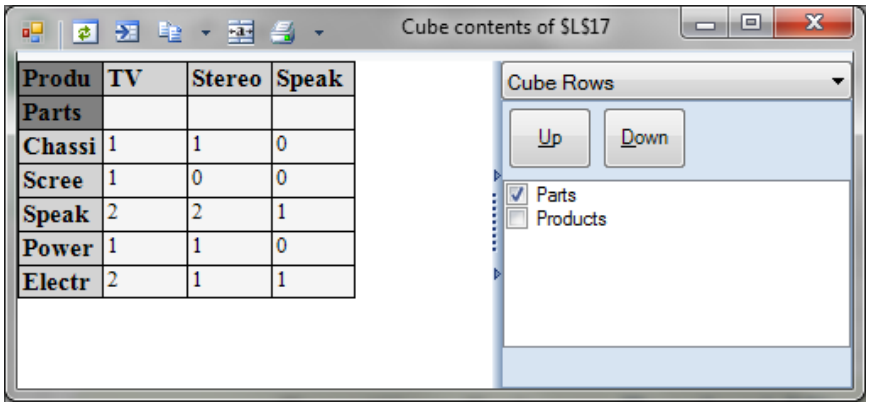
are the number of products to build - the decision variables. The data for the cube located in cell L16 can be found in cells C24:E24. This 1 dimensional cube contains the profit values for each of the products. This cube is also calculated over the Products dimension. In the 1 – dimensional cube located in cell K17 (the cube holding the constraint right hand sides), the data is contained in cells H18:H22. In cell L17, a 2-dimensional cube has been created using the *Products* and *Parts* dimensions. This cube holds the fact table containing the parts required per product (cells C18:E22).

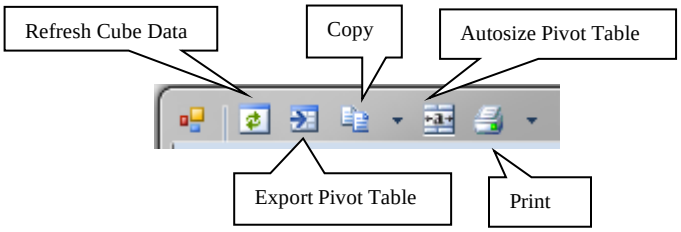
Note: When calculating a cube over multiple dimensions, the "most rapidly changing" dimension *must* be first, while the "most slowly changing" dimension *must* appear last. Take the example table below.

	A	B	C	D
1	Part Name	LCD TV	Stereo	Speakers
2	Chassis	1	1	0
3	Screen	1	0	0
4	Speaker	2	2	1
5	Power Supply	1	1	0
6	Electronics	2	1	1

Starting from cell B2 (the start of the fact table) and reading from left to right, the 1st element of the cube will be 1 (Chassis & **LCD TV**), the 2nd element of the cube will be 1 (Chassis & **Stereo**), the 3rd element of the cube will be 0 (Chassis & **Speakers**). The 4th element of the cube will be 1 (Screen & **LCD TV**), the 5th element of the cube will be 0 (Screen & **Stereo**) and the 6th element of the cube will be 0 (Screen & **Speakers**). Between Products and Parts, which dimension is changing more frequently as we read from left to right? Correct! Products is changing more frequently which means this dimension should come first in the AddCube dialog or *PSICube()* function.

Double click cell L17 to open the fact table for the cube located in this cell. The following window appears. The data contained in this fact table is the same data contained in cells C18:E22. Click the arrows on the right side of the dialog to open an additional pane. Here you can control the display formatting of the cube by selecting **Cube Rows** or **Cube Columns** from the drop down menu or by simply dragging **Parts** to **Products** and vice versa.





Click the Refresh Cube Data icon when changes have been made to the contents of the cube on the spreadsheet. Click the Export Pivot Table icon to export the contents of the cube to an Excel Pivot Table. Click the Copy icon (or click the down arrow to the right of the icon) to copy the grid to the spreadsheet, to Outlook, Word, etc. Click the Autosize Pivot Table icon to autosize the columns in the grid. Click the Print icon (or click the down arrow to the right of the icon) to send the grid to the printer, see a print preview, or to change printer or page settings.

Cube Formulas: Operations and Dimensions

When executing an operation over cubes, if all participating cubes have the same dimensions, then the result cube will have the same dimensions too. For example, if a cube with 4 dimensions is multiplied (or added, subtracted, divided, etc.) with another cube also containing the same 4 dimensions, the result cube will contain the same 4 dimensions.

Otherwise, the result cube will be a *union* of the participating dimension sets. For example, if a cube B2 with two dimensions is multiplied by a cube C3 with one dimension *that also appears in the first cube*, the result B2*C3 will be two-dimensional. If C3 is defined over a dimension *different from* either of the two dimensions in B2, the result cube will be three-dimensional.

You can use almost any Excel arithmetic or intrinsic operations, as well as almost all Excel built-in functions in cube formulas. There are a few Excel functions that are not supported by the PSI Interpreter and are thus not supported in Dimensional Modeling. These functions include: CubeX(), Call(), Cell(), EuroConvert(), GetPivotData(), Info(), Hyperlink(), Indirect(), RegisterID() and SQLRequest().

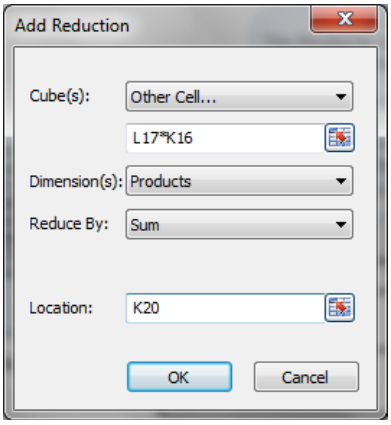
Now let's calculate the constraints. In the original model, the constraints are the number of parts used (cells G18:G22) must be less than the inventory (found in cells H18:H22).

To calculate the constraint in this example using Dimensional Modeling, we must use the *PsiReduce()* function. This function reduces or aggregates a multi-dimensional cube along one dimension. A cube may be aggregated using the following supported functions: average, sum, max, min, stdev, or var. (For example, if PsiReduce() is used to aggregate a 3 –dimensional cube, the resultant cube would contain 2 dimensions.) A cube reduced along all its dimensions is called a Degenerated Cube and will be a single value, or scalar.

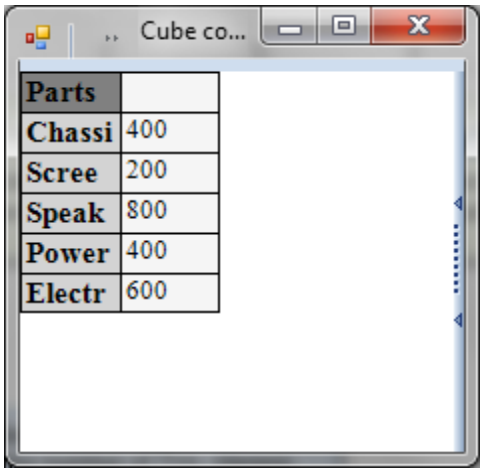
Select cell K20, then click **Model – Reduction**. The *Add Reduction* dialog appears.

Select **Other Cell** from the *Cube* drop down menu, then enter **L17*K16** into the empty field. Since we want to reduce the cube along the Products dimension, select **Products** from the *Dimension* drop down menu. Next select **Sum** from the *Reduce By* drop down menu. This is how the cube will be aggregated.

Confirm that *Location* is cell K20, then click **OK**. The formula, =PsiReduce($L$17*$K$16, "sum","Products"), is entered into cell K20. In general, the equation for this cube is: $R = \sum_j Xj * Yij$, for each i= 1 to 5, where X equals the products (TVs, stereos, and speakers), Y equals the parts (chassis, screen, speaker, power supply, & electronics) and R is a 1-dimensional vector containing 5 elements.

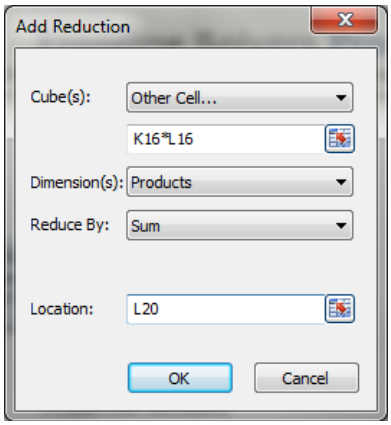


The multiplication of the two cubes in cells L17 and K16 in the first argument of PsiReduce will result in a third cube containing the product of the *number of parts per product* and the *variable values* in cells C14:E14. The cube in cell L17 contains 15 elements and is calculated along two dimensions, Products and Parts. The cube in cell K16 has 3 elements and holds the fact table for only 1 dimension, Products. Remember, when multiplying two cubes with different dimension sets, the resultant cube will be structured along the Union of both dimension sets. In this case, the resultant cube will be structured along both the Products and Parts dimensions and will also contain 15 elements. PsiReduce() reduces or eliminates the specified dimension in the third argument, in this case the Products dimension. The cube multiplication and reduction occurring in this single cell (cell K20) perform the same operations as cells G18:G22 in the original problem! Since Cubes are single cells, they can display only the first element of their cube result. In order to see all cube elements, simply double click cell K20. A popup window appears containing the following fact table.



It's also possible to check the contents of a cube on the worksheet using the PsiCubeData() function. Please see the Frontline Solvers Reference Guide for more information on this function.

PsiReduce() is also used to calculate the objective function. To compute the objective, we must multiply the cube containing the decision variables (cell K16) by the cube containing the Profit values (cell L16). Select cell L20 and click **Model – Reduction**. The *Add Reduction* dialog appears.



Select **Other Cell** from the *Cube* drop down menu and enter **K16*L16** in the blank field. Since we are looking to sum over the Products dimension (sum the products of Products * Profits), select **Products** from the *Dimension* menu and **Sum** from the *Reduce By* menu. Confirm the *Location* is cell **L20** and then click **OK**. The formula, =PsiReduce($K$16*$L$16, "sum","Products"), is entered into cell L20. The result of this cube is a scalar or a single value.

Defining Outputs in Dimensional Models

It's also possible to use an output function such as PsiOptData() to observe the contents of a fact table on the spreadsheet, rather than in a pop up fact table. Let's designate cells K25:K29 as output cells to observe the final values of all five constraints calculated in cell K20. To do so highlight cells K25:K29, then enter "=PsiOptData(K20)", then CTRL + SHIFT + ENTER on the keyboard to enter this formula as an array. Once Solver finds a solution, these cells will be populated with the left hand side of each constraint. For example, cell K25 will display the left hand side of the first constraint, cell K26 will display the left hand side of the 2nd constraint, cell K27 will display the left hand side of the 3rd constraint, and so on.

It's also possible to create "what if" scenarios using Dimensional Modeling without ever having to run an optimization (or simulation) using a 2nd type of output function, PsiCubeOutput(). For more information, please see below under **Additional Functions**.

Now let's create our Solver model by adding the variables and constraints to the Platform Task Pane.

Building the Model

At this point we can now start building our model in the Platform Task Pane.

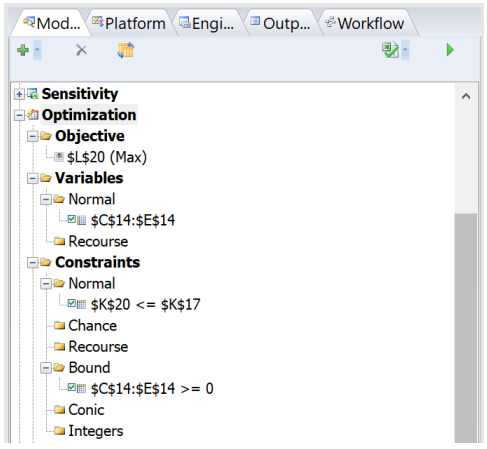
1. Add the Variables: Select cells C14:E14, then click **Decisions** on the Ribbon. (Alternatively, click Decisions – Normal on the Ribbon.) If you inspect the Task Pane, you will find that cells C14:E14 now appear under the Normal Variables section.

2. Add the Constraints: Select cell K20, then click **Constraints** on the Ribbon. The Add Constraint dialog will appear. (Alternatively, click the down arrow under Constraints, then select Normal -- <= from the menu.) Enter cell K20 as the left hand side of the constraint and cell K17 as the right hand side of the constraint, then click OK. If you inspect the Task Pane, you will find K20 <= K17 now appears under Normal Constraints.

3. Add the Objective: Select cell L20, then click **Objective**, then **OK**. (Alternatively click the down arrow under **Objective**, then select **Max – Normal** from the menu.) If you inspect the Task Pane, you will find that cell L20 now appears under Objective with "(Max)" appearing to the right.

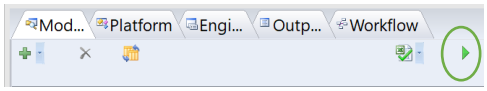
4. Add Variable Bounds: Since it would be impossible to make a negative amount of products, we must add a non-negativity bound. To do so, select cells C14:E14, then click Constraints. (Alternatively, click the down arrow under **Constraints**, and select **Variable Type/Bound** -- >= from the menu**.)** The Add Constraint dialog will open. Select >= for the "sense" of the constraint (drop down menu in the middle). Enter "0" as the constraint left hand side, then click OK. If you inspect the Task Pane, you will find C14:E14 >= 0 now appears under Bound.

The Task Pane will look like the following.



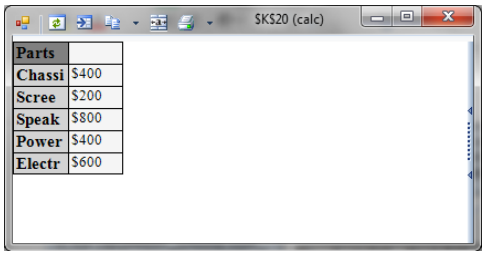
Solving the Model

Enter 0's into cells C14:E14 then solve the model by clicking the green arrow on the Model Task Pane.



Solver will solve the model and display the final variable values in cells C14:E14: 200, 200, and 0, respectively. The status bar (found beneath the Task Pane) will display the message *Solver found a solution* with a green background. Analytic Solver will populate the objective formula located in L20 when the optimization finishes successfully. Note: All Solver engines *except* Interval Global Solver support Dimensional Modeling.

Double click cell K20 to open a grid displaying the right hand sides of the constraints or the number of parts used to manufacture the three products.



As you can see by the comparison of these two models, using a cube to model a problem will result in a more compact and easier to read model. Continue reading the next section to learn about the 2nd goal of dimensional modeling, the parametric dimension.

Now close this example, and continue reading to discover how to use a parametric dimension within an optimization model.

Additional Functions

Using Dimensional Modeling, it's possible to create what if scenarios without ever having to run an optimization (or simulation). The function PsiCubeData() will list the contents of any cube on the spreadsheet much like PsiOptData() listed the left hand sides of the constraints in the example above. The difference between these two functions is that PsiOptData() will only be populated after an optimization is run, while PsiCubeData can be populated at any time. Let use *PsiCubeData()* to list the contents of the Cube located in cell K17. (This cube holds the constraint right hand sides.) First, highlight 5 blank cells, say K31:K35, enter "=*PsiCubeData(K17)*", then press CTRL + SHIFT + ENTER to enter the formula as an array in all five cells. Next, click **Model – Cube Result – Calculate** to calculate the cube *without performing an optimization*. Afterwards, Cell K31 will display 450, cell K32 will display 250, cell K33 will display 800, cell K34 will display 450, and cell K35 will display 600. These values correspond to the values in cells H18:H22.

You'll notice that after you performed a manual cube calculation (by clicking Model – Cube Result – Calculate), the objective function cell (cell L20) now displays #NA. To calculate and display the value of a degenerated cube (a cube that has been reduced to a scalar value), click **Model – Cube Result – Output** to append "+PsiCubeOutput()" to the existing formula to designate this cell as a cube output. Afterwards, click **Model – Cube Result – Calculate** to recalculate all cubes on the worksheet. Note: PsiCubeOutput is not required in cell L20 when running an optimization as Solver will calculate and display the contents of the objective function after a solution is found.

Now let's use PsiCubeData() to display the multidimensional cube in cell L17. First, we need to determine whether the result in L17 is a cube and which dimensions constitute that cube. Since no more than two dimensions (Parts and Products) are defined in the worksheet, we'll highlight two blank cells and enter *PsiCubeData()* as an array formula in these cells. (Note: If you aren't sure how many dimensions are contained in a cube, select a few extra columns and rows for the array formula. The excess cells will simply display #N/A.) Let's pretend that we aren't sure of the number of dimensions contained in this cube, we know there are at least two, so let's highlight three cells, K32:M32. With all three cells highlighted, enter the following formula: =PsiCubeData(L17, "dims"). When "dims" is passed for the *struc_format* argument (2nd argument), the name and size of each dimension will be returned. Afterwards, press SHIFT + CTRL + ENTER to enter this formula as an array in cells K32:M32. Afterwards, K32 will display "Parts[5]" indicating that there are 5 elements in the Parts dimension. L32 will display "Products[3]" indicating that there are 3 elements in the Products dimension. M32 will display "#N/A" indicating that a third dimension does not exist in the cube. Now that we know the number of elements (or size) of the dimensions, we can display the fact table again by entering *PsiCubeData()* as an array, but this time we'll use "vals" for the *struc_format* argument.

When passing "vals" for this argument, *PsiCubeData(),* when entered as an array, will display the data as a relational table. Since there are 3 elements in the Products table and 5 elements in the Parts table, the fact table for this cube will contain 15 (3 x 5) elements. Therefore, we will need to highlight 1 column for the first dimension (Parts), a 2nd column for the 2nd dimension (Products), a 3rd column for the actual values and 15 rows to hold all 15 values in the fact table. In this example, we'll use the blank cells K33:M47. (This area encompasses three columns and 15 rows.) Select these cells, enter "=PsiCubeData(L17, "vals"), then press SHIFT + CTRL + ENTER to enter this formula as an array formula. The following table will be displayed.

Important Note: While PsiCubeData() formulas are populated when **Model – Cube Result** – **Calculate** is selected, these formulas will *not* be populated during the optimization unless Dimensional Calculation is set to Automatic on the Platform tab in the Task Pane. If Dimensional Calculation is set to Manual, *PsiOptData()* can be used in place of PsiCubeData() but *only* with cubes holding an optimization model component, such as a cube holding decision variables (K16) or calculating constraints (K20). *PsiOptData()* will be populated after an optimization even when Dimensional Calculation is set to Manual. However, *PsiOptData()* will *not* be populated when **Model – Cube Result – Calculate** is selected on the Ribbon. Please see *PsiOptData()* in the Frontline Solvers Reference Guide for more information on this function.

	K	L	M
32	Parts[5]	Products[3]	#N/A
33	Chassis	TV	1
34	Chassis	Stereo	1
35	Chassis	Speakers	0
36	Screen	TV	1
37	Screen	Stereo	0
38	Screen	Speakers	0
39	Speaker	TV	2
40	Speaker	Stereo	2
41	Speaker	Speakers	1
42	Power Suppl	TV	1
43	Power Suppl	Stereo	1
44	Power Suppl	Speakers	0
45	Electronics	TV	2
46	Electronics	Stereo	1
47	Electronics	Speakers	1

If you wanted to display *only* the values in the fact table, then you would need to highlight 15 blank cells, in say the M column (we'll use cells M33:M47), then enter *PsiCubeData()* without the 2nd argument or "=PsiCubeData(L17)" then press SHIFT + CTRL + ENTER to enter the formula as an array formula in cells M33:M47. Afterwards, these cells would display only the *values* of the fact table as shown in cells M33:M47 in the above screenshot.

PsiCubeData() can also be used to display a slice or even a single element of the fact table. For example, to display the cube data only for Part: Screen and Product: TV, select three cells, say N36:P36 and enter the following formula: =PsiCubeData(L17, "[Parts].[Screen], [Products].[TV]"). Then press SHIFT + CTRL + ENTER to enter as an array formula. Afterwards, the following table will be displayed.

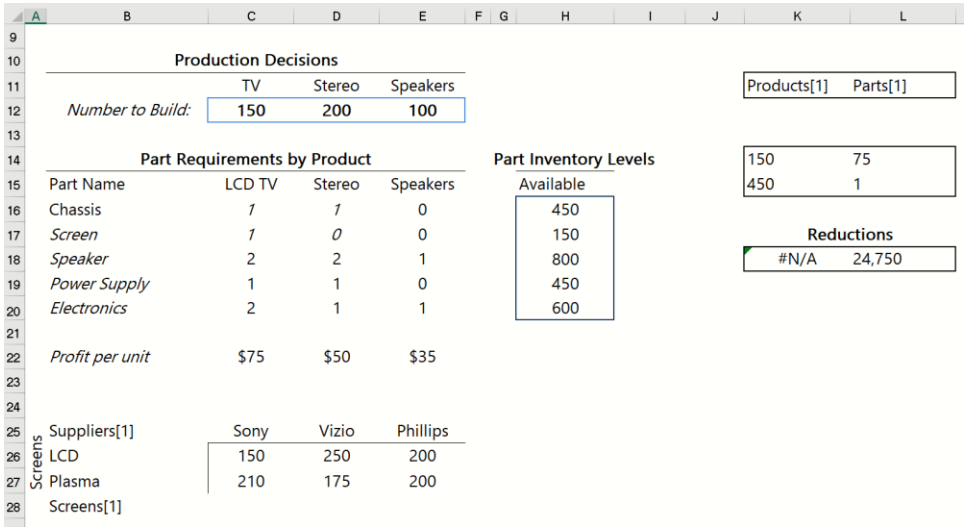
	N	O	P
36	Screen	TV	1

Parametric Dimensions with Optimization

You can define and use a Parametric Dimension to run multiple optimizations, simulations, and/or calculations. Analytic Solver treats all data included in a parametric cube as parameter values, such as ones defined by PsiOptParam(), PsiSimParam() and PsiSenParam(). Recall that these parameters are automatically varied by ASP in order to create a type of "what-if" analysis. Please see the chapter "Examples: Parameters and Sensitivity Analysis" in this Guide for more information on the PsiOptParam(), PsiSimParam() and PsiSenParam() functions. *If a model only includes Parametric Dimensions, each value in the Output cube will be associated with a different simulation or optimization parameter, rather than a set of model functions.*

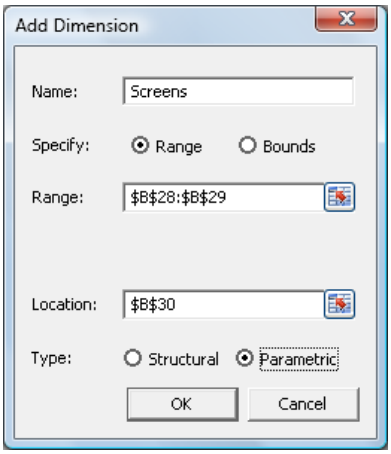
Open the example, Parametric Dimensions.xlsx by clicking **Help -- Examples** on the Analytic Solver ribbon. The Frontline Example Models Overview.xls file will open. Select the *Optimization* tab and choose the **ParametricDimensions** workbook from the list.

In this example, we will illustrate the use of a Parametric Dimension by adding an additional element to the model. Imagine that you have a choice to purchase two different types of TV screens, plasma or LCD, from three different suppliers, Sony, Vizio, and Phillips, for about the same price. Each supplier can deliver a specific number of screens depending on the type of screen chosen. For example, Sony can only deliver 150 LCD screens, but 210 Plasma screens while Vizio can deliver 250 LCD screens but only 175 Plasma. Your job is to now not only decide how many TVs, stereos, and speakers to make, but also to decide what type of screen will go into the TVs: plasma or LCD.



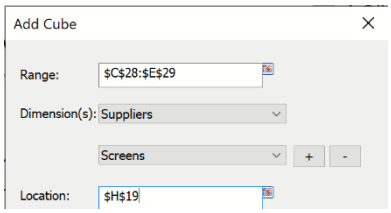
9											
10		**Production Decisions**									
11			TV	Stereo	Speakers					Products[1]	Parts[1]
12		*Number to Build:*	150	200	100						
13											
14		**Part Requirements by Product**					**Part Inventory Levels**			150	75
15		Part Name	LCD TV	Stereo	Speakers		Available			450	1
16		Chassis	*1*	*1*	0		450				
17		*Screen*	*1*	*0*	0		150			**Reductions**	
18		*Speaker*	2	2	1		800			#N/A	24,750
19		*Power Supply*	1	1	0		450				
20		*Electronics*	2	1	1		600				
21											
22		*Profit per unit*	$75	$50	$35						
23											
24											
25	Screens	Suppliers[1]	Sony	Vizio	Phillips						
26		LCD	150	250	200						
27		Plasma	210	175	200						
28		Screens[1]									

Cell B30 contains a parametric dimension. To add this dimension, click **Model – Dimension – From Cell Range** to open the Add Dimension dialog. Enter **Screens** for *Name*, Select the *Range* radio button, select or enter cells **B28:B29** in the *Range* field, confirm cell B30 is selected for *Location*, then select **Parametric**. Then click **OK**.



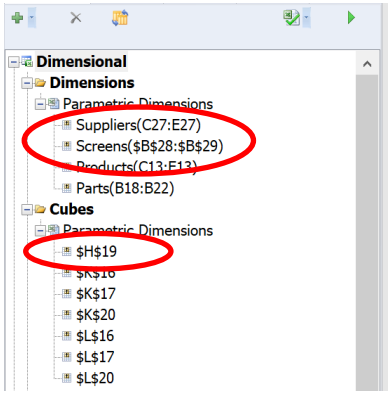
The following formula is entered into cell B30, = *PsiParamDim("Screens", B28:B29*). As you can see, the arguments for *PsiParamDim()* are identical to *PsiDim()*. The first argument is the name of the dimension and the 2nd argument is an Excel range. It's also possible to enter upper and lower bounds for the 2nd argument (select Bounds on the Add Dimension dialog) or to simply enter an integer n which will create a parametric dimension with n elements. (In this case, there will be no names associated with the elements other than indices from 1 to n.) Repeat the steps above to create a second Parametric Dimension in cell H19 using the name **Suppliers** and the Excel range **C27:E27**.

Now select cell H19 and click **Model – Cube – From Cell Range** to bring up the *Add Cube* dialog. This cube will contain the values from cells C28:E29. Therefore, select cells **C28:E29** for *Range*. Select **Suppliers** for *Dimensions*, then click the "+" command button to add a 2nd dimension, **Screens**. Note: As mentioned above, when calculating over multiple dimensions, the "columns" dimension, or the dimension that is most often changing, must always come first. Confirm that H19 is listed for Location and click OK.



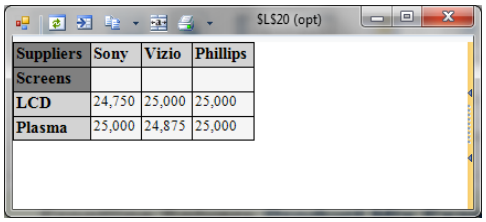
The formula *=PsiCube($C$28:$E$29,"Suppliers","Screens")* will be entered into cell H19.

If you inspect the Model tab on the Task Pane, you'll see that two more dimensions (Suppliers and Screens) and one more cube ($H$19) appear under the appropriate headings.



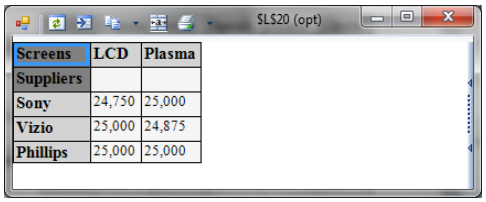
Now click the green arrow on the Model tab to run Solver. Solver will run six different optimizations each time using a different value from the cell range C28:E29 for cell H19. For example, for the first optimization, Solver will use 150 for the value of H19, for the 2nd optimization, Solver will use 210 for the value in cell H19, for the 3rd optimization, Solver will use 250 for the value in cell H19, etc.

To easily. view the results of the six different optimizations, simply double click cell L20 to display the grid shown below.



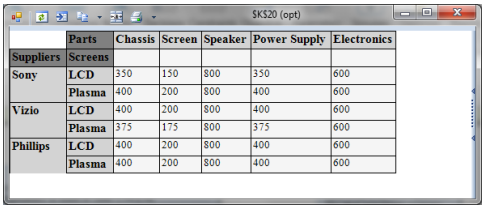
Suppliers	Sony	Vizio	Phillips
Screens			
LCD	24,750	25,000	25,000
Plasma	25,000	24,875	25,000

Instantly six different "what if" scenarios are displayed organized by supplier and screen. (Click the resize icon to autofit the columns to display all values/text.) As you can easily see there are four different options that result in the largest profit. Purchasing LCD screens from either Vizio or Phillips or Plasma screens from Sony or Phillips will result in a Gross Profit of $25,000. Purchasing Plasma screens from Vizio will result in a decreased profit of $24,875 and purchasing LCD screens from Sony results in an even smaller profit of $24,750. To view the products across the top and the manufacturers down the left of the grid, simply drag "Screens" above "Suppliers".



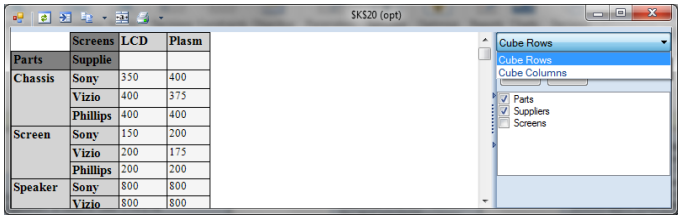
Screens	LCD	Plasma
Suppliers		
Sony	24,750	25,000
Vizio	25,000	24,875
Phillips	25,000	25,000

Double click cell K20 to view the number of parts required in the construction of the TVs for each of the six different screen options. (Click the icon to autofit the columns to display all values/text.)



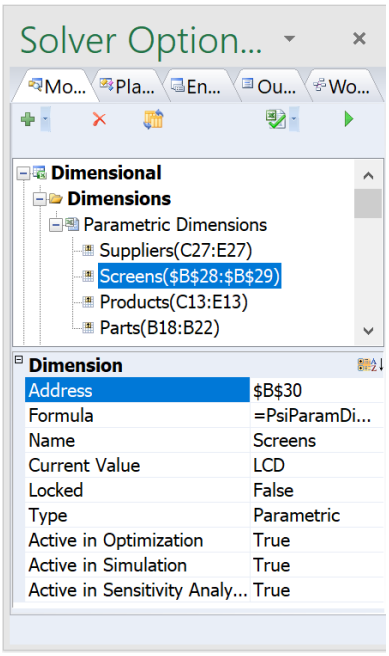
	Parts	Chassis	Screen	Speaker	Power Supply	Electronics
Suppliers	Screens					
Sony	LCD	350	150	800	350	600
	Plasma	400	200	800	400	600
Vizio	LCD	400	200	800	400	600
	Plasma	375	175	800	375	600
Phillips	LCD	400	200	800	400	600
	Plasma	400	200	800	400	600

Note: The organization of the grid can be easily changed to meet your needs by simply dragging the dimensions Parts, Suppliers, and Screens into the formulation of your choice. Or click the double arrows on the right side of the dialog to open the options window. Check the dimensions to be listed by row and by column.

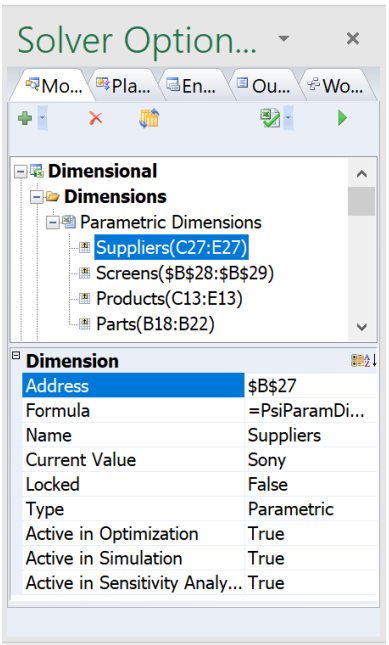


	Screens	LCD	Plasm
Parts	Supplie		
Chassis	Sony	350	400
	Vizio	400	375
	Phillips	400	400
Screen	Sony	150	200
	Vizio	200	175
	Phillips	200	200
Speaker	Sony	800	800
	Vizio	800	800

If you wanted to view the final objective value when Sony Plasmas as used in the construction of the TVs, first select *Screens* on the Model tab, then select *Plasma* for Current Value.



Now select *Suppliers* on the Model tab, then select *Sony* for *Current Value*.

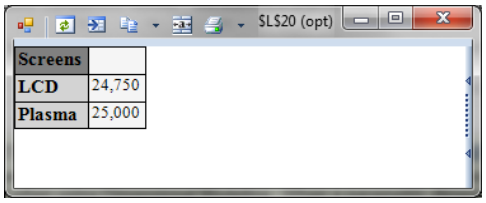


Cell H19 will change to 210 to reflect the value in cell C29 which is the number of Plasma screens Sony can supply. In addition, the final variable values in cells C14:E14 will change to 200, 200, 0, the objective shown in cell L20 will change to $25,000, the parametric dimensions in cells B27 and B30 will change to Suppliers[1] (to reflect that the first element of the Suppliers dimension is

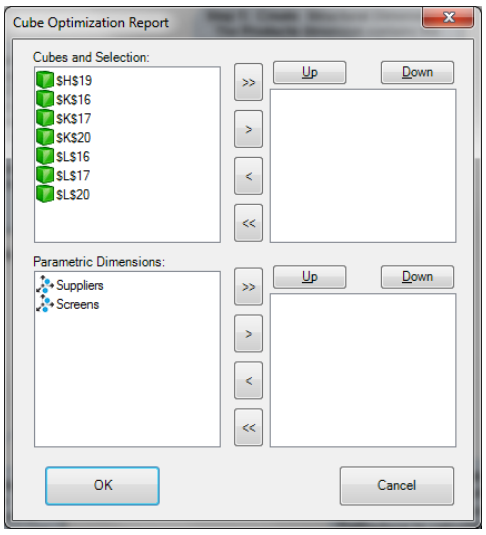
selected as the current value) and Screens[2] (to reflect that the 2nd element of the Screens dimension is selected as the current value).

As with *PsiParamDim()*, several options will appear at the bottom of the task pane under Dimension (as shown in the screenshot above). Here you can view the cell where the dimension is located (B27), the formula, the name of the dimension (Suppliers) and the type of dimension (structural or parametric). These fields are all read-only. However, Current Value, Locked, Active in Optimization, Active in Simulation, and Active in Sensitivity Analysis can all be edited. Current Value controls the values displayed in the cube cells. For example, select Vizio for Current Value. The value in cell H19 will change to reflect the Vizio value for the Current Value of the Screens dimension (210).

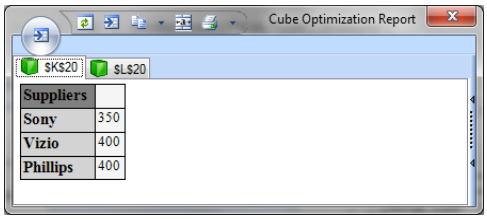
Setting Locked to True, will result in the dimension being "locked" or "frozen" to the Current Value element during optimization. For example, if Current Value is set to Sony for the Suppliers Parametric Dimension and Locked is set to True only two optimizations will be ran when the green arrow is clicked, one optimization for the value 150 (cell C28) and one optimization for the value 210 (cell C29). Double click the objective cell (L20) to display the results for the two different screens supplied by Sony.



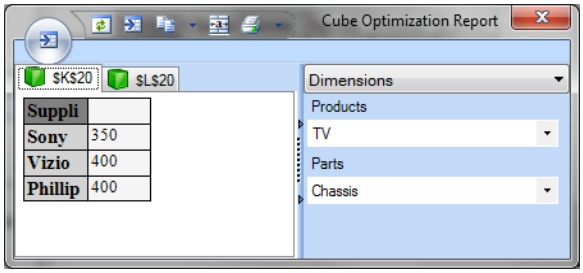
You can also reduce the dimensions displayed in the grid by performing a Parametric Analysis. Click **Reports – Optimization – Parameter Analysis** to open the Cube Optimization Report dialog.



All seven cubes appear under Cubes and Selection, select cells L20 and K20 and click > to select. Both dimensions (Suppliers and Screens) appear under Parametric Dimensions, select one dimension, say Suppliers, then click > to select. Afterwards, click OK. The following grid appears.



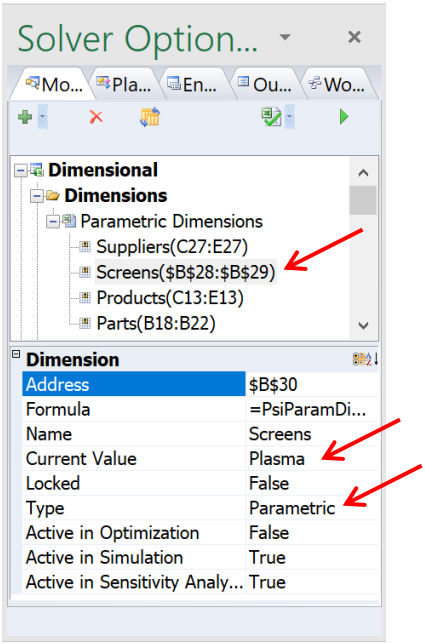
Here the "slices" of the structural dimensions can be viewed. Click the two arrows on the right of the dialog to open the "options" pane.



This grid displays the number of chassis parts required when Screens are purchased from each Supplier. For example, if the screens are purchased from Sony, only 350 chassis will be needed. If screens are purchased from Vizio or Phillips, 400 chassis will be required. Note: When a dimension is deactivated, it is essentially locked to its first element. In this case, the Screens dimension is locked to the LCD values of 150, 250, and 200. Click the down arrow under Parts to see how many of each part will be required when screens are purchased from each supplier.

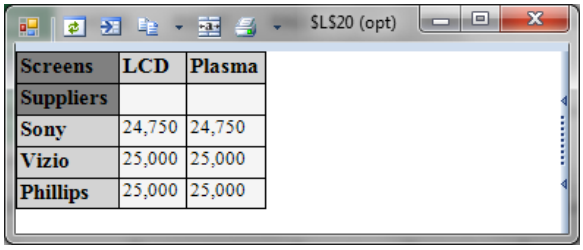
Currently both the Screens and Suppliers Parametric Dimensions are active in all three types of analyses: optimization, simulation and sensitivity. As stated earlier, this means that if you wanted to use these dimensions for a parameter analysis, you could do so as an optimization parameter, sensitivity parameter, and/or simulation parameter. To remove this Parametric dimension from any of these analyses, simply change True to False. If Active in Optimization is set to False, this dimension will be ignored in the next optimization. Likewise, if Active in Simulation or Active in Sensitivity Analysis is set to False, then this dimension will be ignored in the next simulation or sensitivity analysis.

For example, select **Screens** in the Model Task Pane, select **Plasma** for *Current Value*, then change *Active in Optimization* to **False**.

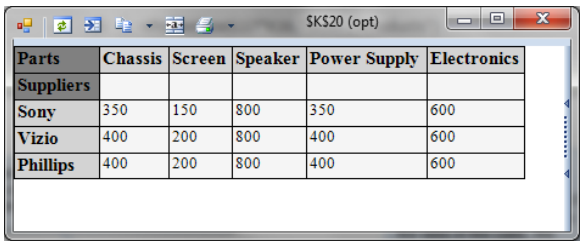


Now run an optimization either by clicking the green arrow on the Task Pane or **Optimize – Solve Complete Problem** on the ribbon.

Solver will run three optimizations – one each for values 150, 250, and 200 or the number of LCD screens (the first element in the Screens dimension) that can be supplied by Sony, Vizio and Phillips, respectively (cells C28:E28). To view the results of each value, simply select Suppliers on the Model Task Pane and select Sony, Vizio, or Phillips or double click any of the cubes to display the values for these three optimizations. For example, click cell L20 and K20 to display the following grids. Both grids only reveal the optimization results for the three suppliers calculated using the first element from the Screens dimension.



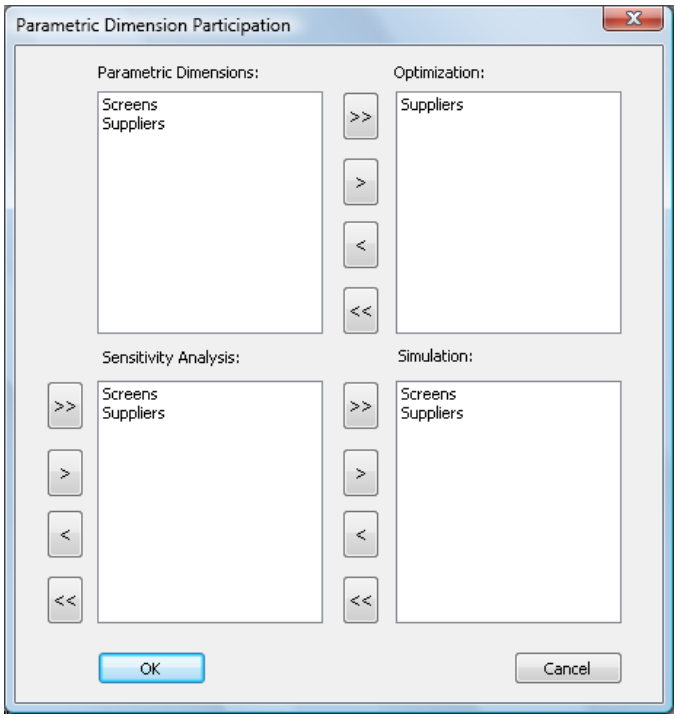
Screens	LCD	Plasma
Suppliers		
Sony	24,750	24,750
Vizio	25,000	25,000
Phillips	25,000	25,000



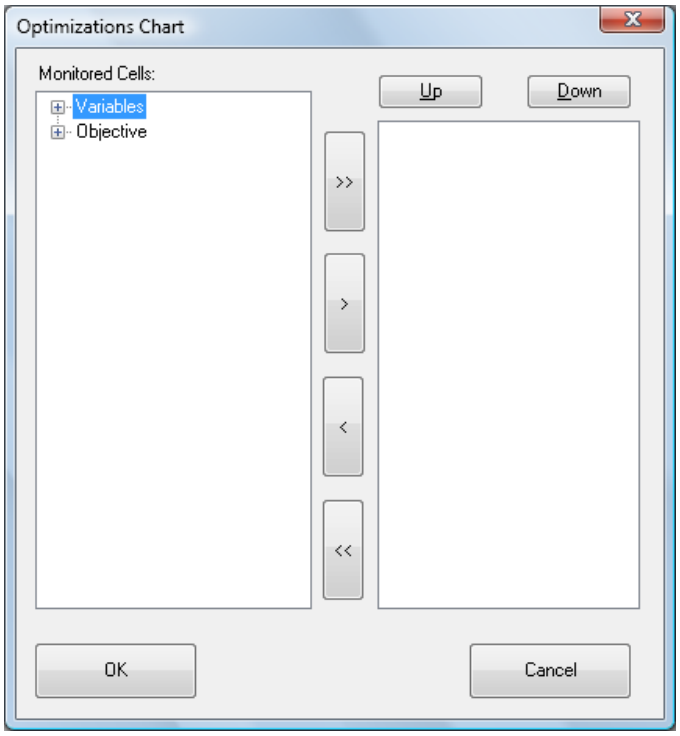
Parts	Chassis	Screen	Speaker	Power Supply	Electronics
Suppliers					
Sony	350	150	800	350	600
Vizio	400	200	800	400	600
Phillips	400	200	800	400	600

It's also possible to view all Parametric Dimensions included in the workbook by clicking **Parameters – Dimension** on the Ribbon to bring up the Parametric Dimension Participation dialog. From here you can select which dimensions are

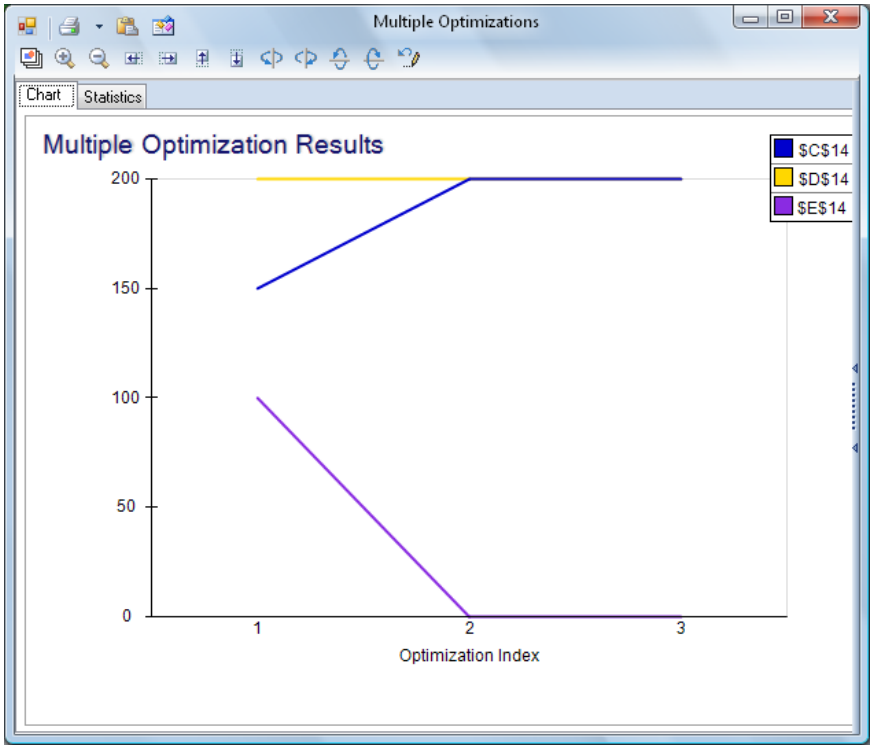
active for Optimization, Sensitivity Analysis and Simulation, all on one screen. For example, to remove the Suppliers Parametric Dimension from Simulation, select Suppliers and click <. To remove all Parametric Dimensions from Simulation, click <<.



After an optimization has finished, click **Charts – Multiple Optimizations – Monitored Cells** to open the Optimizations Chart dialog.



Expand Variables (by clicking the "+"), then expand C14:E14. Select **C14**, then click > to add the decision variable to the chart. Repeat this step for cells D14 and E14, then click OK to create the chart below, which tracks the decision variable values for each of the three optimizations.



Using Dimensional Modeling in Simulation

Dimensional modeling can also be used with simulation models as well as with simulation optimization models. (Note: Dimensional Modeling is not available with Stochastic Transformation.) Open the example, CityCube.xlsx by clicking **Help -- Examples** on the Analytic Solver ribbon. The Frontline Example Models Overview.xls file will open. Select the Simulation tab and choose CityCube.xlsx from the list.

	A	B	C	D	E	F	G	H	I	J	K	L
12		*Tax Rate*	*9%*									
13								City[4]				
14		City	Gross Income ($M)						PsiMean()		PsiStdDev()	PsiVar()
15		San Francisco	40		Dimension:	City[1]		San Francisco	36.3923408		18.165084	329.97
16		San Diego	25		Cube:	39.9916		San Diego	22.7498793		1.85834381	3.45344
17		San Jose	20		Cube:	36.3923		San Jose	18.2004632		2.72726908	7.438
18		Los Angeles	30		Output Cell	36.3923		Los Angeles	27.2999987		5.2570197	27.6363
19						22.7499						
20						18.2005		San Diego	22.7498793			
21						27.3						

Defining a Dimension

In this simple example, a dimension, City, has been created in cell F15 which is comprised of the names of major cities in California (cells B15:B18). Cells C15:C18 contain the gross income per city. Each Gross Income is uncertain. The Gross Income for San Francisco follows the Gamma distribution, Gross Income for San Diego follows a Triangular distribution, San Jose follows a Normal distribution and Los Angeles follows a Uniform distribution.

Defining a Cube

One key benefit of this model is that it defines a simulation output in one cell which would require four cells without dimensional modeling. In cell F16, a cube has been created along the City dimension which is comprised of each city's gross income in $Millions. Double click this cell to display the grid. (Click the icon to autofit the columns to display all values/text.)

City	
San Francisco	81.53672838
San Diego	23.22228049
San Jose	22.48399618
Los Angeles	31.37893588

In cell F17, a 2nd cube has been created by using the cube in cell F16 in the formula, =F16*(1-C12), which multiplies the elements of the cube in cell F16 by the after tax rate or 91% (1-.09). If dimensional modeling is not used, four output cells would be required to capture the simulation statistics, percentiles, etc, for the after-tax income of each city. However, in this example, the cube in cell F17 captures all relevant information.

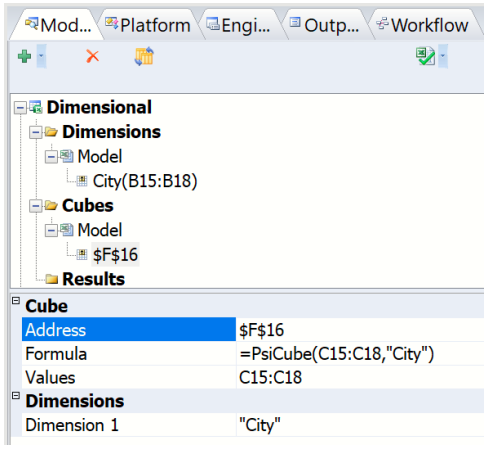
Mean

City	
San Francisco	36.4216781
San Diego	22.75006667
San Jose	18.20025418
Los Angeles	27.29991035

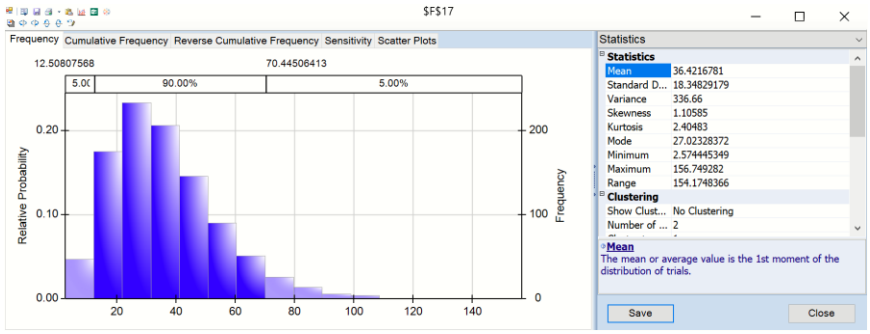
Notice that "calc" follows the cell address in the dialog title. This means that a trial value is being displayed.

Defining an Output

Cell F18 contains the PsiMean() function which creates both a simulation output as well as a dimensional modeling output. To view the statistics and percentiles for each city's Gross Income, simply set the Current Value of the City dimension to the desired city. For example, to view the simulation results for San Diego, select City under Dimensions in the Model tab of the Task Pane, then set Current Value to San Jose.



Now click the green arrow on the Output tab to run a simulation. The Simulation results window that appears contains simulation results for San Jose's after-tax income.



To view the mean results for each city, double click cell F18 to display the following grid. Notice that (sim-mean) now follows the cell address ($F$18) in

the dialog title. This title signifies that these results are the mean from a simulation.

$F$18 (sim-mean)

City	
San Francisco	36.4216781
San Diego	22.75006667
San Jose	18.20025418
Los Angeles	27.29991035

Note: PsiMean() can be substituted with any PsiXxx statistic function except PsiCorrelation and PsiFrequency.

Double click cell F17.

Mean

$F$17 (sim)

City	
San Francisco	36.4216781
San Diego	22.75006667
San Jose	18.20025418
Los Angeles	27.29991035

Currently, this grid displays the mean results from the simulation. Click the down arrow next to Mean and select Trials.

Trials

$F$17 (sim)

All Trials	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	1
City																		
San Francisco	46.73104715	28.50234861	26.64188513	24.81682615	32.51009874	19.1973942	44.35022594	26.76710583	34.85920528	32.09188667	6.869595363	31.96459227	54.63578132	30.62519996	30.37984111	29.05095757	32.84009747	3
San Diego	23.78496263	24.4175617	21.88641358	21.62422916	21.81232927	22.06340036	25.89311021	20.70553354	20.74490302	26.51731955	21.68554585	24.35080203	22.36153494	24.22777704	22.24093291	22.0681291	23.42134436	1
San Jose	15.70337748	15.45680491	15.50883072	17.77177431	14.54440514	19.0651959	14.37933422	12.84754711	18.37034326	20.19144585	24.25352266	16.53079484	18.30399536	18.82129562	17.70032358	17.81623657	15.92430292	2
Los Angeles	27.33247531	24.89468829	27.83510196	22.11157063	32.63412365	22.16627514	26.68264409	18.30830876	29.07680146	21.52200865	20.18418465	22.72200942	31.74608083	34.55448539	26.04643611	30.25830272	25.78047491	2

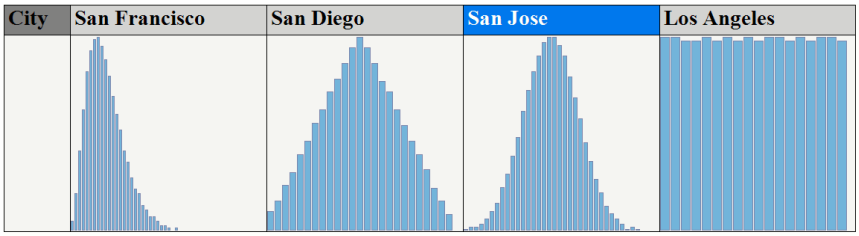
All 1000 trial values for each city are listed. Drag "City" above "All Trials" to list the trials vertically.

Trials

$F$17 (sim)

City	San Francisco	San Diego	San Jose	Los Angeles
All Trials				
1	46.73104715	23.78496263	15.70337748	27.33247531
2	28.50234861	24.4175617	15.45680491	24.89468829
3	26.64188513	21.88641358	15.50883072	27.83510196
4	24.81682615	21.62422916	17.77177431	22.11157063
5	32.51009874	21.81232927	14.54440514	32.63412365
6	19.1973942	22.06340036	19.0651959	22.16627514
7	44.35022594	25.89311021	14.37933422	26.68264409
8	26.76710583	20.70553354	12.84754711	18.30830876
9	34.85920528	20.74490302	18.37034326	29.07680146
10	32.09188667	26.51731955	20.19144585	21.52200865
11	6.869595363	21.68554585	24.25352266	20.18418465
12	31.96459227	24.35080203	16.53079484	22.72200942
13	54.63578132	22.36153494	18.30399536	31.74608083
14	30.62519996	24.22777704	18.82129562	34.55448539
15	30.37984111	22.24093291	17.70032358	26.04643611
16	29.05095757	22.0681291	17.81623657	30.25830272
17	32.84009747	23.42134436	15.92430292	25.78047491
18	37.3186006	18.83368801	20.27071854	24.82295575
19	18.8592001	23.67908844	18.14147651	32.38158684
20	40.91573504	21.02691071	18.75345555	26.01503544
21	29.38835589	23.04590371	13.99833298	30.99934192
22	10.58599076	23.84557209	16.08843037	19.85978889
23	21.91861684	20.56851089	16.11807878	18.95312582
24	24.66213494	20.5524382	23.0151251	36.25948923
25	27.75309312	23.37803736	20.03588951	36.31332384
26	54.53244865	19.97095841	14.03012481	29.72126311
27	5.375523606	20.98075534	14.22825254	27.95981685
28	58.78720991	23.59414957	15.54084297	32.50387071
29	48.46922285	22.99483866	24.03641769	18.49940487
30	47.02225697	22.82942212	20.01391644	22.12987859
31	42.69087371	22.77737985	22.72582395	28.10527839
32	28.32905983	22.89583852	21.77874654	31.10294683
33	45.55272443	19.34548716	21.58094157	20.42497507

To see mini histograms for each uncertain function, click the down arrow next to Trials and select Histogram.



Cells F18:F21 contain the PsiMean() simulation statistic entered as an array formula. The results of this function are similar to the results of PsiCubeData() and PsiOptData() (for objective and constraint cubes only) in that when entered as an array, the function will display the fact table for the desired cube.

When a Psi Statistic function (such as PsiMean(), PsiStdDev(), PsiVariance(), etc.) is entered as an array formula and used with a simulation model using Dimensional Modeling, the statistic function will display all elements of the cube fact table formatted according to the optional 3rd argument, *struc_format*. To begin, we'll need to determine the size of our array. Since the cube in cell F17 is comprised of one dimension (Cities), we'll need to select one cell and enter "=PsiMean(F17, 1, "dims")" in this cell. (When "dims" is passed for the *struc_format* argument (3rd argument), the size of each dimension contained in the cube in cell F17 will be returned.) Afterwards, this cell will display "City[4]" indicating that there are 4 elements in the City dimension. Now that we know the number of elements (or size) of the dimensions, we can display the entire fact table by entering PsiMean() as an array, but this time we'll use "vals" for the *struc_format* argument. When passing "vals" for this argument, PsiMean(), when entered as an array, will display the data as a relational table. Since there are 4 elements in the City dimension, the fact table for this cube will contain 4 elements. Therefore, we will need to highlight 1 column for the first dimension (City) and a 2nd column for the actual values and 4 rows to hold all 4

values in the fact table. In this example, we'll use the blank cells H15:I18. (This area encompasses 2 columns and 4 rows.) Select these cells, enter "=PsiMean(F17, 1, "vals"), then press SHIFT + CTRL + ENTER to enter this formula as an array formula. The following table will be displayed. *Note: PsiMean() can be substituted with any PsiXxx statistic function except PsiCorrelation and PsiFrequency.*

	H	I
6	SanFrancisco	36.42570457
7	SanDiego	22.74976078
8	SanJose	18.20078012
9	LosAngeles	27.29994228

Now we'll use a different statistic, PsiStdDev() but this time we'll list *only* the values in the fact table To do so, select cells K15:K18, then enter "=PsiStdDev(F17)", then press SHIFT + CTRL + ENTER to enter the formula as an array. Notice we are *only supplying the first argument*. Afterwards, these cells will display only the *values* of the fact table as shown in cells K15:K18 in the screenshot below. Repeat the same steps in cell L15:L18 but this time using the statistic, PsiVariance() ("=PsiVariance(F17)").

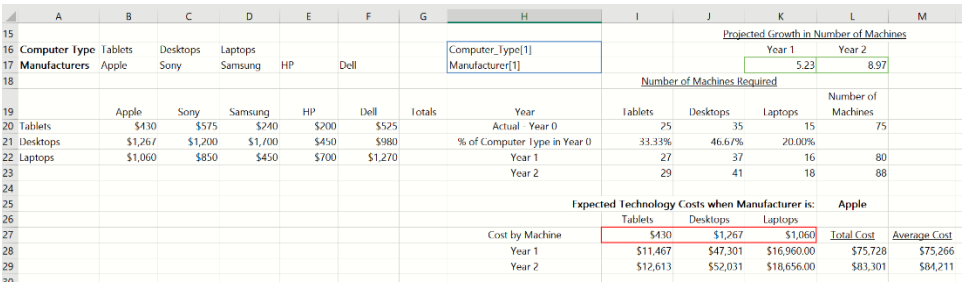
A statistics function can also be used to display a slice or even a single element of the fact table. For example, to display the mean gross margin for the City of San Diego, select two blank cells, say H20:I20, and enter the following formula: =PsiMean(F17,1, "[City].[SanDiego]"). Then press SHIFT + CTRL + ENTER to enter as an array formula. Afterwards, the following table will be displayed.

	H	I
11	San Diego	22.75017814

Now let's close this example and continue on to the next section to learn about using a parametric dimension in a simulation model.

Parametric Dimensions

Now let's see how Parametric Dimensions can be used with simulation. Open the example, ParametricCube_SimExample.xlsx by clicking **Help -- Examples** on the Analytic Solver ribbon. The Frontline Example Models Overview.xls file will open. Select the *Simulation* tab and choose **Parametric Cube Simulation Example.** ParametricCube_SimExample.xls opens.



	A	B	C	D	E	F	G	H	I	J	K	L	M
15											Projected Growth in Number of Machines		
16	**Computer Type**	Tablets	Desktops	Laptops				Computer_Type[1]			Year 1	Year 2	
17	**Manufacturers**	Apple	Sony	Samsung	HP	Dell		Manufacturer[1]			5.23	8.97	
18										Number of Machines Required			
19		Apple	Sony	Samsung	HP	Dell	Totals	Year	Tablets	Desktops	Laptops	Number of Machines	
20	Tablets	$430	$575	$240	$200	$525		Actual - Year 0	25	35	15	75	
21	Desktops	$1,267	$1,200	$1,700	$450	$980		% of Computer Type in Year 0	33.33%	46.67%	20.00%		
22	Laptops	$1,060	$850	$450	$700	$1,270		Year 1	27	37	16	80	
23								Year 2	29	41	18	88	
24													
25										Expected Technology Costs when Manufacturer is:		Apple	
26									Tablets	Desktops	Laptops		
27								Cost by Machine	$430	$1,267	$1,060	Total Cost	Average Cost
28								Year 1	$11,467	$47,301	$16,960.00	$75,728	$75,266
29								Year 2	$12,613	$52,031	$18,656.00	$83,301	$84,211

This example models the Estimated Technology costs for two years in the future (year 1 and year 2) for JoeBen Gaming based on which computer manufacturer the company selects. This model includes a structural dimension and a parametric dimension. The structural dimension is held in cell H16. This dimension contains the type of technology that JoeBen gaming will purchase for their employees: Tablets, Desktops, and Laptops. The parametric dimension is contained in cell H17. This dimension contains the manufacturers of the technology: Apple, Sony, Samsung, HP, and Dell.

Cells L22 and L23 contain the projected number of machines needed for years 1 and 2, respectively, based on the projected growth distributions in cells K17 and L17. The ratio of tablets, desktops, and laptops, to the total number of machines will remain constant. Therefore, the percentage of tablets will remain at 33%, the percentage of desktops will remain at 46.7%, and the percentage of laptops will remain at 20% for the next two years. As a result, the values in cells I28:K29 are calculated by multiplying the number of machines (cells L22 and L23) by the percentages in cells I21:K21.

Three cubes are located in cells I27:K27. These cubes contain the data for the Manufacturer dimension. The values in these cells will determine the total technology costs for each year. Cell I27 contains pricing data for each tablet by manufacturer, cell J27 contains pricing data for each desktop by manufacturer, and cell K27 contains pricing data for each laptop by manufacturer. Double click each of these cells to display their data values. For example, double clicking cell I27 brings up the following dialog which displays tablet pricing for each manufacturer.

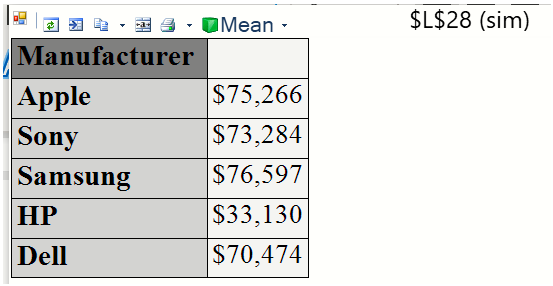
$I$27 (calc)

Manufacturer	
Apple	$430
Sony	$575
Samsung	$240
HP	$200
Dell	$525

Once the green arrow has been clicked in the Model tab of the Solver task pane, or Simulate – Run Once is clicked on the ASP Ribbon, **five** different simulations will be run simultaneously in *less than one second* – one simulation for each manufacturer.

Double click cell L28 to display a grid revealing the total technology costs for Year 1 *for each manufacturer*. (Click the icon to expand the columns to

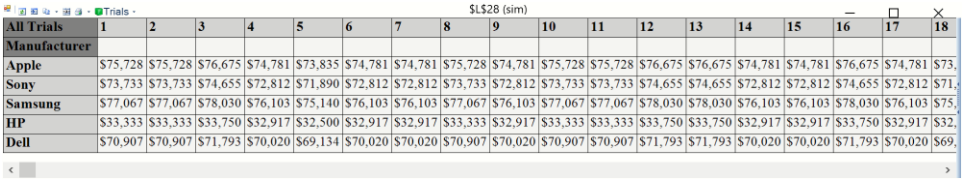
display the full text in the first column.) With Dimensional Modeling, you can perform a What If analysis with the double click of one button!



Manufacturer	
Apple	$75,266
Sony	$73,284
Samsung	$76,597
HP	$33,130
Dell	$70,474

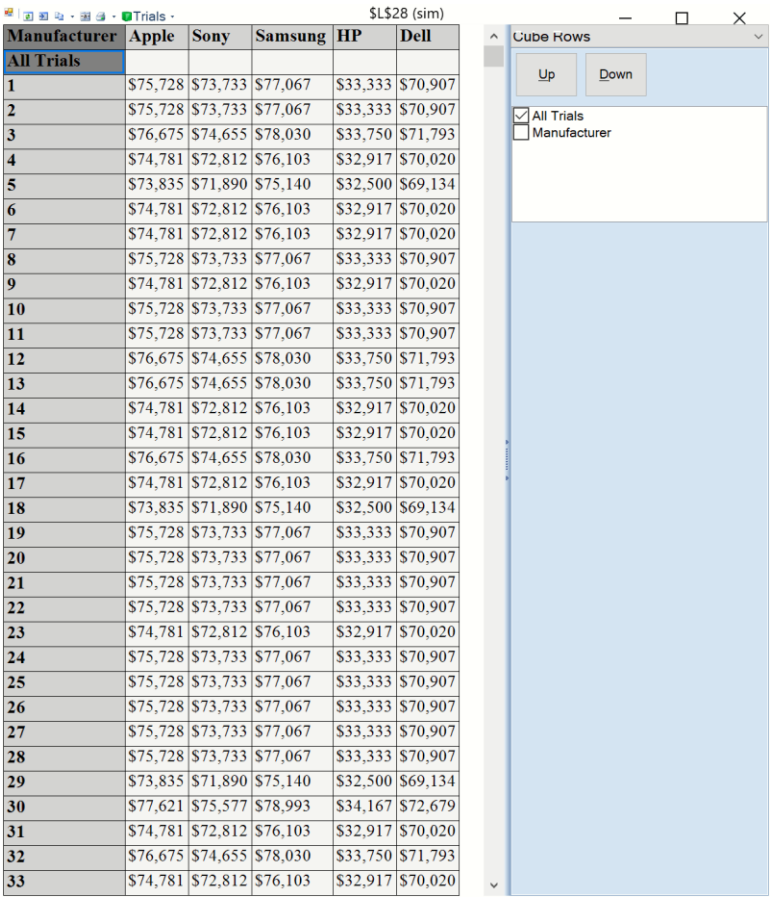
Click the down arrow next to Mean and select Trials from the drop-down menu.

1000 trial values are displayed for each manufacturer. (Click the icon to expand the columns to display the full text in the first column.) 1000 what-if scenarios are again available at the double click of a button!



All Trials	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Manufacturer																		
Apple	$75,728	$75,728	$76,675	$74,781	$73,835	$74,781	$74,781	$75,728	$74,781	$75,728	$75,728	$76,675	$76,675	$74,781	$74,781	$76,675	$74,781	$73,
Sony	$73,733	$73,733	$74,655	$72,812	$71,890	$72,812	$72,812	$73,733	$72,812	$73,733	$73,733	$74,655	$74,655	$72,812	$72,812	$74,655	$72,812	$71,
Samsung	$77,067	$77,067	$78,030	$76,103	$75,140	$76,103	$76,103	$77,067	$76,103	$77,067	$77,067	$78,030	$78,030	$76,103	$76,103	$78,030	$76,103	$75,
HP	$33,333	$33,333	$33,750	$32,917	$32,500	$32,917	$32,917	$33,333	$32,917	$33,333	$33,333	$33,750	$33,750	$32,917	$32,917	$33,750	$32,917	$32,
Dell	$70,907	$70,907	$71,793	$70,020	$69,134	$70,020	$70,020	$70,907	$70,020	$70,907	$70,907	$71,793	$71,793	$70,020	$70,020	$71,793	$70,020	$69,

To view the trial values vertically (rather than horizontally), simply drag **Manufacturer** above **All Trials** in the grid or simply click the double arrows on the right of the dialog and select Manufacturer on the Cube Columns menu.

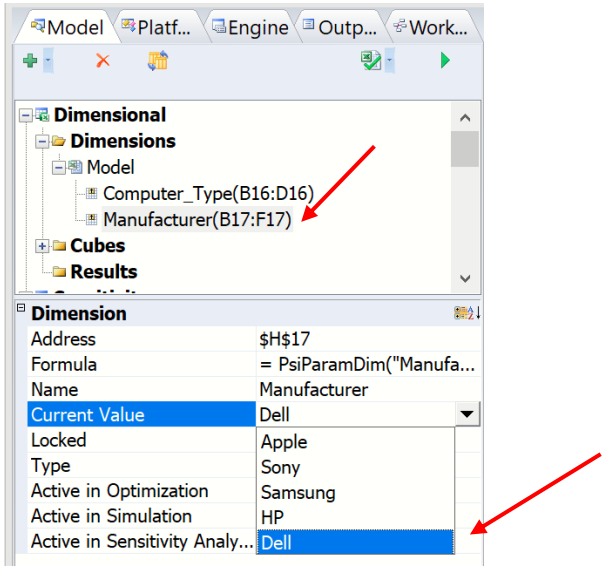


Trials

$L$28 (sim)

Manufacturer	Apple	Sony	Samsung	HP	Dell
All Trials					
1	$75,728	$73,733	$77,067	$33,333	$70,907
2	$75,728	$73,733	$77,067	$33,333	$70,907
3	$76,675	$74,655	$78,030	$33,750	$71,793
4	$74,781	$72,812	$76,103	$32,917	$70,020
5	$73,835	$71,890	$75,140	$32,500	$69,134
6	$74,781	$72,812	$76,103	$32,917	$70,020
7	$74,781	$72,812	$76,103	$32,917	$70,020
8	$75,728	$73,733	$77,067	$33,333	$70,907
9	$74,781	$72,812	$76,103	$32,917	$70,020
10	$75,728	$73,733	$77,067	$33,333	$70,907
11	$75,728	$73,733	$77,067	$33,333	$70,907
12	$76,675	$74,655	$78,030	$33,750	$71,793
13	$76,675	$74,655	$78,030	$33,750	$71,793
14	$74,781	$72,812	$76,103	$32,917	$70,020
15	$74,781	$72,812	$76,103	$32,917	$70,020
16	$76,675	$74,655	$78,030	$33,750	$71,793
17	$74,781	$72,812	$76,103	$32,917	$70,020
18	$73,835	$71,890	$75,140	$32,500	$69,134
19	$75,728	$73,733	$77,067	$33,333	$70,907
20	$75,728	$73,733	$77,067	$33,333	$70,907
21	$75,728	$73,733	$77,067	$33,333	$70,907
22	$75,728	$73,733	$77,067	$33,333	$70,907
23	$74,781	$72,812	$76,103	$32,917	$70,020
24	$75,728	$73,733	$77,067	$33,333	$70,907
25	$75,728	$73,733	$77,067	$33,333	$70,907
26	$75,728	$73,733	$77,067	$33,333	$70,907
27	$75,728	$73,733	$77,067	$33,333	$70,907
28	$75,728	$73,733	$77,067	$33,333	$70,907
29	$73,835	$71,890	$75,140	$32,500	$69,134
30	$77,621	$75,577	$78,993	$34,167	$72,679
31	$74,781	$72,812	$76,103	$32,917	$70,020
32	$76,675	$74,655	$78,030	$33,750	$71,793
33	$74,781	$72,812	$76,103	$32,917	$70,020

Let's view the results for Dell only. First, select the **Manufacturer** parametric dimension in the Model tab of the Solver task pane. Then select **Dell** for *Current Value*.



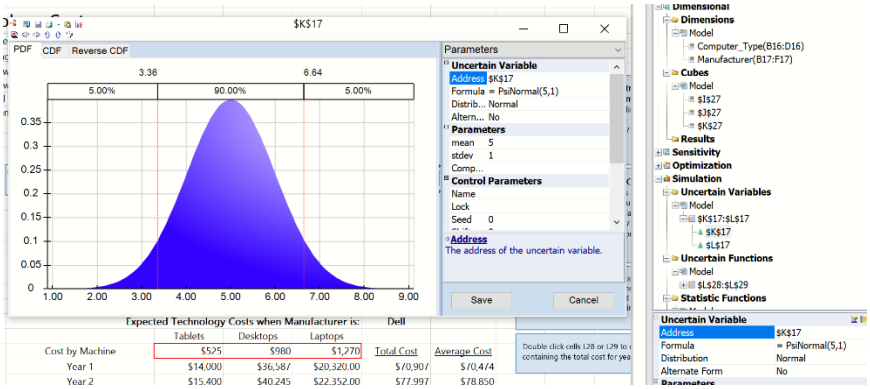
The values in cells I27:K27 display $525, $980 and $1,270, respectively, which equals the value for Dell in cells F20:F22.

The PsiMean() functions in cells M28 and M29 display the projected mean technology costs for years 1 and 2, respectively, when computers manufactured by Dell are purchased.

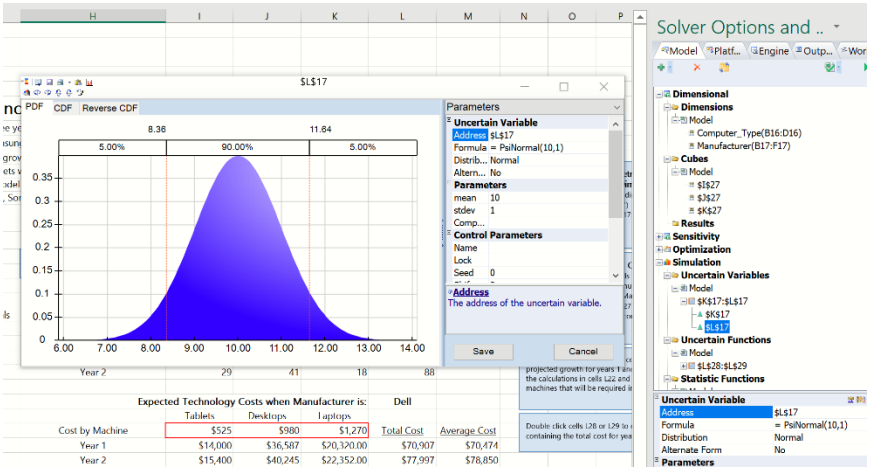
Note: Double clicking the cubes in cells I27:K27 will display the tablet, desktop, or laptop values by Manufacturer. For example, double click cell I27 to open the following grid which displays the tablet costs for Year 1 for each manufacturer.

Manufacturer	
Apple	$430
Sony	$575
Samsung	$240
HP	$200
Dell	$525

Double click K17 in the Model tab of the Solver Task Pane to display the simulation results for technology costs for Year 1.

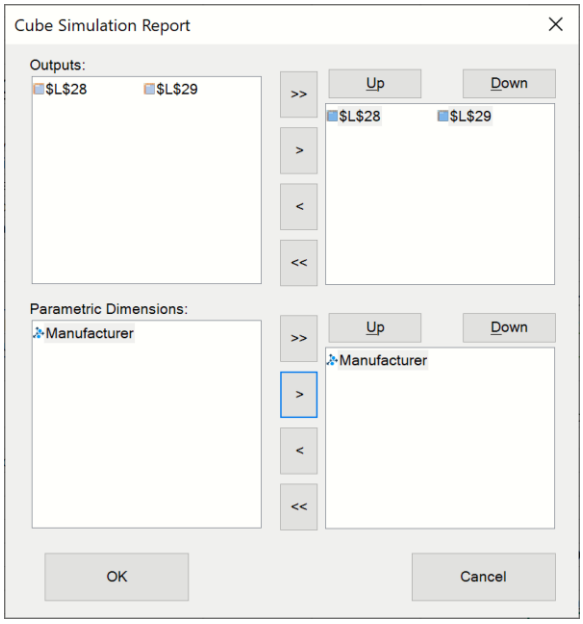


Then double click cell L16 to display the simulation results for Year 2.

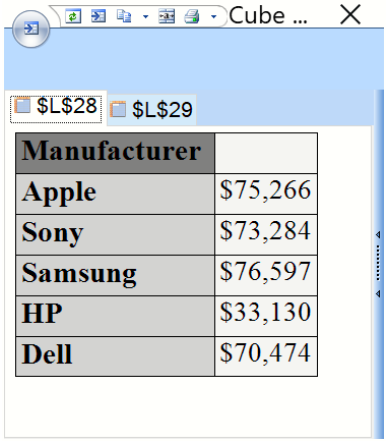


Note: To obtain simulation results for a different manufacturer, select the Manufacturer dimension in the Model tab of the Solver task pane, select the desired manufacturer for the Current Value field, then double click K17 or L17 on the Model tab of the Solver task pane. The uncertain function dialog will update to display the current element of the Manufacturer dimension.

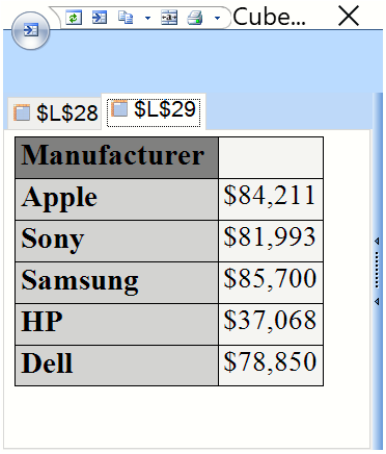
To view the results of cells L28 and L29 at the same time, click **Reports – Simulation – Parameter Analysis.** The *Cube Simulation Report* dialog opens displaying the two uncertain function cells L15 and L16 under *Results* and the two dimensions (Manufacturer and Computer Type) under *Parametric Dimensions.*



Click >> under Outputs to select both L15 and L16. Highlight the Manufacturer dimension, then click > to select. Afterwards, click OK. The following dialog opens.



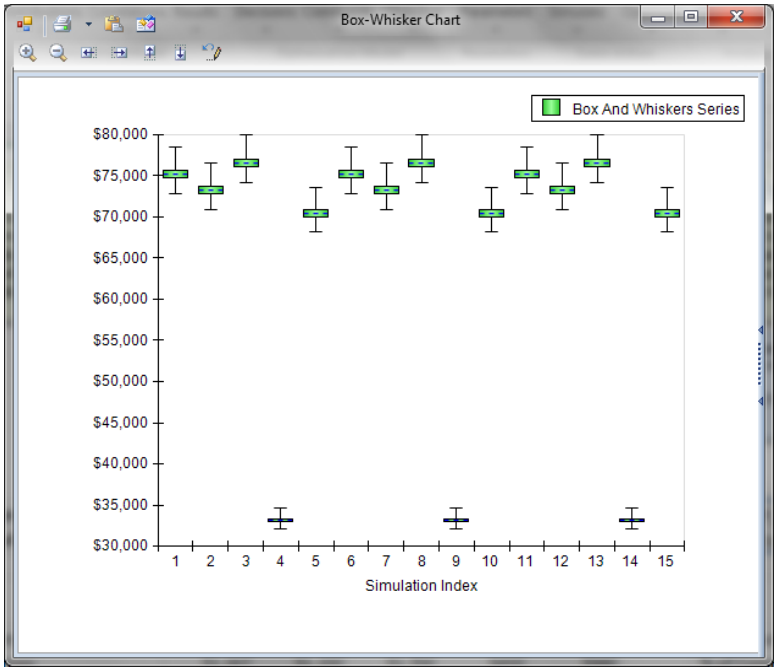
Within this dialog, you can toggle between the results for cells L28 (which contains the total technology cost for year 1 by Manufacturer) and L29 (which contains the total technology cost for year 2 by Manufacturer).



Manufacturer	
Apple	$84,211
Sony	$81,993
Samsung	$85,700
HP	$37,068
Dell	$78,850

As you can easily see, purchasing machines from HP will yield the least amount of technology costs for both Years 1 and 2.

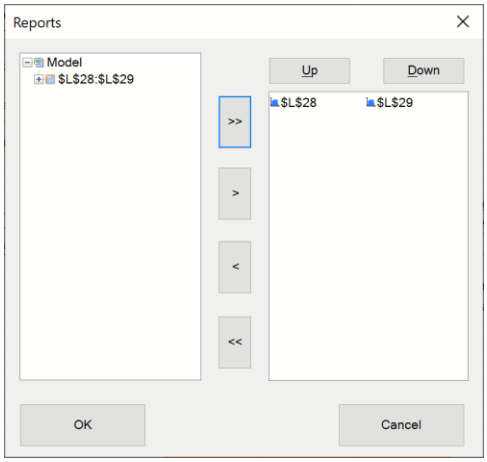
All charts under Multiple Simulations now also support Dimensional Modeling. ("Locked" or non-active dimensions will not appear in the charts.) Click **Charts – Multiple Simulations – Box-Whisker** to open the Multiple Simulations Chart dialog. Click >> to select Simulation 1 and click OK. Analytic Solver draws the following chart.



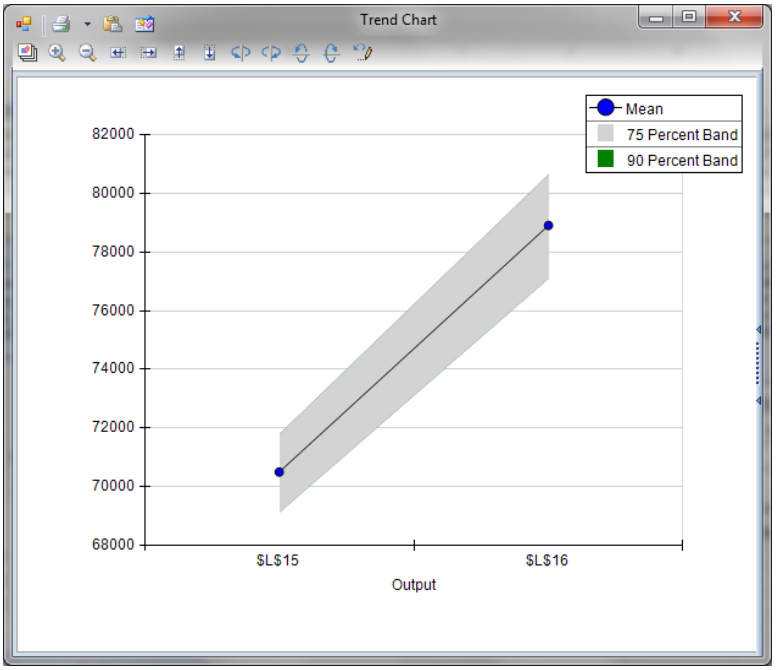
This shows a Box-Whisker diagram for each of the 15 simulations, with the mean, median, 25th and 75th percentiles, and the minimum and maximum value for net revenue on each one. You can click the right edge of the Trend and Box-Whisker charts to open a right panel with options for customizing these charts. You can use the icons on the title toolbar to print the chart, or copy it to the Clipboard, where it can be pasted into another application such as PowerPoint.

Perform the same steps for each of the remaining charts: Trend, Overlay, and Statistics. For more information on these charts, please see the Frontline Solvers Reference Guide.

In addition, the three reports under Charts – Multiple Simulation Results are also supported in Dimensional Modeling. Click **Charts – Multiple Simulation Results -- Trend** to open the Multiple Simulation Results dialog.



Click >> to select both output cells L28 and L29, then click **OK**. A trend chart of both uncertain functions is produced.



Here we can see a steep upward climb of the mean value of the total technology costs, and also the volatility around the mean, depicted here with the 25th and 75th percentiles.

Repeat the same steps to produce the remaining charts: Overlay and Box-Whisker. For an explanation of these reports, please see the Frontline Solvers Reference Guide.

Now close this example and continue onto the next section to learn how to use a pivot table with Dimensional Modeling.

Using Dimensional Modeling with Pivot Tables

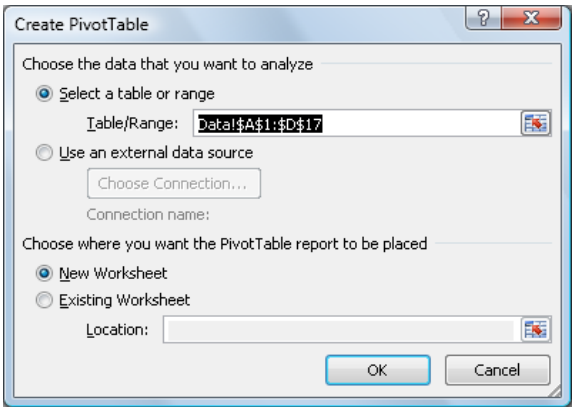
In general, cubes are defined as multi-dimensional, not just two – dimensional as shown in the examples above. Unfortunately, a normal Excel worksheet is not the easiest medium for working with multidimensional cubes. An Excel pivot table, however, lends itself to this very practice. An Excel Pivot Table is a tool within Excel that can be used to summarize data located in an Excel worksheet. Once data is inserted into a pivot table, it can easily be sorted, counted, totaled, etc. by dragging and dropping the fields into the desired layout.

Click **Help -- Examples** on the Analytic Solver ribbon. The Frontline Example Models Overview.xls file will open. Select the Simulation tab and choose **Pivot Table Simulation Example** from the list. (This example uses parametric dimensions but structural dimensions are also supported.)

An Excel Pivot table is located in cells B13:F27. This table is comprised of the Product Line for Mark's Breakfast Delights. This company has two product lines: Waffle Mix and Pancake Mix. Each of these product lines contain two flavors: blueberry and plain. The Sales team is comprised of 4 individuals who are responsible for a specific region of the Las Vegas area where the company is based: Henderson, Summerlin, North Las Vegas, and Fremont Street. Sales figures for each product and region are located in the Sales column. *Note: Since values in a pivot table cannot be evaluated, pivot table values must be constants.*

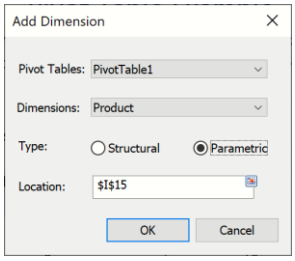
How to create the Pivot Table

Highlight the data on the worksheet, then click **Insert – Pivot Table – Pivot Table** on the Excel ribbon. The Create PivotTable dialog opens. *Select a table or range* is prefilled, leave this selection as is. Select New **Worksheet**, then select a blank cell for Location. Then click OK.

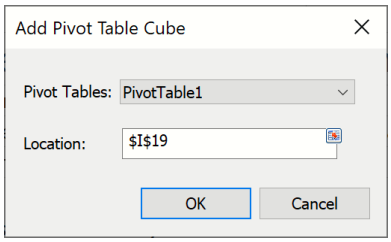


The pivot table will be inserted into a new worksheet. Manipulate the table as desired. Afterwards, click **Design – Report Layout – Show in Tabular Form**.

Next, we'll create three dimensions, one each for *Product*, *Product_Line*, and *Region*. Select a blank cell, in this case cell I15 was used, then click **Model – Dimension – From Pivot Table** to open the *Add Dimension* dialog. Select the name of the pivot table, in this case **PivotTable1**, select **Product** for *Dimensions*, select **Parametric** for *Type* and cell **I15** for *Location*. Then click **OK**. The formula =PsiPivotDim(B13,"Product", TRUE) will be inserted into cell I15. Repeat these steps in cells I16 and I17 to create parametric dimensions for Product_Line and Region, respectively. Alternatively, this formula could also be typed directly into the cell.



Now we will create a cube from the pivot table. Select a blank cell, in this example cell I19, then click **Model – Cube – From Pivot** Table to open the *Add Pivot Table* Cube dialog.

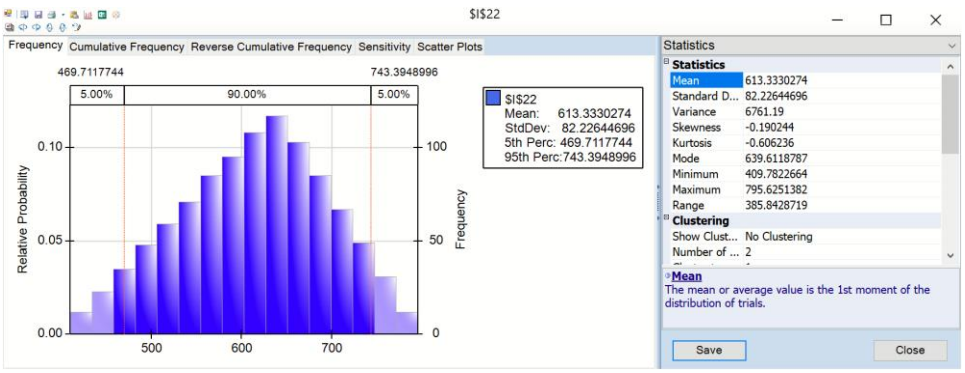


Leave PivotTable1 and Location at their defaults, and click OK. The following formula will be inserted into cell I19 =PsiPivotCube($B$13:$F27). Alternatively, this formula could have been entered into the cell directly.

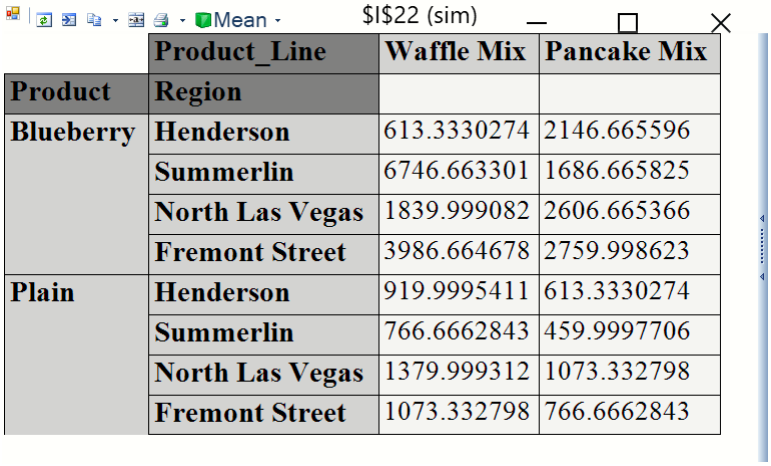
From here we can create a simulation or optimization model. In this example, we've created a simulation model. Cell I21 holds an uncertain variable which calculates a selling price using a triangular distribution with a minimum parameter of 100, a maximum parameter of 200, and a likely parameter of 160. This sales price is multiplied by the cube result in cell I19.

To simulate gross sales for the Western region, select the **Product** Dimension on the Model tab in the Task Pane, then change *Current Value* to "Blueberry". Afterwards, perform the same steps for the remaining dimensions (Product_Line and Region) changing the current value of the **Product_Line** dimension to "Pancake Mix" and the current value of the **Region** dimension to "Blueberry". Cell I15 will display the value in cell F15, 18. Now click the green arrow on the Model tab to run a simulation. The simulation runs using the value of 18 as the number of products sold. The simulation results for the uncertain function in cell I22 are below.

Important Note: Pivot tables cannot be evaluated by the PSI Interpreter. This means that decision variables, uncertain variables, uncertain functions, and constraint or objective functions must not be used within an Excel Pivot Table. All values inside of a pivot table must be constant, or computed from constants.

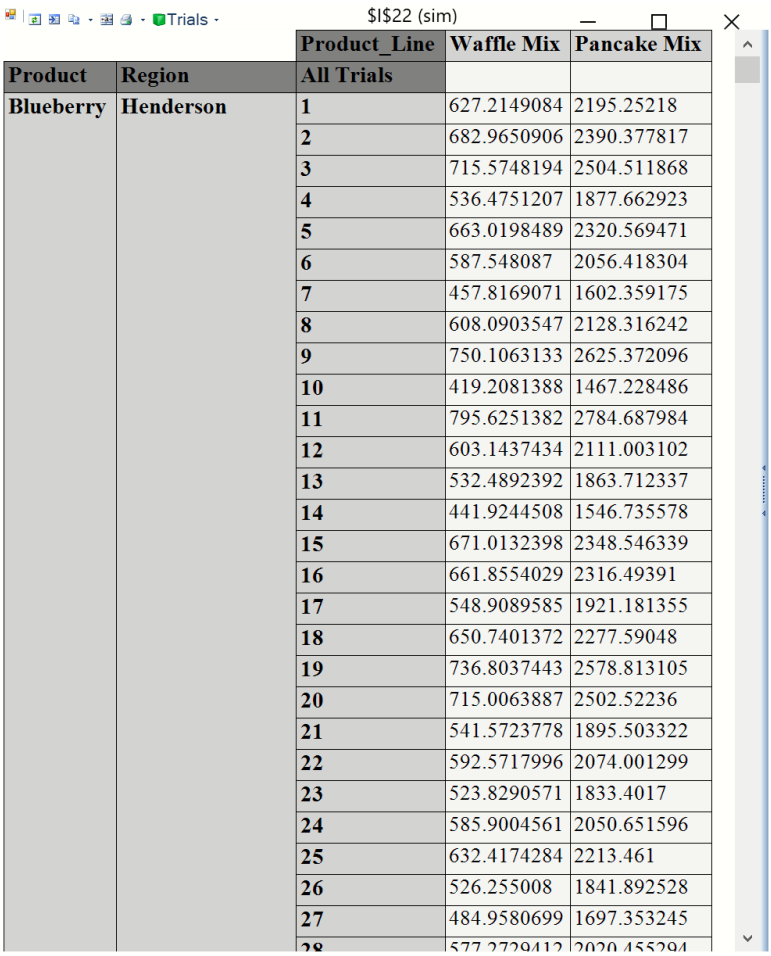


Double click the cube in cell I22 to display a grid containing the Gross Sales by product and region.



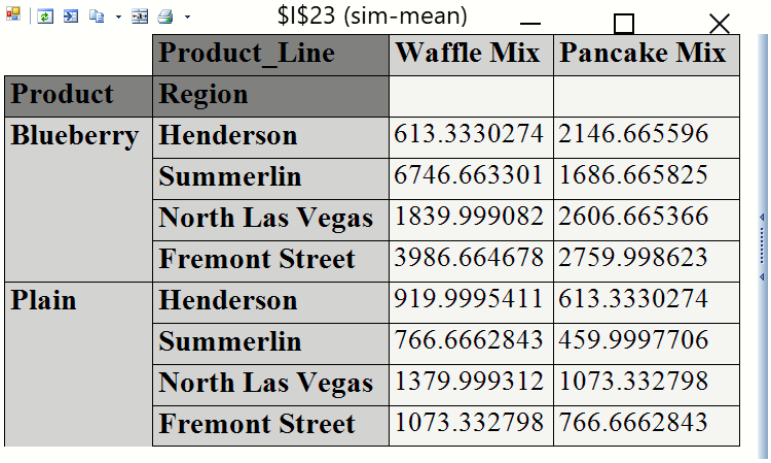
	Product_Line	Waffle Mix	Pancake Mix
Product	**Region**		
Blueberry	**Henderson**	613.3330274	2146.665596
	Summerlin	6746.663301	1686.665825
	North Las Vegas	1839.999082	2606.665366
	Fremont Street	3986.664678	2759.998623
Plain	**Henderson**	919.9995411	613.3330274
	Summerlin	766.6662843	459.9997706
	North Las Vegas	1379.999312	1073.332798
	Fremont Street	1073.332798	766.6662843

Click the down arrow next to *Mean* and select **Trials** to display the 1000 trial values used in the simulation.



		Product_Line	Waffle Mix	Pancake Mix
Product	**Region**	**All Trials**		
Blueberry	**Henderson**	**1**	627.2149084	2195.25218
		2	682.9650906	2390.377817
		3	715.5748194	2504.511868
		4	536.4751207	1877.662923
		5	663.0198489	2320.569471
		6	587.548087	2056.418304
		7	457.8169071	1602.359175
		8	608.0903547	2128.316242
		9	750.1063133	2625.372096
		10	419.2081388	1467.228486
		11	795.6251382	2784.687984
		12	603.1437434	2111.003102
		13	532.4892392	1863.712337
		14	441.9244508	1546.735578
		15	671.0132398	2348.546339
		16	661.8554029	2316.49391
		17	548.9089585	1921.181355
		18	650.7401372	2277.59048
		19	736.8037443	2578.813105
		20	715.0063887	2502.52236
		21	541.5723778	1895.503322
		22	592.5717996	2074.001299
		23	523.8290571	1833.4017
		24	585.9004561	2050.651596
		25	632.4174284	2213.461
		26	526.255008	1841.892528
		27	484.9580699	1697.353245
		28	577.2729412	2020.455294

Double click cell I23 to open the grid containing the Mean Gross Sales by product and region.



	Product_Line	Waffle Mix	Pancake Mix
Product	Region		
Blueberry	Henderson	613.3330274	2146.665596
	Summerlin	6746.663301	1686.665825
	North Las Vegas	1839.999082	2606.665366
	Fremont Street	3986.664678	2759.998623
Plain	Henderson	919.9995411	613.3330274
	Summerlin	766.6662843	459.9997706
	North Las Vegas	1379.999312	1073.332798
	Fremont Street	1073.332798	766.6662843

It's also possible to list the trial values in cells in the spreadsheet. Cells I25:I39 contain the function PsiData(I22) entered as an array function. These cells display the first 15, of 1000, trial values for cell I22, or Gross Sales.

	A	B	C	D	E	F	G	H	I
1	Mark's Breakfast Delights								
2									
3	Sum of Sales		Product_Line						
4	Region	Product	Waffle Mix	Pancake Mix	Grand Total				
5	Henderson	Blueberry	4	14	18		Dimension:	Product[1]	
6		Plain	6	4	10		Dimension:	Product_Line[2]	
7	Henderson Total		10	18	28		Dimension:	Region[4]	
8	Summerlin	Blueberry	44	11	55				
9		Plain	5	3	8		Cube:	18	
10	Summerlin Total		49	14	63				
11	North Las Vegas	Blueberry	12	17	29		Sales Price:	190.7106	
12		Plain	9	7	16				
13	North Las Vegas Total		21	24	45		Gross Sales	3432.792	
14	Fremont Street	Blueberry	26	18	44				
15		Plain	7	5	12		Gross Sales Trial 1	3266.218	
16	Fremont Street Total		33	23	56		Gross Sales Trial 2	2570.79	
17	Grand Total		113	79	192		Gross Sales Trial 3	2728.214	
18							Gross Sales Trial 4	3043.153	
19							Gross Sales Trial 5	2657.786	
20							Gross Sales Trial 6	3432.792	
21							Gross Sales Trial 7	2487.242	
22							Gross Sales Trial 8	3173.078	
23							Gross Sales Trial 9	2865.978	
24							Gross Sales Trial 10	3068.264	
25							Gross Sales Trial 11	3170.518	
26							Gross Sales Trial 12	3006.086	
27							Gross Sales Trial 13	2285.32	
28							Gross Sales Trial 14	2798.585	
29							Gross Sales Trial 15	3179.391	

Using Sparse Cubes

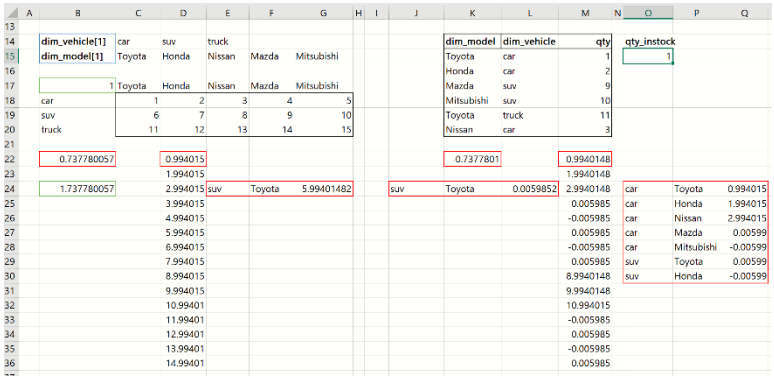
Analytic Solver provides the option to calculate cubes defined by PsiCube() or PsiTableCube() when the Optimization or Simulation Interpreter option is set to **Psi Interpreter**.

Most large cubes are *sparse* in nature. While they may contain thousands of elements, in practice, not all combinations of dimension elements are possible;

therefore, not all will define a model function during the Psi Interpreter's evaluation of the problem. This means that most cubes will provoke output results as sparse cubes (with missing constraints). Such sparsity in a cube (also known as structural sparsity) can be exploited to save memory and gain speed.

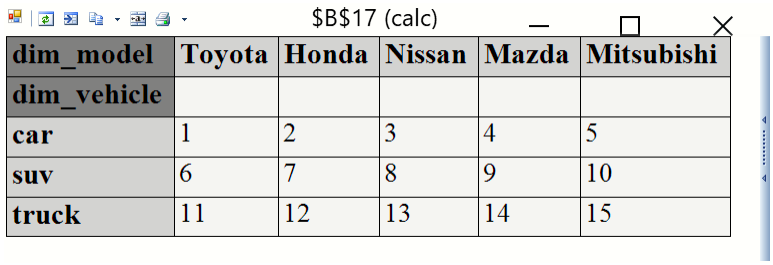
A sparse cube is defined by missing *values* in cells for PsiCube() and by missing *records* for PsiTableCube(). If this option is equal to False, and you have defined a cube using PsiCube() or PsiTableCube(), elements missing from the cube will be considered equal to 0. If you set this option to True, you have defined a cube using PsiCube() with missing values or PsiTableCube() with missing records, *and* the percentage of elements missing or empty is more than 30% of the total possible cube elements, those missing elements or records will not be included in the model.

To illustrate this new feature, we will use the newly added example, **Sparse_Cubes.xlsx**. To open, click **Help – Examples** on the Analytic Solver ribbon, click the *Simulation* tab, then the link to **Sparse_Cubes.xlsx**.



Two dimensions have been created in cells B14 and B15, dim_vehicle and dim_model, respectively. The dim_vehicle dimension (cell B14) contains three items or elements: car, suv, and truck. The dim_model dimension (cell B15) contains five items or elements: Toyota, Honda, Nissan, Mazda, and Mitsubishi. Both dimensions together specify the number of cars, SUVs and trucks available on a car lot, organized by manufacturer.

One cube is defined using PsiCube() in cell B17 = PsiCube(C18:G20, "dim_model", "dim_vehicle"). The first argument is the cell address of the data, "C18:G20". The second and third arguments are the dimensions for which the data will be calculated. To display the contents of the cube, double-click cell B17.



dim_model	Toyota	Honda	Nissan	Mazda	Mitsubishi
dim_vehicle					
car	1	2	3	4	5
suv	6	7	8	9	10
truck	11	12	13	14	15

Cell B24 contains the PsiNormal distribution with mean equal to 0, and standard deviation equal to 1. This is a simple error term that will be added to each cube element.

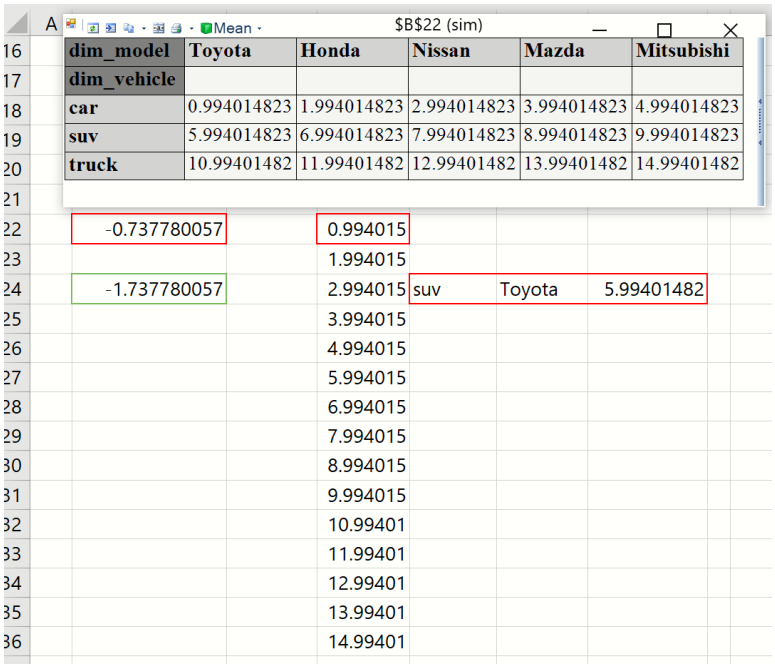
The formula in cell B22 (B22 = B17 + B24 + PsiOutput()) adds the error term (that follows the PsiNormal distribution) to each element in the cube in cell B17

(i.e., the first element of the cube = 1 + PsiNormal(0,1), the second element of the cube = 2 + PsiNormal(0, 1) and so on). PsiOutput is used to designate cell B22 as an output function. For details on the PsiOuput() function see the previous chapter, "Examples: Stochastic Optimization."

PsiMean() has been array entered into cells D22:D36. After a simulation has been run, these cells will display the PsiMean() value as calculated for each of the 15 elements of the cube (i.e., cell D22 will contain the mean for the first cube element, D21 will contain the mean for the second cube element, and so on).

The formula, = PsiMean(B22, 1, "[dim_vehicle].[suv], [dim_model].[maz]"), has been array entered into cells E24:G24 to illustrate how to display just one element of the cube (i.e., the number of Toyota SUVs available).

Run a simulation by clicking the down arrow beneath Simulate and selecting **Run Once**. Instantly, Analytic Solver performs a new simulation of 1,000 Monte Carlo trials, and updates each of the 15 cube elements and the worksheet with the results. The mean of each element can be found in cells D22:D36 or by double clicking cell B22, as shown in the screenshot below.



Notice that the value of the first cube element (Toyota/Car) corresponds to the value in cell D22, the value of the second cube element (Honda/Car) corresponds to the value in cell D23, and so on. In addition, the value for the number of available Toyota SUVs in cell G24 corresponds to the number of Toyota SUVs in the cube display.

Next, let's move to the right of the spreadsheet. Cell O15 contains PsiTableCube(). PsiTableCube() defines a *sparse* table. The first argument passes the dimension elements, while the second argument passes the values. (For more information on PsiTableCube, see PsiTableCube() in the Frontline Solvers Reference Guide.)

Notice that only *6 out of a possible 15* elements are used in the table. When **Use Sparse Cubes** is set to **False** (the default), the missing 9 elements will be set to 0 during the Psi Interpreter's evaluation of the problem. To display the following cube, double-click cell O15.

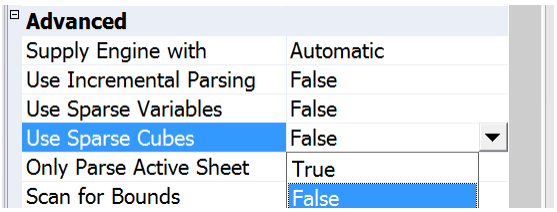
qty_instock (calc)

dim_model	Toyota	Honda	Nissan	Mazda	Mitsubishi
dim_vehicle					
car	1	2	3	0	0
suv	0	0	0	9	10
truck	11	0	0	0	0

PsiMean has been array entered into cells M22:M36. Cell K22 contains the formula "= B24 + M15 + PsiOutput()", which adds an error term to each element in the cube table. (This formula re-uses the PsiNormal() distribution in cell B24 as the error term).

Use Sparse Cubes = False

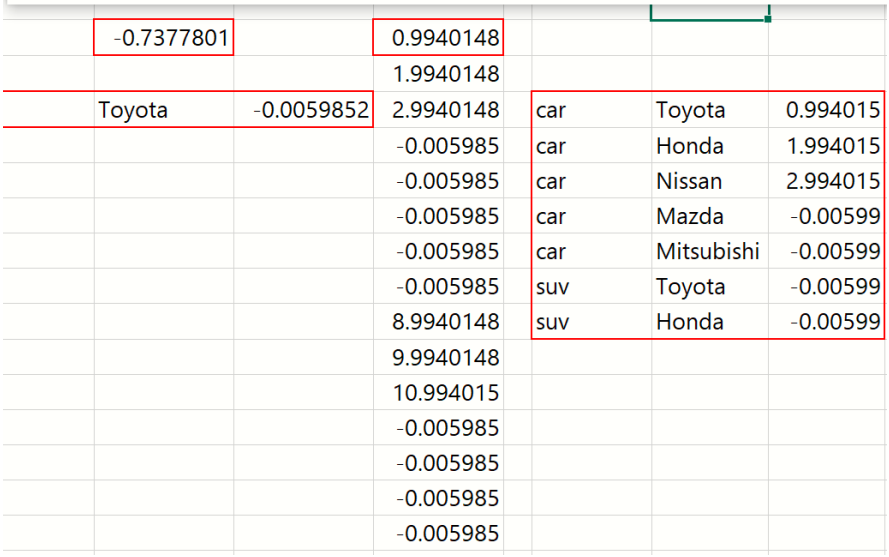
With **Use Sparse Cubes = False** on the Platform tab on the Solver Task Pane, run a simulation by clicking the down arrow beneath Simulate and selecting Run Once.



Instantly, Analytic Solver performs a new simulation of 1,000 Monte Carlo trials, and updates each of the 15 cube elements and the worksheet with the results. The mean of each element can be found in cells M22:M36 or by double-clicking cell K22, as shown in the screenshot below.

Mean — $K$22 (sim)

dim_model	Toyota	Honda	Nissan	Mazda	Mitsubishi
dim_vehicle					
car	0.994014823	1.994014823	2.994014823	-0.005985177	-0.005985177
suv	-0.005985177	-0.005985177	-0.005985177	8.994014823	9.994014823
truck	10.99401482	-0.005985177	-0.005985177	-0.005985177	-0.005985177

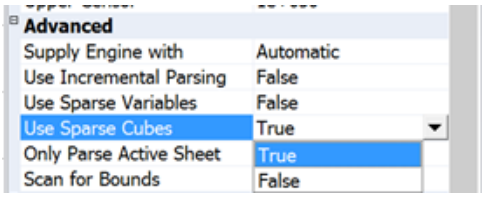


The formula, = PsiMean(K22, 1, "[dim_vehicle].[suv], [dim_model].[maz]"), array entered into cells J24:L24, illustrates how to display a single element of the cube, in this case the number of available Toyota SUVs. Notice this number is a fraction because the value for a Toyota SUV was *missing* in PsiTableCube(). Since Use Sparse Cubes is equal to false, the value for this element was set to 0.

The formula, =PsiMean(K22, "vals") has been array entered into cells M24:Q29 to illustrate how to display the cube dimensions and values in the worksheet. Since this formula has been array entered into only seven rows, only the first seven cube elements will be displayed.

Use Sparse Cubes = True

Click the **Platform** tab on the Solver Task Pane, scroll down to *Advanced* and enter **True** for **Use Sparse Cubes**.



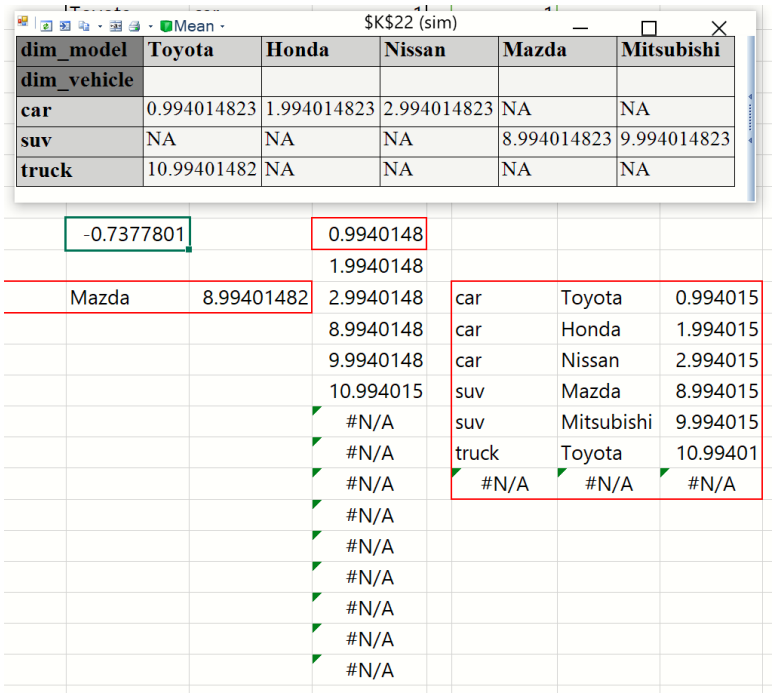
Since the ratio of the number of missing elements to the total number of possible elements is greater than 30% (6 out of a possible 15), Solver will only consider those six elements included in PsiTableCube() in the model formulation. In other words, while **Use Sparse Cubes** is set to **True**, only 6 elements are contained in the cube.

Run a simulation by clicking the down arrow beneath Simulate and selecting **Run Once**.

Notice that only the first *six* cells within the range M22:M36 hold values. This is because the cube only contains six elements! The remaining nine elements have not been included in the model. The value in cell M22 corresponds to the first cube element, Toyota cars, the value in cell M23 corresponds to the second cube element, Honda cars, the value in cell M24 corresponds to the third cube element Nissan cars, the value in cell M25 corresponds to the fourth cube element, Mazda SUVs, the value in cell M26 corresponds to the fifth cube element, Mitsubishi SUVs, and the value in cell M27 corresponds to the sixth cube element Toyota trucks.

The same is true for the elements in cells O24:O30. Cells O30:O30 show #N/A because only six elements are included in the model. Those six elements are displayed in cells O24:O29.

To display the cube output, double-click cell K22. Notice that the missing elements are now labeled as "NA," which means they do not exist in the simulation model. Our 15 element cube has been reduced to 6.


Mean
$K$22 (sim)
dim_model | Toyota | Honda | Nissan | Mazda | Mitsubishi
dim_vehicle
car | 0.994014823 | 1.994014823 | 2.994014823 | NA | NA
suv | NA | NA | NA | 8.994014823 | 9.994014823
truck | 10.99401482 | NA | NA | NA | NA
-0.7377801
Mazda 8.99401482
0.9940148
1.9940148
2.9940148
8.9940148
9.9940148
10.994015
#N/A
car Toyota 0.994015
car Honda 1.994015
car Nissan 2.994015
suv Mazda 8.994015
suv Mitsubishi 9.994015
truck Toyota 10.99401
#N/A #N/A #N/A

Automating Optimization in VBA

Introduction

This chapter explains how to use the Object-Oriented API in Analytic Solver Desktop to create, modify and solve optimization models under the control of your custom application written in VBA.

Note: Analytic Solver Cloud does not currently support this functionality.

This API is compatible with the object-oriented API offered by Frontline's Solver SDK Platform and Solver SDK Pro, used to build custom applications of optimization and simulation using C++, C#, VB.NET, Java, MATLAB and other languages.

Analytic Solver also supports "traditional" VBA functions, which are upward compatible from the VBA functions supported by the standard Excel Solver. This API is described in the Frontline Solvers Reference Guide.

Why Use the Object-Oriented API?

The new object-oriented API is more powerful and much more convenient for programming than the "traditional" VBA functions.

With the "traditional" VBA functions:

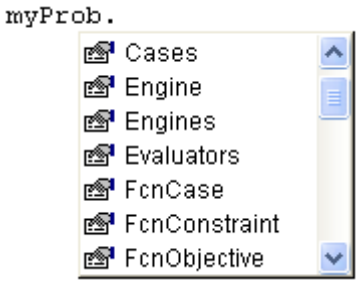
- You work with procedural functions that correspond to operations – such as **SolverOK** and **SolverSolve** – you can perform interactively in the Solver dialogs. To access the model and its variables and constraints, you must process the arrays of text and numbers returned by the **SolverGet** function.
- To obtain solution values, you must use the Excel object model (usually the **Range** object) to access the decision variable cells on the worksheet. You must take care to access the correct cells for specific decision variables.
- To obtain dual values and ranges, you must call the **SolverFinish** function to insert a report worksheet into the workbook, then use the Excel object model to access cells in the report. You must take *extra* care to access the correct report cells containing dual values and ranges.

With the new Object-Oriented API:

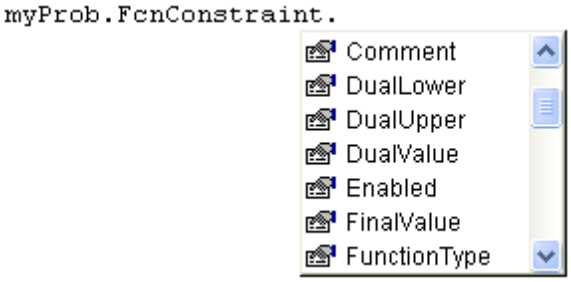
- You work with objects that correspond to the **Problem**, **Model**, **Solver**, **Engine**, **Variables**, and **Functions**. You can access sets of variables and constraints in the current model directly with expressions such as myProb.VarDecision and myProb.FcnConstraint.
- You can obtain solution values directly, with expressions such as myProb.VarDecision.FinalValue(i). If you need the cell address for a set of decision variable cells, you can write myProb.VarDecision.Name.
- You can access dual values and ranges for variables and constraints directly, with expressions such as myProb.VarDecision.DualValue(i) or myProb.FcnConstraint.DualValue(i).

The result is VBA code that's easier to read, and easier to write in the first place. Since the VBA Editor recognizes the object model exposed by Analytic Solver –

just as it recognizes the object model exposed by Excel – you'll receive **IntelliSense** prompts as you write code. For example, if you type a line **Dim myProb as New Problem**, then start a new line with **myProb.**, you'll be prompted with the properties and methods available for Problems:



If you select FcnConstraint and then type a period, you'll be prompted with the properties and methods available for Functions:



This makes it much easier to write correct code, without consulting the manual. What's more, you can use this object-oriented API when programming Excel and Analytic Solver from new languages such as **VB.NET** and **C#**, working in Visual Studio, and receive IntelliSense prompts in the syntax of these languages!

If you're using new functionality in Analytic Solver, the object-oriented API is your best bet. And if you're planning to move your application outside of Excel in the future – so it will run as a standalone program – you'll find that Frontline's **Solver Platform SDK** offers an object-oriented API that closely resembles the new APIs in Analytic Solver.

Running Predefined Solver Models

Controlling the Solver can be as simple as *adding two lines* to your VBA code! Each worksheet in a workbook may have a Solver problem defined, which is saved automatically with the workbook. You can create this Solver model interactively if you wish. If you distribute such a workbook, with a worksheet containing a Solver model and a VBA module, you can simply add a reference to the Analytic Solver COM server (see below), activate the worksheet, and add these two lines of code:

```
Dim prob As New Problem
prob.Solver.Optimize
```

Using the Macro Recorder

If you want to set up a Solver model "from scratch" programmatically, one easy way to see how to use the object-oriented API is to turn on the Excel Macro Recorder (click Record Macro on the Developer tab in Excel 2010 and then set

up a Solver model interactively. Microsoft Excel will record a macro in VBA that calls the object-oriented API to mimic the actions you perform. You can then edit and customize this macro, and incorporate it into your application.

Note: You must use the classic Solver dialog to record a macro, rather than the Solver Task Pane. To open, click Add-ins – Premium Solver. By default, the Excel Macro Recorder will record calls to the object-oriented API.

Adding a Reference in the VBA Editor

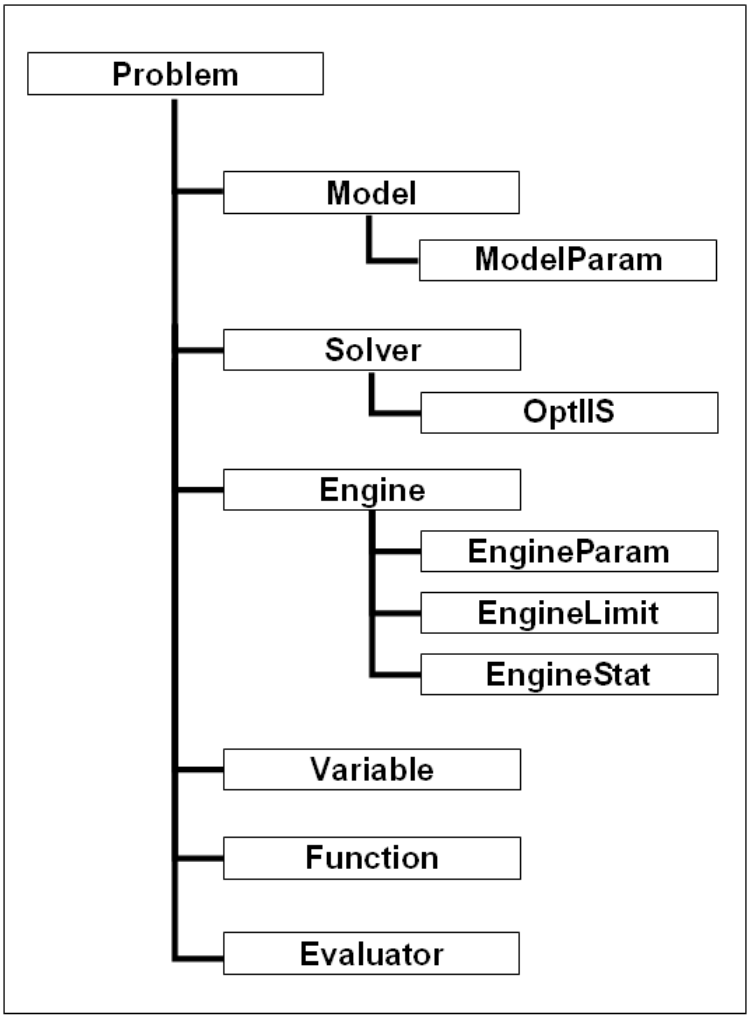
To use the new object-oriented API in VBA, you must first add a reference to the type library for the Analytic Solver COM server. To do this:

1. Press Alt-F11 to open the VBA Editor.
2. Select menu choice **Tools References**.
3. Scroll down until you find **Analytic Solver 2020 Type Library**.
4. Check the box next to this entry, and click OK to close the dialog.
5. Use File Save to save your workbook.

Note that this is a **different** reference from **Solver**, which is the reference you add in order to use the "traditional" VBA functions.

Analytic Solver Object Model

Analytic Solver makes available a hierarchy of objects for describing optimization problems, as pictured on the next page. Note that the same objects are used for both optimization and simulation problems; see the next chapter, "Automating Simulation in VBA," for more information.

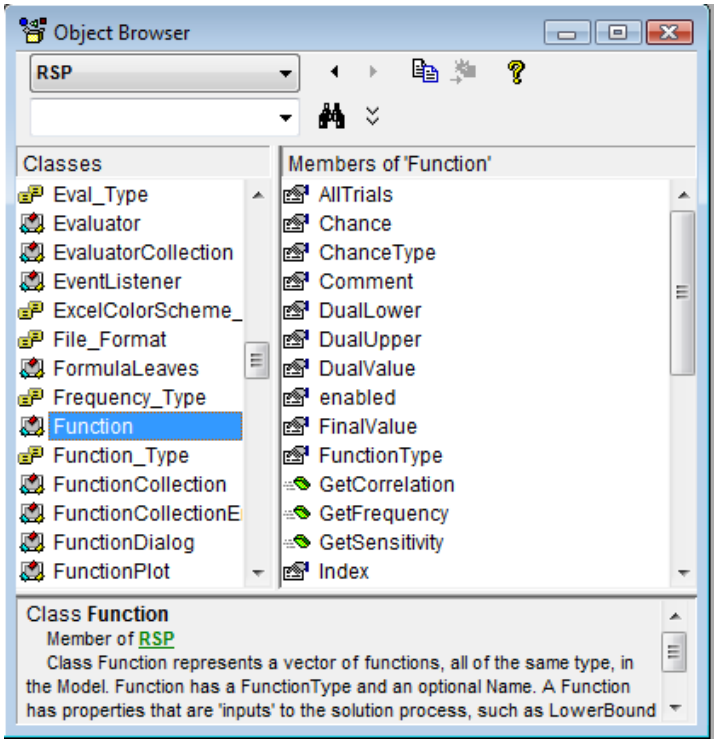


The **Problem** object represents the whole problem, and the **Model** object represents the internal structure of the model, which in Analytic Solver is defined by your formulas on the spreadsheet. The **Solver** object represents the optimization process – you call its Optimize method to find an optimal solution. The **Engine** object represents either a built-in or plug-in Solver engine. A **Variable** object represents a range of one or more contiguous cells that contains decision variables, while a **Function** object represents a range of cells that contains either constraint left hand sides or the objective. Each Problem has a collection of Variable objects, and a collection of Function objects. An **Evaluator** represents a function you write that the Solver will call on each iteration (Trial Solution), or on each subproblem in a larger problem.

The Model has a collection of **ModelParam** objects, each representing a single option or parameter of the PSI Interpreter (appearing in the Task Pane Platform tab). An Engine has a collection of **EngineParam** objects, each representing a single option or parameter of a Solver engine (appearing in the Task Pane Engine tab). It also has an **EngineLimit** object, holding problem size limits for this Solver engine, and an **EngineStat** object, holding performance statistics for the last optimization problem solved by this engine. An **OptIIS** object holds results of an infeasibility analysis of the problem.

Using the VBA Object Browser

You can examine Analytic Solver objects, properties and methods in the VBA Object Browser. To do this, press **Alt-F11** to open the VBA Editor, and select menu choice **View Object Browser**. This displays a child window like the one pictured below.



The dropdown list at the top left corner of the Object Browser initially displays <All Libraries> – change this to select **RSP**. In the object browser pictured, we've highlighted the properties of the Function object

Programming the Object Model

You use the Analytic Solver object-oriented API by first creating an instance of a **Problem**, and initializing it with the Solver model defined on a worksheet in an open workbook. When you do this, a collection of **Variable** objects and a collection of **Function** objects are created automatically. Each Variable object corresponds to a cell range of decision variables that appears in the outlined list of variables, and each Function object corresponds to a cell range of constraints that appears in the list of constraints in the Task Pane.

Once you have an initialized Problem object, you can do several things:

- Set Solver and Engine parameters such as the maximum time or number of iterations, the method used to compute gradients, and other options and tolerances.
- Perform an optimization, and check the final status of the solution process.
- Get results of the optimization, by accessing properties of the Variable and Function objects, and performance statistics, by accessing properties of the EngineStat object.

Example VBA Code Using the Object Model

Below is an example of VBA code that could be linked to a command button on the worksheet:

```
Private Sub CommandButton1_Click()
  Dim prob As New RSP.Problem

  prob.Engine = prob.Engines("Standard LP/Quadratic")
  prob.Engine.Params("MaxTime") = 600

  prob.Solver.Optimize
  MsgBox "Status = " & prob.Solver.OptimizeStatus
  MsgBox "Obj = " & prob.FcnObjective.FinalValue(0)

  For i = 0 To prob.Variables.Count - 1
    For j = 0 To prob.Variables(i).Size - 1
      MsgBox prob.Variables(i).FinalValue(j)
    Next j
  Next i

  Set prob = Nothing
End Sub
```

The first line creates an instance of a Problem, which by default is associated with the Solver model defined on the active worksheet. You could associate the Problem object with a different worksheet by calling the prob.Init method:

```
Private Sub CommandButton1_Click()
  'create new problem
  Dim prob As New RSP.Problem
'initialize model on Invent2 worksheet
  prob.Init Worksheets("Invent2")
```

The second line selects the Standard LP/Quadratic Solver engine, and the third line sets the maximum solution time to 600 seconds. The **string names** of parameters such as "MaxTime" are documented in the Frontline Solvers Reference Guide.

The next set of three lines performs the optimization, displays the Solver Result status code (for example 0), and displays the final value of the objective.

The double for-loop in the next five lines steps through the Variable objects – each one representing a range of contiguous cells – and displays the final value for each variable cell in each range.

Evaluators Called During the Solution Process

You can write a VBA function that Analytic Solver will call at certain points during the solution process. In this "callback function," you can access information about the problem and solution so far, to monitor or report progress and decide whether to stop or continue the solution process.

The object-oriented API defines an Evaluator object that is associated with your "callback function" and specifies when Analytic Solver should call it. You can define Evaluators to be called on each iteration or Trial Solution, or on each subproblem or each new solution ("incumbent") when the solution process involves multiple subproblems (global optimization problems, and problems with integer variables).

The VBA function you write to serve as an Evaluator must be contained in a **class module** – not a 'regular' VBA module – and it must be declared to have the **With Events** property.

On the next page is an example of code for an Evaluator, in a class module named Class1.

```
Private WithEvents EvalIterator As RSP.Evaluator

Private Function EvalIterator_Evaluate _
  (ByVal Evaluator As RSP.IEvaluator) As _
  RSP.Engine_Action

  MsgBox "Iteration = " _
    & Evaluator.Problem.Engine.Stat.Iterations _
    & Chr(13) & Chr(10) & "Objective = " _
    & Evaluator.Problem.FcnObjective.Value(0) _
    & Chr(13) & Chr(10)

  EvalIterator_Evaluate = Engine_Action_Continue
End Function

Public Sub MySolve()
  Set EvalIterator = New RSP.Evaluator
  Dim prob As New RSP.Problem
  prob.Evaluators(Eval_Type_Iteration) = EvalIterator
  prob.Solver.Optimize
  Set EvalIterator = Nothing
End Sub
```

```
Having created the class module Class1, in a
'regular' VBA module you can create an instance of
Class1, and then call the MySolve method in Class1:
```

```
Private Sub CommandButton1_Click()
  Dim c As New Class1
  c.MySolve
End Sub
```

Refinery.xls: Multiple Blocks of Variables and Functions

A further example of programming the object-oriented API is shown in the model **Refinery.xls**, which is installed in the Examples folder, normally at the path C:\Program Files\Frontline Systems\Analytic Solver Platform\Examples. (You can also open this example by clicking Help – Examples on the Ribbon, then click Optimization Examples.)

The Refinery.xls model, which is based on Problem 12.6 in the 3rd edition of *Model Building in Mathematical Programming* by H.P. Williams (see the Recommended Books on www.solver.com for details), has ten blocks of decision variables and eleven blocks of constraints, plus bounds on certain variables.

The VBA code for this model illustrates some of the many ways you can use the object-oriented API. For example, the following line displays the time that was required to solve the problem:

```
MsgBox prob.Engine.Stat.Milliseconds & " msec"
```

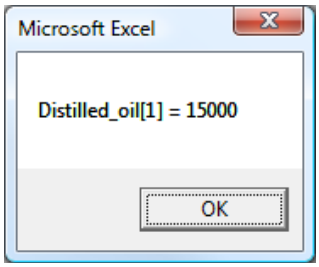
The following line inserts an Answer Report into the active workbook:

```
prob.Solver.Report "", "Answer"
```

The VBA code on the next page illustrates one way to display final solution values for each of the ten blocks of decision variables in this problem:

```
For i = 0 To prob.Variables.Count - 1
  prob.Variables(i).MakeCurrent
  For j = 0 To prob.VarDecision.Size - 1
    MsgBox prob.VarDecision.Name _
      & "[" & j+1 & "] = " & _
      prob.VarDecision.FinalValue(j)
  Next j
Next i
```

When executed, this code displays MessageBoxes such as:



The line `prob.Variables(i).MakeCurrent` associates the Problem property VarDecision (a single block of decision variables) with each of the ten blocks of variables in turn, allowing you to refer to solution values and dual values of this block in more compact notation. A similar line of code can be used to make the Problem property FcnConstraint represent one of the eleven blocks of constraints. The .Name property of the block, which usually returns a string such as "$A$1:$A$10", returns "Distilled_oil" in this case, since the Excel model has a defined name for this block of cells.

Adding New Variables and Constraints to a Model

So far, we've seen how to access variables and constraints that were defined interactively through the Ribbon and Task Pane (or the Solver Parameters dialog), using the Problem object and its VarDecision and FcnConstraint properties, as well as the Variables and Functions collections. But you can also add new variables and constraints to a model through the Object-Oriented API, and have them appear in the Task Pane Model tab. To illustrate some additional properties used in full Analytic Solver Comprehensive, let's add a *recourse* decision variable and a *chance* constraint.

To add a new decision variable, we create a Variable object, associate it with a worksheet cell, set its properties, and add it to the Variables collection. To make this a recourse decision variable, we simply set its VariableType property:

```
Dim v As New RSP.Variable
  v.Init "$D$18"
  v.VariableType = Variable_Type_Recourse
  v.NonNegative
  prob.Variables.Add v
```

Similarly, to add a new constraint, we create a Function object, associate it with a formula cell on the worksheet, set its properties, and add it to the Functions collection. To make this a chance constraint, we simply set its FunctionType, ChanceType and Chance properties:

```
Dim f As New RSP.Function
  f.Init "$C$23"
  f.FunctionType = Function_Type_Chance
  f.ChanceType = Chance_Type_VaR
  f.Chance = 0.95
  f.LowerBound.Array = 0 '>= 0
  prob.Functions.Add f
```

CuttingStock.xls: Multiple Problems and Dynamically Generated Variables

A more ambitious example of programming the object-oriented API is shown in the model **CuttingStockVBA(Opt).xls**, which is installed in the Examples folder, normally at the path C:\Program Files\Frontline Systems\Analytic Solver Platform\Examples. (You can also open this example by clicking Help – Examples on the Ribbon, then click Optimization Examples.)

This application uses the object-oriented API to define and repeatedly solve two optimization problems, passing information back and forth between the two problems. One problem is instantiated from a worksheet with the prob.Init method as mentioned earlier; the other problem is created "from scratch," with new dynamically generated decision variables added each time the problem is solved.

Cutting Stock Problem

CuttingStockVBA(Opt).xls solves a classical "cutting stock" problem, which arises for example in lumber and paper mills. Imagine that you have a number of sheets of wood or rolls of paper of a fixed width, waiting to be cut; you have customer orders for sheets or rolls of various different widths. Your task is to cut the larger, fixed-width sheets or rolls into different sizes in a way that minimizes the total stock used while meeting customer demand.

You might for example cut a 100 inch sheet into two sheets of 45 inches (leaving 10 inches wasted), three sheets of 31 inches (leaving 7 inches wasted), one 45-inch sheet and one 31-inch sheet (leaving 24 inches wasted), etc. Each of these is called a *pattern*, and the main problem will have a decision variable representing the number of copies of that pattern to cut. In a 'real-life" application, the number of possible patterns is exponentially large, yielding a model that's too large to solve.

Column Generation Method

We can instead use the technique of *column generation* ('columns' here refers to variables in the main problem). We choose a small initial set of patterns to include in the model, and solve the main problem (an LP). Since it is unlikely that we chose the perfect set of patterns initially, we use the dual variable information from the main problem to generate a new pattern. We generate this new pattern by solving a second optimization problem, called a 'knapsack' problem. A decision variable for the new pattern is dynamically created and added to the main problem, which is solved again. These two problems, the

main problem and the knapsack problem, are solved in turn until no more patterns can be generated that will reduce the total stock used.

Worksheets and VBA Code

In CuttingStockVBA(Opt).xls, sheet Input contains the 'knapsack' problem, which is solved to generate new patterns, and sheet Patterns contains the main problem. Our VBA code executes a loop, alternately solving the main problem and the knapsack problem. When the solution to the main problem can no longer be improved, we solve a final problem where we add integer constraints on the variables, so the final solution yields an exact count of the patterns that should be cut.

Open CuttingStockVBA(Opt).xls and press Alt-F11 to view its VBA code in the VBA Editor. The first block of code clears the Patterns sheet and sets up the initial patterns. This code simply sets values and formulas into cells, using the Excel object model.

```
Dim nPat As Integer, i As Integer, _
nNumDemands As Integer
nPat = Range("Demands").Count

nNumDemands = nPat
Worksheets("Patterns").Activate
Range("$A$1:$Z$100").Clear

' create initial patterns
For i = 1 To nPat
  Cells(2 + i, i) = Int(Range("RollSize").Value2 _
      / Range("Widths").Cells(i).Value2)
  Cells(2 + i, nPat + 1).Formula = "=sumproduct(" _
      & Range(Cells(1, 1), Cells(1, nPat)).Address
      & "," & Range(Cells(2 + i, 1), _
        Cells(2 + i, nPat)).Address & ")"
  Cells(3 + nPat, i) = Range("RollSize").Value2 - _
        Cells(2 + i, i) *
Range("Widths").Cells(i).Value2
Next i
```

The code then enters the main loop in which we add a new pattern to the main problem, and set up and solve that problem using Analytic Solver's object model:

```
  'generate patterns
  Cells(2, 1).Formula = "=sum(" _
    & Range(Cells(1, 1), Cells(1, nPat)).Address &
")"
  For i = 1 To nNumDemands
    Cells(2 + i, nPat + 1).Formula = "=sumproduct(" _
      & Range(Cells(1, 1), Cells(1, nPat)).Address _
      & "," & Range(Cells(2 + i, 1), Cells(2 + i, _
        nPat)).Address & ")"
  Next i

  Dim prob As New RSP.Problem

  ' variables
  prob.Variables.Clear
  prob.Functions.Clear
  Dim vars As New RSP.Variable
  vars.Init Range(Cells(1, 1), Cells(1, nPat))
```

```
  vars.NonNegative
  prob.Variables.Add vars
  Set vars = Nothing

  ' objective
  Dim objective As New RSP.Function
  objective.Init Range(Cells(2, 1), Cells(2, 1))
  objective.FunctionType = Function_Type_Objective
  prob.Functions.Add objective
  Set objective = Nothing

  ' constraints
  ReDim constraints(1 To nNumDemands) As _
    New RSP.Function
  For i = 1 To nNumDemands
    constraints(i).Init Range(Cells(2 + i, nPat + 1),
_
      Cells(2 + i, nPat + 1))
    constraints(i).LowerBound(0) = _
      Range("Demands").Cells(i).Value2
    prob.Functions.Add constraints(i)
  Next i

  prob.Solver.SolverType = Solver_Type_Minimize
  prob.Engine = prob.Engines("Standard LP/Quadratic")
  prob.Solver.Optimize
```

Next, the code obtains the dual values from the solution to the main problem, via the Analytic Solver object model, and stores these values as parameters of the knapsack problem on the Input worksheet, via the Excel object model:

```
  ' capture shadow prices
  For i = 1 To nNumDemands
    Worksheets("Input").Cells(2 + i, 5) = _
      prob.Functions(Range(Cells(2 + i, nPat + 1), _
      Cells(2 + i, nPat + 1))).DualValue(0)
  Next
  Worksheets("Input").Activate
  Dim j As Integer
  j = 1
  For i = 1 To prob.Functions.Count
    If prob.Functions(i - 1).FunctionType = _
       Function_Type_Constraint Then
         Cells(2 + j, 5) = _
           prob.Functions(i - 1).DualValue(0)
         j = j + 1
    End If
  Next i
```

The code then sets up and solves the knapsack problem, again using the Analytic Solver object model:

```
  Dim prob1 As New RSP.Problem
  prob1.Init Worksheets("Input")
  prob1.Engine = prob1.Engines("Standard

  LP/Quadratic")
  prob1.Engine.Params("IntTolerance").Value = 0
  prob1.Solver.Optimize
```

If the objective value of the knapsack problem is less than 1 (allowing for rounding error) – meaning that there are no more patterns that will improve the solution – we can exit the loop.

```
If 1 - prob1.FcnObjective.FinalValue(0) _
   >= -0.00001 Then
   Exit Do
End If
```

Otherwise, the code writes the new pattern to the Patterns (main problem) worksheet, using the Excel object model:

```
Worksheets("Patterns").Activate
Cells(nNumDemands + 3, nPat + 1) = _
  Range("RollSize").Value2
' write out new pattern, and associated waste
For i = 1 To nNumDemands
  Cells(2 + i, nPat + 1) = _
    prob1.VarDecision.FinalValue(i - 1)
  Cells(nNumDemands + 3, nPat + 1) = _
    Cells(nNumDemands + 3, nPat + 1).Value2 - _
    prob1.VarDecision.FinalValue(i - 1) * _
    Range("widths").Cells(i).Value
Next i

nPat = nPat + 1
Set prob1 = Nothing
```

When the Do … Loop is exited, all patterns have been generated. Finally, the code solves one more problem with integer constraints on the variables, to ensure that we produce the exact count needed to meet customer demand:

```
 Worksheets("Patterns").Activate
  prob.Init Worksheets("Patterns")
  prob.Functions.Clear
  prob.Variables.Clear

  ' variables
  Dim finalvars As New RSP.Variable
  finalvars.Init Range(Cells(1, 1), Cells(1, nPat))
  For i = 1 To nPat
    finalvars.IntegerType(i - 1) =
Integer_Type_Integer
  Next i
  finalvars.NonNegative
  prob.Variables.Add finalvars

  ' objective
  Cells(3 + nNumDemands, nPat + 1).Formula = _
    "=sumproduct(" & Range(Cells(1, 1), _
    Cells(1, nPat)).Address & "," _
    & Range(Cells(3 + nNumDemands, 1), _
    Cells(3 + nNumDemands, nPat)).Address & ")"
  Dim TotalWaste As New RSP.Function
  TotalWaste.Init Range(Cells(3 + nNumDemands, _
    nPat + 1), Cells(3 + nNumDemands, nPat + 1))
  TotalWaste.FunctionType = Function_Type_Objective
  prob.Functions.Add TotalWaste

  ' constraints
  ReDim constraints(1 To nNumDemands) As _
```

```
    New RSP.Function
  For i = 1 To nNumDemands
    Cells(2 + i, nPat + 1).Formula = "=sumproduct(" _
      & Range(Cells(1, 1), Cells(1, nPat)).Address _
      & "," & Range(Cells(2 + i, 1), Cells(2 + i, _
      nPat)).Address & ")"
    constraints(i).Init Range(Cells(2 + i, nPat + 1),
_
      Cells(2 + i, nPat + 1))
    constraints(i).LowerBound(0) = _
      Range("Demands").Cells(i).Value2
    prob.Functions.Add constraints(i)
  Next i

  prob.Engine = prob.Engines("Standard LP/Quadratic")
  prob.Engine.Params("IntTolerance").Value = 0
  prob.Solver.Optimize
  Set prob = Nothing
```

This example illustrates some of the power of the object-oriented API. Although you could use the "traditional" VBA functions to obtain similar results, it would require quite a bit more code to do so, especially at the step of obtaining the dual values from the solution of the main problem and using them to solve the next knapsack problem.

If you wanted to move this application from Excel to a standalone program, you'd find that nearly all the code in CuttingStockVBA(Opt).xls that references the Analytic Solver object model could be re-used, with few or no changes, in building an application for the Solver Platform SDK. You'd have to rewrite the code that references cells via the Excel object model to use arrays in a programming language instead, but this would not be difficult.

Automating Simulation in VBA

Introduction

This chapter explains how to use the Object-Oriented API in Analytic Solver Desktop to create, modify and solve simulation models under the control of your custom application written in VBA.

Note: Analytic Solver Cloud does not currently support this functionality.

In the simplest case, you can use a few standard lines of VBA code to enable and disable Interactive Simulation, as described below. But you can do much more in VBA, to create custom risk analysis applications.

You can define a **Problem** and instantiate it from the spreadsheet with two lines of code, then access the uncertain elements of your model via **Variable** and **Function** objects. You can perform simulations, access trials and summary statistics, and present them the way you want to your end user. All the power of the Excel object model is available, including database access, charts and graphs, and custom dialogs and controls.

Analytic Solver's VBA object model closely resembles the object-oriented API of Frontline's **Solver SDK Platform** or **Solver SDK Pro** – which both include a complete toolkit for Monte Carlo simulation. This makes it easier to move an application from Excel to a custom program written in C/C++, Visual Basic, VB.NET, Java or MATLAB.

Adding a Reference in the VBA Editor

To use the new object-oriented API in VBA, you must first add a reference to the type library for the Analytic Solver COM server. To do this:

1. Press Alt-F11 to open the VBA Editor.
2. Select menu choice **Tools References**.
3. Scroll down until you find **Analytic Solver 2020 Type Library**.
4. Check the box next to this entry, and click OK to close the dialog.
5. Use File Save to save your workbook.

Note that this is a **different** reference from **Solver**, which is the reference you add in order to use the "traditional" VBA functions.

You need this reference if your VBA code uses the Event Listener as described in the next section, or uses other elements of the Analytic Solver VBA object model, described in later sections of this chapter (or both).

Activating Interactive Simulation

If you simply want to activate or deactivate Interactive Simulation under program control, you need a few standard lines of VBA code. You can place this code in any VBA procedure you write, and cause it to be run in any manner that is convenient for your application. For example, you could use:

```
Public Sub ISActivate
    Dim ev As New EventListener
    ev.AttachEvent Application
    Set ev = Nothing
End Sub

Public Sub ISDeactivate
    Dim ev As New EventListener
    ev.DetachEvent
    Set ev = Nothing
End Sub
```

You could use the Tools Macro Run menu choice in Excel to run these VBA procedures, or you could associate a Ctrl-Key combination with each procedure, so it is run when that key combination is pressed.

Another approach appears in the example workbook **BusinessPlanPsiChart.xls** (normally installed at C:\Program Files\Frontline Systems\Analytic Solver Platform\Examples): Two buttons named CommandButton1 and CommandButton2 are placed on the spreadsheet, along with two images named Picture Bulb On and Picture Bulb Off, that are stacked on top of each other. The VBA code is:

```
Private Sub CommandButton1_Click()
    Dim ev As New EventListener
    ev.AttachEvent Application
    Set ev = Nothing
    Me.Shapes("Picture Bulb On").Visible = True
    Me.Shapes("Picture Bulb Off").Visible = False
End Sub

Private Sub CommandButton2_Click()
    Dim ev As New EventListener
    ev.DetachEvent
    Set ev = Nothing
    Me.Shapes("Picture Bulb On").Visible = False
    Me.Shapes("Picture Bulb Off").Visible = True
End Sub
```

When the "On" button (CommandButton1) is clicked, Interactive Simulation is activated, and the light bulb is "turned on." When the "Off" button is clicked, Interactive Simulation is deactivated, and the light bulb is "turned off."

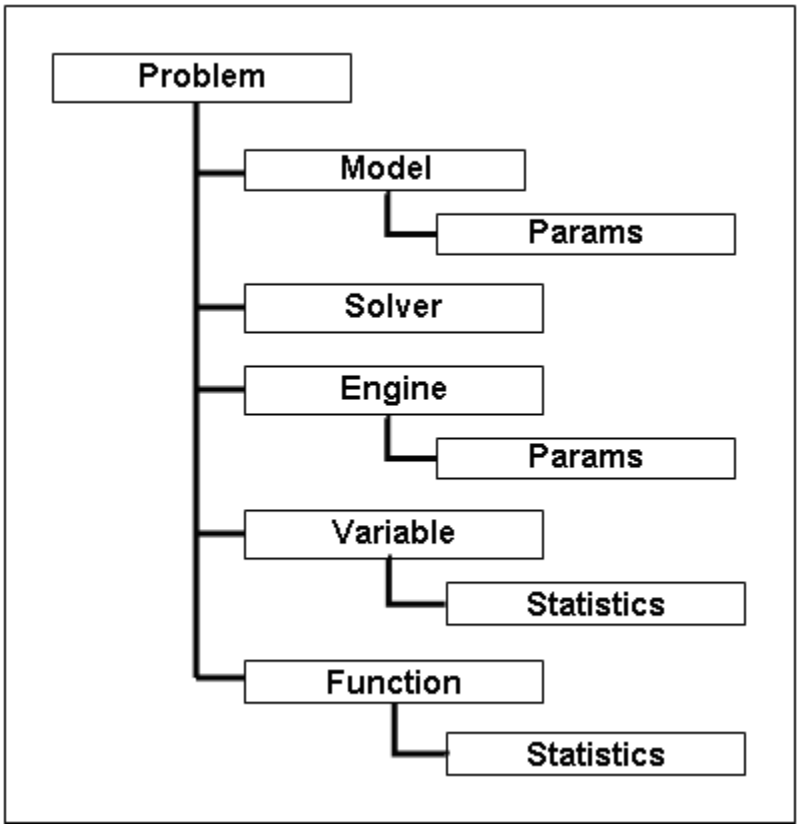
Using VBA to Control Analytic Solver

You can do much more with VBA: You can perform simulations under your control, rather than on every worksheet recalculation. You can obtain results of the simulation – statistics, percentiles, or even raw trial data – that you'd otherwise obtain through worksheet functions such as PsiMean(), PsiPercentile(), or PsiData(). You can even define certain worksheet cells as uncertain variables and supply trial data for them in a simulation, without using functions such as PsiNormal() or PsiUniform() in cell formulas.

You also have access in VBA to the Excel object model, which provides a very rich source of high-level functions for manipulating cells and ranges, creating charts and graphs, accessing external databases, and much more. This gives you a powerful set of tools for developing custom risk analysis applications.

Analytic Solver Object Model

Analytic Solver makes available a hierarchy of objects for describing Monte Carlo simulation problems, pictured below. This object model is a simplified subset of the object hierarchy offered by Frontline's Solver Platform SDK product, which is used to build custom applications in C/C++, Visual Basic, VB.NET, Java or MATLAB. Note that the same objects are used for both optimization and simulation problems.

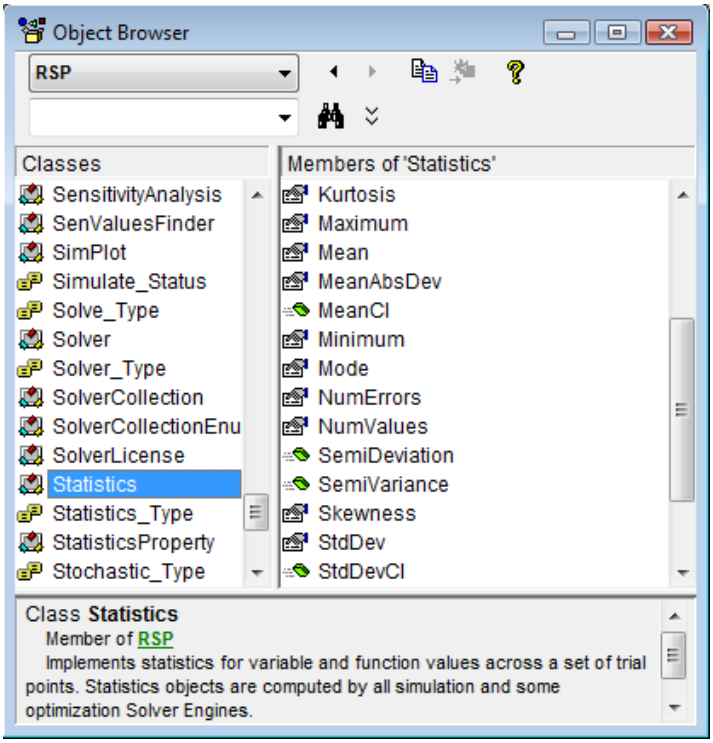


The **Problem** object represents the whole problem, and the **Model** object represents the internal structure of the model, which in Analytic Solver is defined by your formulas on the spreadsheet. The **Solver** object represents the Monte Carlo process – you call its Simulate method to perform a simulation. The **Engine** object represents the PSI Technology "engine" – its parameters include the sampling method, for example. A **Variable** object represents a range of one or more contiguous cells that contains uncertain variables, while a **Function** object represents a range of cells that contains uncertain functions. You may have a collection of Variable objects, and a collection of Function objects in one Problem.

Using the VBA Object Browser

You can examine the Analytic Solver objects, properties and methods in the VBA Object Browser. To do this, press Alt-F11 to open the VBA Editor, and select menu choice View Object Browser. This displays a child window like the one pictured below. The dropdown list at the top left corner of the Object Browser initially displays <All Libraries> – change this to select RSP. Below,

we've highlighted the properties of the Statistics object, which is a child of the Variable and Function objects.



Using Analytic Solver Objects

You use the Analytic Solver object model by first creating an instance of a **Problem**, and initializing it with the simulation model defined in your Excel workbook. Once you have an initialized Problem object, you can do several things:

- Add one or more new Variable objects to the problem. (This is an advanced step, covered near the end of this chapter.)
- Set Solver and Engine parameters such as the number of simulations, number of trials per simulation, the sampling method, and the random seed.
- Perform a simulation.
- Get results of the simulation, by accessing properties of the Variable and Function objects, and of their "child" Statistics objects.

The simplest action you might want to take is to create a Problem representing the workbook, set parameters, perform a simulation, and display results. Below is an example that could be linked to a command button on the worksheet:

```
Private Sub CommandButton3_Click()
   Dim prob As New RSP.Problem
   prob.Init ActiveWorkbook

   prob.Solver.NumTrials = 5000
   prob.Engine.Params("SamplingMethod") = 2
   prob.Solver.Simulate
```

```
   For i = 0 To prob.Functions.Count - 1
      MsgBox prob.Functions(i).Statistics.Mean(0)
   Next i
   Set prob = Nothing
End Sub
```

The first two lines create an instance of a Problem, and initialize it with the simulation model defined in your Excel workbook. The next two lines set the number of trials in the simulation to 5000, and the sampling method to Latin Hypercube. The fifth line performs a simulation.

The for-loop in the next three lines will step through the Function objects – assuming, for simplicity here, that each Function object represents just one cell – and display the Mean property of the child Statistics object (the mean or average value of the function across all trials) for each one.

Using Variable and Function Objects

When you create and initialize a **Problem**, a collection of **Variable** objects and a collection of **Function** objects are created automatically. Each Variable object corresponds to a range of one or more cells that contain PSI Distribution functions. Each Function object corresponds to a formula cell referenced as the first argument of a PSI Statistics function, or a range of one or more formula cells referenced by PsiOutput(). For more information on the grouping of cells into Function objects, please see the Frontline Solvers Reference Guide.

Indexing Variable and Function Objects

The VBA code example above assumes that any cells containing =PsiOutput() are separated from each other on the worksheet. When uncertain variable and uncertain function cells lie in a contiguous range – for example A1:A5 or A1:E1 – one Variable or Function object is created to represent all the cells in the range. The Size property of this object tells you the number of cells in the range, and its other properties may be indexed to access statistics – for example – of individual cells. The for-loop above could be written in more general form as:

```
For i = 0 To prob.Functions.Count - 1
     For j = 0 To prob.Functions(i).Size - 1
        MsgBox prob.Functions(i).Statistics.Mean(j)
     Next j
  Next i
```

Percentiles and AllTrials Properties

In addition to the Statistics child object used above, Variable and Function objects have properties named Percentiles and AllTrials (the raw trial data).

The Percentiles property plays the same role as the PsiPercentile() function on the spreadsheet. It yields a DoubleMatrix object that takes two subscripts: the index (starting from 0) of the cell in the range represented by the Variable or Function object, and the percentile index, which runs from 0 to 98 for the 1st through 99th percentile.

The AllTrials property plays the same role as the PsiData() function on the spreadsheet. It yields a DoubleMatrix object that takes two subscripts: the index (starting from 0) of the cell in the range represented by the Variable or Function object, and the index of the Monte Carlo trial (starting from 0).

The example code below illustrates how to obtain and display the values of the uncertain functions for each simulation trial.

```
For i = 0 To prob.Functions.Count - 1
      For j = 0 To prob.Functions(i).Size - 1
      MsgBox prob.Functions(i).Percentiles(j,94)
        For k = 0 To prob.Solver.NumTrials -1
            MsgBox prob.Functions(i).AllTrials(j, k)
        Next k
    Next j
Next i
```

GetFrequency Method

Variable and Function objects also have a GetFrequency method, that plays the same role as the PsiFrequency() function on the spreadsheet. It takes an argument specifying the type of frequency distribution (density, cumulative, etc.) and an array argument specifying the upper limits of the "bins" for which you want to obtain frequency data. It yields a DoubleMatrix object that takes two subscripts: the index (starting from 0) of the cell in the range represented by the Variable or Function object, and the index (starting from 0) of the frequency bin.

The example code below illustrates the use of the Get Frequency method to create 14 different "bins" for categorizing the values of the uncertain functions for each simulation trial.

```
      For i = 0 To prob.Functions.Count - 1
           For j = 0 To prob.Functions(i).Size - 1
                 Dim binlimits(14) As Double
                 binlimits(0) = -125000
           For Count = 1 To 13
                        binlimits(Count) =
                        binlimits(Count - 1) + 25000
                 Next
                    Dim mymat As New RSP.DoubleMatrix
                    Set mymat =
prob.Functions(i).GetFrequency(Frequency_Type_Density
,                     binlimits)
                    For Count = 0 To 13
                            MsgBox "Upper Bin Limit"
& ": " & binlimits(Count) & " = " &
mymat(0, Count)
                 Next Count
           Next j
      Next i
```

Controlling Simulation Parameters in VBA

Analytic Solver provides a number of parameters you can use to control the simulation process, such as the number of Monte Carlo trials to perform, or the random number seed. You can set these parameters interactively, or by setting certain Solver properties or Engine.Params properties in VBA.

For example, the first line below sets the number of Monte Carlo trials to 5000. The second line set the random number seed to a fixed value – so the same

random number sequence is used on each run. The third line sets the sampling method to Latin Hypercube:

```
prob.Solver.NumTrials = 5000
prob.Engine.Params("RandomSeed") = 12345
prob.Engine.Params("SamplingMethod") = 2
```

For a list of simulation parameters that you can set in VBA, see the descriptions of the "EngineParam Object" and the "ModelParam Object" in the Frontline Solvers Reference Guide.

Evaluators Called During the Simulation Process

You can write a VBA function that Analytic Solver will call at certain points during the simulation process. In this "callback function," you can access information about the problem and simulation so far, to monitor or report progress and decide whether to stop or continue the simulation process.

The object-oriented API defines an Evaluator object that is associated with your "callback function" and specifies when Analytic Solver should call it. The VBA function you write to serve as an Evaluator must be contained in a **class module** – not a 'regular' VBA module – and it must be declared to have the **WithEvents** property.

Here is an example of code for an Evaluator, in a class module named Class1:

```
Private WithEvents EvalSim As RSP.Evaluator

Private Function EvalSim_Evaluate _
  (ByVal Evaluator As RSP.IEvaluator) As _
  RSP.Engine_Action

  MsgBox "Current Simulation = " _
    & Evaluator.Problem.Engine.Stat.Simulations

  EvalSim_Evaluate = Engine_Action_Continue
End Function

Public Sub MySim()
  Set EvalSim = New RSP.Evaluator
  Dim prob As New RSP.Problem
  prob.Init ActiveWorkbook
  prob.Evaluators(Eval_Type_Simulation) = EvalSim
  prob.Solver.Simulate
  Set EvalSim = Nothing
End Sub
```

Having created the class module Class1, in a 'regular' VBA module you can create an instance of Class1, and then call the MySim method in Class1:

```
Private Sub CommandButton1_Click()
  Dim c As New Class1
  c.MySim
End Sub
```

You can define Evaluators to be called when the random sample for all uncertain variables is generated (Eval_Type_Sample), after each simulation is completed (Eval_Type_Simulation), or after each trial is completed (Eval_Type_Trial). However, because PSI Technology *evaluates all trials in parallel*, an Evaluator to be called on each trial is meaningful only if you use the

Excel Interpreter rather than the PSI Interpreter to calculate the worksheet on each trial.

Working with Trials and Simulations in VBA

Analytic Solver can perform multiple simulations in one run, where each simulation consists of a number of Monte Carlo trials that you specify. Multiple simulations can be run whenever you choose **Simulate – Run Once**, whenever you change a number with Interactive Simulation, or whenever you call the Problem.Solver.Simulate method in VBA.

In VBA, you can set the property **Problem.Solver.NumSimulations** = *n* to perform *n* different simulations on a single call to Problem.Solver.Simulate.

After a simulation is run, Analytic Solver Simulation can display each Monte Carlo trial from the simulation on the Excel worksheet, if desired. In VBA, you can set the property **Problem.Solver.TrialIndex** = *n* to display the *n*th trial, or you can call the method **Problem.Solver.TrialStep** to cycle through the trials.

Displaying Normal or Error Trials

Analytic Solver **filters out** 'error trials' from your simulation results when computing statistics and displaying charts. An 'error trial' is a Monte Carlo trial where *any* uncertain function returns an Excel error value. However, all trials are saved in memory, and you can access the values of uncertain variables and uncertain functions for each trial, or display each trial on the Excel worksheet.

The Variable and Function objects contain an embedded Statistics object (described later in this chapter). The property **Statistics.NumValues** gives the number of 'normal' trials, over which statistics were calculated, and property **Statistics.NumErrors** gives the number of error trials that occurred.

You can cause a specific Monte Carlo trial to be displayed on the Excel worksheet by setting the property **Problem.Solver.TrialIndex** = *n* to the index (starting from 1) of the trial you want. This causes the PSI Distribution function for each uncertain variable to return the sample value it had on the *n*th trial. The worksheet is then recalculated, so that each uncertain function will have the value it had on the *n*th trial.

To "step through" all trials, normal trials only, or error trials only, and display them on the Excel worksheet, call the method **Problem.Solver.TrialStep** *stepsize*, *trialtype*. Trialtype is 0 for all trials, 1 for normal trials, and 2 for error trials. The *stepsize* may be positive (1, 2, etc.) or negative (-1, -2, etc.). After each call to the TrialStep method, the TrialIndex property is set to the index of the trial just displayed. If stepsize is so large that it would go beyond the last trial (if positive, or the first trial if negative), the TrialIndex will be set to the last (or first) trial, and that trial will be displayed.

Using Multiple Simulations

For multiple simulations to be useful, some parameter of the model – normally something you can control – must have a different value in each individual simulation. Also, you must access statistics, percentiles, and trial data (if used) for each simulation, so you can compare the results.

If you set **Problem.Solver.NumSimulations** = *n* to perform several simulations on each run, you can use the function **PsiSimParam()**. This function takes

either two arguments *lower* and *upper*, as in PsiSimParam(1,3), or one argument that's a cell range or array of numbers, such as PsiSimParam({6.0, 7.5, 9.0}). On the *n*th simulation, PsiSimParam() returns the *n*th value from its argument list, held constant for all the trials in that simulation. In calls to the **PSI Statistics** functions, you can select the simulation for which you want results. For example, if you have an uncertain function in cell F1, you can write =PsiMean(F1,1), =PsiMean(F1,2), and =PsiMean(F1,3) to access the mean value of F1 across all the trials in the first simulation, second simulation, and third simulation, respectively.

If you leave the NumSimulations property at its default value of 1, and call **Problem.Solver.Simulate** inside a for-loop, you can set parameter values that you compute on-the-fly in cells before each simulation using the Excel Range object. You can either get the values of PSI Statistics functions through the Excel object model, or (often better) you can access the Statistics, Percentiles and AllTrials properties, or call the GetFrequency method of your Variables and Functions, to retrieve the results of that simulation.

Creating Uncertain Variables and SLURPs in VBA

The chapter "Mastering Simulation and Risk Analysis Concepts" describes Stochastic Library Units, Relationships Preserved or SLURPs, and shows how to create a SLURP on the spreadsheet. You can also create SLURPs in VBA, and use the SLURP trial data for uncertain variables in your spreadsheet model.

To do this, you first create a Problem object, and initialize it with the simulation model defined in your Excel workbook. At this point, the Problem's collection of Variables will contain Variable objects for each contiguous range of cells containing PSI Distribution functions in the workbook (if any). You can then:

1. Create a new Variable object in VBA.
2. Set its Name property to an unused cell range (say "Sheet1:A1:A5").
3. Set its AllTrials property to the SLURP trial data.
4. Add the Variable object to the Problem's collection of Variables.

The simulation model then behaves just as if these cells contained =PsiSlurp() function calls that referred to the SLURP trial data you supplied via VBA. The SLURP data could be generated by your VBA program, read from a database, or otherwise obtained – it never appears on the Excel spreadsheet. For example:

```
Dim prob As New RSP.Problem
prob.Init ActiveWorkbook

Dim trials As RSP.DoubleMatrix
Set trials = New RSP.DoubleMatrix
trials.InitDense 1, prob.Solver.NumTrials

Randomize
For i = 0 To prob.Solver.NumTrials - 1
    trials(0, i) = Rnd()
Next i

Dim var As New RSP.Variable
var.VariableType = Variable_Type_Uncertain
var.Init Range("Sheet1$A$1")
var.AllTrials = trials
```

```
prob.Variables.Add var
prob.Solver.Simulate
```

The first two lines create an instance of a Problem, and initialize it with the simulation model defined in your Excel workbook. The next three lines create a DoubleMatrix object named *trials* to hold SLURP data, and set its dimensions – just 1 x NumTrials in this case, since we're adding just one uncertain variable.

The next four lines show how the trials matrix can be initialized with newly generated values. Of course, you'd want to use a better, application-specific method – not the Rnd() function – to generate this trial data, or perhaps read the trial data from a database or external file.

In the next three lines, we create a Variable object, set its Name property to the cell address Sheet1!A1 (this must be an empty cell on the spreadsheet), and set its AllTrials property to the trial data we just generated.

In the last two lines, we add the new Variable object to the Problem's collection of Variables, and then perform a simulation.

The newly added Variable object, and the SLURP data represented by its AllTrials property, participates in the simulation model only for so long as the VBA Problem object exists – it is "transient" and is not saved in the workbook. Of course, your VBA program code *is* saved with the workbook, and it can be run at a later time to re-create the Variable object and re-generate or retrieve the SLURP data.

Mastering Conventional Optimization Concepts

Introduction

This chapter explains basic and advanced concepts of optimization, such as the types of problems you can solve, types of constraints (regular, integer, conic, alldifferent) you can specify, the nature of linear, quadratic and nonlinear functions, convex and non-convex functions, smooth and non-smooth functions, and the algorithms and methods used by Analytic Solver (or its optimization sub-set products) and plug-in Solver engines.

This chapter focuses on conventional or *deterministic* optimization models, which do not include any uncertainty. The next chapter "Mastering Simulation and Risk Analysis Concepts" explains the concepts of *stochastic* optimization models – those that do include uncertainty – and solution methods such as robust optimization, stochastic programming, and simulation optimization.

If you are using Analytic Solver for the first time, we recommend that you try out the examples described in the chapter "Examples: Conventional Optimization" before tackling this material. If you are relatively new to optimization, you may find it useful to read the first section below, "Elements of Solver Models," and then proceed to the Examples chapters. If you've been using the Solver for a while, and you'd like a more in-depth review of the mathematical relationships found in Solver models, and the optimization methods and algorithms used by the Solver, read the more advanced sections of this chapter, and the next chapter.

Elements of Solver Models

The basic purpose of the Solver is to find a *solution* – that is, values for the *decision variables* in your model – that satisfies all of the *constraints* and maximizes or minimizes the *objective function* value (if there is one). Let's examine this framework more closely.

The model you create for use with the Solver is no different from any other spreadsheet model. It consists of input values; formulas that calculate values based on the input values or on other formulas; and other elements such as formatting. You can play "what if" with a Solver model just as easily as with any other spreadsheet model. This familiar concept can be very useful when you wish to present your results to managers or clients, who are usually "spreadsheet literate" even if they are unfamiliar with Solvers or optimization.

Decision Variables and Parameters

Some of the input values may be numbers that you use, but you cannot change on your own – for example, prevailing interest rates or supplier's prices. We'll call these values *parameters* of the model. You may have several cases, scenarios, or variations of the same problem to solve, and the parameter values

will change in each problem variation; you can define these parameters via the Parameters button on the Ribbon. In this chapter, we'll assume that parameter values are *certain*, but the chapter "Mastering Stochastic Optimization Concepts" will cover situations where the parameter values are *uncertain*.

Other input values may be quantities that are variable, or under your control in the course of finding a solution. We'll refer to these as the variables or *decision variables*; the Excel Solver refers to them as Changing Cells. The Solver will find optimal values for these variables or cells. Often, some of the same cell values you use to play "what if" are the ones for which you'll want the Solver to find solution values. These cells are listed in the Variables group in the Task Pane Model tab, or the Solver Parameters dialog.

The Objective Function

The quantity you want to maximize or minimize is called the *objective* or *objective function*; the Excel Solver often uses the term Set Cell for the objective. For example, this could be a calculated value for projected profits (to be maximized), or costs, risk, or error values (to be minimized). It appears under 'Objective' in the Task Pane Model tab, or the Solver Parameters dialog.

You may have a Solver model that has nothing to maximize or minimize, in which case no cell will be listed for the objective. In this situation the Solver will simply find a solution that satisfies the constraints. Typically this will be only one of many such solutions, located close to the starting values of the decision variables.

The Solver also permits you to enter a specific value that you want the objective function to achieve. This feature was originally included in the Excel Solver to match the Excel Goal Seek... command, which allows you to seek a specific value for a cell by adjusting the value of one other cell on which it depends. Using the 'Value Of' option for the objective cell has the same effect as adding an = constraint in the outlined list, with the objective cell on the left hand side and the constant value on the right hand side; again there is nothing to maximize or minimize.

There is rarely a good reason to use the Value of option. If your problem requires only a single objective cell and a single variable cell with no constraints, you can just use the Goal Seek... command. If you have nothing to maximize or minimize, we recommend that you omit the objective and enter all of your constraints in the outlined list under "Constraints."

Constraints

Constraints are relations such as A1 >= 0. A constraint is *satisfied* if the condition it specifies is true *within a small tolerance.* This is a little different from a logical formula such as =A1>=0 evaluating to TRUE or FALSE which you might enter in a cell. In this example, if A1 were -0.0000001, the logical formula would evaluate to FALSE, but with the default Solver Precision setting, the constraint would be satisfied. Because of the numerical methods used to find solutions to Solver models and the finite precision of computer arithmetic, it would be unrealistic to require that constraints like A1 >= 0 be satisfied exactly – such solutions would rarely be found.

In the Excel Solver, constraints are specified by giving a cell reference such as A1 or A1:A5 (the "left hand side"), a relation (<=, = or >=), and an expression for the "right hand side." Although Excel allows you to enter any numeric expression on the right hand side, for reasons that will be explained in the

chapter "Best Practices for Building Large-Scale Models," we strongly encourage you to use only *constants*, or references to cells that contain *constant values* on the right hand side. (A constant value to the Solver is any value that does not depend on any of the decision variables.)

A constraint such as A1:A5 <= 10 is shorthand for A1 <= 10, A2 <= 10, A3 <= 10, A4 <= 10, A5 <=10. A constraint such as A1:A5 <= B1:B5 is shorthand for A1 <= B1, A2 <= B2, A3 <= B3, A4 <= B4, A5 <= B5.

Another type of constraint is of the form A1:A5 = integer, where A1:A5 are decision variables. This specifies that the solution values for A1 through A5 must be integers or whole numbers, such as -1, 0 or 2, *to within a small tolerance*. This form of constraint, and related forms such as A1:A5 = binary, A1:A5 = semicontinuous, and A1:A5 = alldifferent, are explored in the section "More About Constraints."

A new type of constraint supported by Analytic Solver is of the form A1:A5 = conic, where A1:A5 are decision variables. This is called a *second order cone* constraint and is further described in "More About Constraints."

Solutions: Feasible, "Good" and Optimal

A solution (set of values for the decision variables) for which all of the constraints in the Solver model are satisfied is called a *feasible solution.* In some problems, a feasible solution is already known; in others, finding a feasible solution may be the hardest part of the problem.

An *optimal solution* is a feasible solution where the objective function reaches its maximum (or minimum) value – for example, the most profit or the least cost. A *globally optimal solution* is one where there are no other feasible solutions with better objective function values. A *locally optimal solution* is one where there are no other feasible solutions "in the vicinity" with better objective function values – you can picture this as a point at the top of a "peak" or at the bottom of a "valley" which may be formed by the objective function and/or the constraints.

The Solver is designed to find feasible and optimal solutions. In the best case, it will find the globally optimal solution – but this is not always possible. In other cases, it will find a locally optimal solution, and in still others, it will stop after a certain amount of time with the best solution it has found so far. But like many users, you may decide that it's most important to find a *good solution* – one that is better than the solution, or set of choices, you are using now.

The kind of solution the Solver can find depends on the nature of the mathematical relationships between the variables and the objective function and constraints (and the solution algorithm used). As explained below, if your model is ***smooth convex***, you can expect to find a globally optimal solution; if it is smooth but ***non-convex***, you will usually be able to find a locally optimal solution; if it is ***non-smooth***, you may have to settle for a "good" solution that may or may not be optimal.

Below, we summarize the capabilities of the five Solver engines bundled with Analytic Solver Comprehensive and Analytic Solver Optimization within both Analytic Solver Desktop and the Cloud app: the LP/Quadratic Solver, SOCP Barrier Solver, nonlinear GRG Solver, Interval Global Solver, and Evolutionary Solver. (Analytic Solver Upgrade uses the LP/Quadratic Solver, the nonlinear GRG Solver, and the Evolutionary Solver.) Later sections of this chapter provide an overview of the optimization methods and algorithms employed by each of these Solver engines.

Linear Simplex and LP/Quadratic Solver

The Simplex LP Solver with the Excel Solver finds optimal solutions to problems where the objective and constraints are all linear functions of the variables. (The term *linear function* is explained below, but you can imagine its graph as a straight line.) Since all linear functions are ***convex***, the Solver normally can find the *globally optimal solution*, if one exists. Because a linear function (a straight line) can always be increased or decreased without limit, the optimal solution is always determined by the constraints; there is no natural "peak" or "valley" for the objective function itself.

In Analytic Solver Comprehensive, Analytic Solver Optimization, Analytic Solver Upgrade and Analytic Solver Basic, the linear Simplex Solver is extended to the LP/Quadratic Solver. This Solver handles problems where the constraints are all linear, and the objective may be linear or quadratic (explained further below). If the quadratic objective function is ***convex*** (if minimizing, or ***concave*** if maximizing) the Solver will normally find a globally optimal solution. If the objective is ***non-convex*** (further explained below), the Solver will find only a locally optimal solution.

SOCP Barrier Solver

The SOCP Barrier Solver, included in all optimization products, finds optimal solutions to problems where the objective and constraints are all linear or convex quadratic functions of the variables. (This is in contrast to the LP/Quadratic Solver, which permits only the objective function to be quadratic.) It also finds optimal solutions to problems with a linear objective, linear constraints, and *second order cone* (SOC) constraints; this is called a second order cone programming (SOCP) problem, as explained further below. Since all linear functions and SOC constraints are ***convex***, the SOCP Barrier Solver normally finds a *globally optimal solution*, if one exists.

Nonlinear GRG Solver

The nonlinear GRG Solver (in all Analytic Solver products except Analytic Solver Simulation) finds optimal solutions to problems where the objective and constraints are all smooth (***convex*** or ***non-convex***) functions of the variables. (The term *smooth function* is explained below, but you can imagine a graph – whether straight or curved – that contains no "breaks.") For non-convex problems, the Solver normally can find a *locally optimal solution*, if one exists – but this may or may not be the globally optimal solution. A nonlinear objective function can have a natural "peak" or "valley," but in most problems the optimal solution is partly or wholly determined by the constraints. The nonlinear GRG Solver can be used on problems with all-linear functions, but it is much less effective and efficient than the LP/Quadratic Solver or the SOCP Barrier Solver on such problems.

If you use multistart methods for global optimization with the nonlinear GRG Solver, you will have a better chance (but not a guarantee) of finding the globally optimal solution. The idea behind multistart methods is to automatically start the Solver from a variety of starting points, to find the best of the locally optimal solutions – ideally the globally optimal solution. These methods are more fully described (and contrasted with other methods for global search) below under "Global Optimization" and in the chapter "Solver Engine Option Reference" in the Frontline Solvers Reference Guide.

Interval Global Solver

The Interval Global Solver, included in all optimization products, finds *globally optimal solutions* to problems where the objective and constraints are all smooth (***convex*** or ***non-convex***) functions of the variables. Unlike the Evolutionary Solver or the GRG Solverswith multistart methods, the Interval Global Solver is normally able to determine *for certain* that the solution is globally optimal. The tradeoff is that the Interval Global Solver usually takes much more time to solve a given problem than the GRG Solver, and this time rises steeply as the number of variables and constraints in the problem increases. Hence, the Interval Global Solver is practically able to solve only smaller problems, compared to the GRG Solver.

Evolutionary Solver

The Evolutionary Solver in Analytic Solver, and all subsets except Analytic Solver Simulation, usually finds *good solutions* to problems where the objective and constraints include non-smooth or discontinuous functions of the variables – in other words, where there are no restrictions on the formulas that are used to compute the objective and constraints. For example, if your model uses IF, LOOKUP or similar functions of the variables, it's likely that the graphs of these functions will contain "jumps" or "breaks." For this class of problems, the Solver will return the best feasible solution (if any) that it can find in the time allowed.

The Evolutionary Solver can be used on problems with all-smooth functions that may have multiple locally optimal solutions, in order to seek a globally optimal solution, or simply a better solution than the one found by the nonlinear GRG Solver alone; however, the Interval Global Solver or the combination of multistart methods and the GRG Solver are likely to do as well or better than the Evolutionary Solver on such problems. It can be used on problems with smooth convex functions, but it is usually less effective and efficient than the nonlinear GRG oSolver on such problems. Similarly, it can be used on problems with all-linear functions, but there is little point in doing so when the Simplex (Excel Solver), LP/Quadratic, or SOCP Barrier Solver is available.

More About Constraints

This section explains in greater depth the role of certain types of constraints, including bounds on the decision variables, equality and inequality constraints, second order cone constraints, and different forms of integer constraints.

Bounds on the Variables

Constraints of the form A1 >= -5 or A1 <= 10 (for example), where A1 is a decision variable, are called *bounds on the variables* and are treated specially by the Solver. These constraints affect only one variable, whereas general constraints have an indirect effect on several variables that have been used in a formula such as A1+A2. Each of the Solver engines takes advantage of this fact to handle bounds on the variables more efficiently than general constraints.

The most common type of bound on a variable is a lower bound of zero (A1 >= 0), which makes the variable non-negative. Many variables represent physical quantities of some sort, which cannot be negative. As a convenience, most Solver Engines offer an option "Assume Non-Negative," which automatically places a lower bound of zero on every variable which has not been given an explicit lower bound in the model outline. If you need bounds other than zero,

the Task Pane Platform tab Default Bounds section lets you set default *lower* and *upper* bounds on every decision variable.

Regardless of the Solver engine chosen, bounds on the variables always help speed up the solution process, because they limit the range of values that the Solver must explore. In many problems, you will be aware of realistic lower and upper bounds on the variables, but they won't be of any help to the Solver unless you include them in the Constraints list box! Bounds on the variables are especially important to the performance of the Evolutionary Solver, the Interval Global Solver, and multistart methods for global optimization. They are also very important if you want the Solver to automatically transform your model, replacing non-smooth functions (such as IF) with additional variables and linear constraints.

Equations and Inequalities

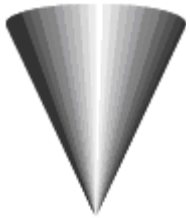
Constraints such as A1 = 0 are called *equality constraints* or *equations*; constraints such as A1 <= 0 are called *inequality constraints* or simply *inequalities*. An equality is much more restrictive than an inequality. For example, if A1 contains the formula =C1+C2, where C1 and C2 are decision variables, then A1 <= 0 restricts the possible solutions to a *half plane*, whereas A1 = 0 restricts the solutions to a *line* where all possible values of C1and C2 must sum to 0 (C1 = -C2 within a small tolerance, as explained above). Since there is only a tiny chance that two randomly chosen values for C1 and C2 will satisfy C1+C2 = 0, solution methods that rely on random choices, such as genetic algorithms, may have a hard time finding any feasible solutions to problems with equality constraints. To satisfy equality constraints, the Solver generally must exploit properties of the constraint formula – such as *linearity* or *smoothness*, discussed below – to solve for one variable in terms of another.

A linear equality constraint (like C1+C2 = 0 above) maintains the convexity of the overall problem, but a nonlinear equality constraint is ***non-convex***, and makes the overall problem non-convex. Interior point methods may have difficulty solving problems with nonlinear equality constraints, since they restrict the ability of the Solver to follow the "central path" inside the feasible region.

A problem with *only* equality constraints (and no objective) is sometimes called a *system of equations*. The Solver can be used to find solutions to systems of both linear and nonlinear equations. If there are several different solutions (sets of values for the decision variables) that satisfy the equations, most Solver engines will find just one solution that is "close" to the starting values of the variables; but the Interval Global Solver can be used to find *all* real solutions to a system of smooth nonlinear equations – a capability that was once felt to be beyond the limits of any known algorithm.

Second Order Cone Constraints

Analytic Solver supports constraints of the form A1:A5 = conic. This is called a *second order cone* (SOC) constraint; it specifies that the vector formed by the decision variables A1:A5 must lie within the second-order cone (also called the Lorentz cone, or "ice cream cone") of dimension 5 – a ***convex*** set that looks like the figure below in three dimensions.



Algebraically, a second-order cone constraint specifies that, given a value for one variable, the *L2*-norm of the vector formed by the remaining variables must not exceed this value: In linear algebra notation, $a_1 \geq \|a_2{:}a_5\|_2$. In Excel, this could be written as A1 >= SQRT(SUMSQ(A2:A5)). You can also use a variant called a "rotated second order cone" constraint. A problem with a linear objective and linear or SOC constraints is called a *second order cone programming* (SOCP) problem; it is always a ***convex*** optimization problem.

Decision variables that are constrained to be non-negative also belong to a cone, called the *non-negative orthant*. A problem with all linear functions – a linear programming problem – is a special case of an SOCP problem, where the only cone constraint is non-negativity.

A convex quadratic objective or constraint can be transformed into an equivalent second order cone constraint. Hence, a problem with a quadratic objective – a quadratic programming or QP problem – or a problem with quadratic constraints – called a QCP problem – is also a special case of an SOCP problem. The SOCP Barrier Solver and the MOSEK Solver will automatically transform quadratics into SOC form internally; you can simply define your quadratic objective and/or constraints using ordinary Excel formulas and <= or >= relations, and use these Solver engines to obtain fast, reliable, globally optimal solutions to your problem.

Integer and Binary Constraints

As explained in the last section, integer constraints are of the form A1:A5 = integer, where A1:A5 are decision variables. This specifies that the solution values for A1 through A5 must be integers or whole numbers, such as -1, 0 or 2, to within a small tolerance. A common special case that can be entered directly in the Add Constraint dialog is A1 = binary, which is equivalent to specifying A1 = integer, A1 >= 0 and A1 <= 1. This implies that A1 must be *either 0 or 1* at the solution; hence A1 can be used to represent a "yes/no" decision. Integer constraints have many important applications, but the presence of even one such constraint in a Solver model makes the problem an integer programming problem (discussed below), which may be much more difficult to solve than a similar problem without the integer constraint.

Semi-Continuous Constraints

It is often useful to place a *semi-continuous* constraint on a decision variable. This specifies that, at the solution, the variable must be either 0, or else a continuous value within a range, determined by the bounds on the variable. For example, if a machine is either "off" or running at a speed between 5 and 50, you can model the machine's speed with A1 = semicontinuous, A1 >= 5 and A1 <= 50. In situations where you might need a binary integer variable *and* a regular (continuous) variable, you can sometimes use a single semi-continuous variable instead – and such a variable can be handled very efficiently by most Solver engines.

Alldifferent Constraints

A special type of integer constraint supported by Analytic Solver and its subset products is called an "alldifferent" constraint. Such a constraint is of the form (for example) A1:A5 = alldifferent, where A1:A5 is a group of decision variables, and it specifies that these variables must be integers in the range 1 to N (N = 5 in this example), with each variable different from all the others at the solution. Hence, A1:A5 will contain a *permutation* of integers, such as 1,2,3,4,5 or 1,3,5,2,4. The alldifferent constraint can be used to model problems involving ordering of choices, such as the Traveling Salesman Problem.

Functions of the Variables

Since there are large differences in the time it takes to find a solution and the *kinds* of solutions – globally optimal, locally optimal, or simply "good" – that you can expect for different types of problems, it pays to understand the differences between linear, quadratic, smooth nonlinear, and non-smooth functions, and especially **convex** and **non-convex** functions. To begin, let's clarify what it means to say that the spreadsheet cells you select for the objective and constraints are "functions of the decision variables."

The objective function in a Solver problem is a cell calculating a value that depends on the decision variable cells; the job of the Solver is to find some combination of values for the decision variables that maximizes or minimizes this cell's value. During the optimization process, *only the decision variable cells are changed*; all other "input" cells are held constant. If you analyze the chain of formulas that calculates the objective function value, you will find that parts of those formulas (those which refer to non-decision variable cells) are unchanging in value and could be replaced by a numeric constant for the purposes of the optimization.

If you have constant values on the right hand sides of constraints, then the same observation applies to the left hand sides of constraints: Parts of the constraint formulas (those which refer to non-decision variable cells) are unchanging in value, and only the parts that are dependent on the decision variables "count" during the optimization.

When you consider whether your objective and constraints are linear, quadratic, smooth nonlinear, or non-smooth, or **convex** or **non-convex** functions of the variables, always bear in mind that only the parts of formulas that are *dependent on the decision variables* "count." Below, we explain that linear functions are most desirable, and non-smooth and non-convex functions are least desirable in a Solver model (if you want the fastest and most reliable solutions). A formula such as =IF(C1>=10,D1,2*D1) is non-smooth if C1 depends on the decision variables; but if C1 *doesn't* depend on the variables, then only D1 or 2*D1 – not both – can be selected during the solution process. Hence if D1 is a linear function of the variables, then the IF expression is also a linear function of the variables.

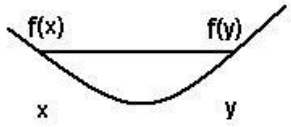
You may also find that a function that is "bad" (non-smooth or non-convex) over its full domain (any possible values for the decision variables) can still be "good" (smooth and/or convex) over the domain of interest to you, determined by other constraints including bounds on the variables. For example, if C1 depends on the variables, then =IF(C1>=10,D1,2*D1) is non-smooth over its full domain, but smooth – in fact linear – if C1 is constrained to be 10 or more. =SIN(C1) is non-convex over its full domain, but is convex from –pi to 0, or from pi to 2*pi.

Convex Functions

The key property of functions of the variables that makes a problem "easy" or "hard" to solve is *convexity*. If *all* constraints in a problem are convex functions of the variables, and if the objective is convex if minimizing, or concave if maximizing, then you can be confident of finding a globally optimal solution (or determining that there is no feasible solution), even if the problem is very large – thousands to hundreds of thousands of variables and constraints.

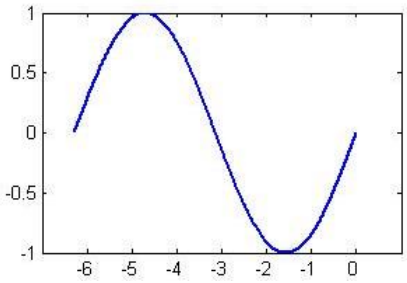
In contrast, if *any* of the constraints are non-convex, or if the objective is either non-convex, concave if minimizing, or convex if maximizing, then the problem is far more difficult: You cannot be certain of finding a feasible solution even if one exists; you must either "settle for" a locally optimal solution, or else be prepared for very long solution times and rather severe limits on the size of problems you can solve to global optimality (a few hundred to perhaps one thousand variables and constraints), even on the fastest computers. So it pays to understand convexity!

Geometrically, a function is *convex* if, at any two points x and y, the line drawn from x to y (called the *chord* from x to y) lies *on or above* the function – as shown in the diagram below, for a function of one variable. A function is *concave* if the chord from x to y lies *on or below* the function. This property extends to any number of 'dimensions' or variables, where x = (x_1, x_2, …, x_n) and y =(y_1, y_2, …, y_n).



Algebraically, a function *f* is *convex* if, for any points x and y, and any t between 0 and 1, *f*(tx + (1-t)y) <= t*f*(x) + (1-t)*f*(y). A function *f* is *concave* if –*f* is convex, i.e. if *f*(tx + (1-t)y) >= t*f*(x) + (1-t)*f*(y). A *linear* function – described below – is both convex and concave: The chord from x to y lies on the line, and *f*(tx + (1-t)y) = t*f*(x) + (1-t)*f*(y). As we'll see, a problem with all linear functions is the simplest example of a convex optimization problem that can be solved efficiently and reliably to very large size.

A non-convex function "curves up and down." A familiar example is the sine function (SIN(C1) in Excel), which is pictured below.



The feasible region of an optimization problem is formed by the intersections of the constraints. The intersection of several convex constraints is always a convex region, but even one non-convex function can make the whole region non-convex – and hence make the optimization problem far more difficult to solve.

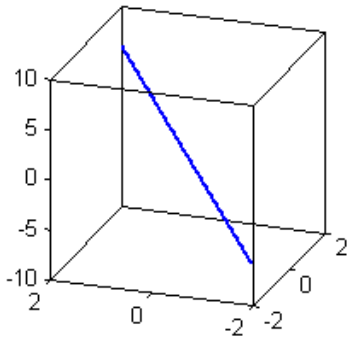
Linear Functions

In many common cases, the objective and/or constraints are *linear* functions of the variables. This means that the function can be written as a sum of terms, where each term consists of one decision variable multiplied by a (positive or negative) constant. Algebraically, we can write:

$a_1x_1 + a_2x_2 + ... + a_nx_n$

where the a_is, which are called the *coefficients*, stand for constant values and the x_is stand for the decision variables. A common example is =SUM(C1:C5), where C1:C5 are decision variables and the a_is are all 1. Note that a linear function does not have to be written in exactly the form shown above on the spreadsheet. For example, if cells C1 and C2 are decision variables, B1 = C1+C2, and B2 = A1*B1 where A1 is constant in the problem, then B2 is a linear function (=A1*C1+ A1*C2).

Geometrically, a linear function is always a straight line, in *n*-dimensional space where *n* is the number of decision variables. On the next page is a perspective plot of $2x_1 + 1x_2$. As noted above, a linear function is always convex.



Remember that the a_is need only be *constant in the optimization problem*, i.e. not dependent on any of the decision variables. For example, suppose that the function is =B1/B2*C1 + (D1*2+E1)*C2, where only C1 and C2 are decision variables, and the other cells contain constants (or formulas that don't depend on the variables). This would still be a linear function, where a_1 = B1/B2 and a_2 = (D1*2+E1) are the coefficients, and x_1 = C1 and x_2 = C2 are the variables.

Note that the SUMPRODUCT and DOTPRODUCT functions compute exactly the algebraic expression shown above. If we were to place the formula =B1/B2 in cell A1, and the formula =(D1*2+E1) in cell A2, then we could write the example function above as:

=SUMPRODUCT(A1:A2,C1:C2)

This is simple and clear, and is also useful for *fast problem setup* as described in the chapter "Best Practices for Building Large-Scale Models." If the decision variable cells that should participate in the expression are not all contiguous on the spreadsheet, the DOTPRODUCT function can be used instead of SUMPRODUCT.

As explained below in the section "Derivatives, Gradients, Jacobians and Hessians," each coefficient a_i in the linear expression $a_1x_1 + a_2x_2 + ... + a_nx_n$ is the first partial derivative of the expression with respect to variable x_i. These partial derivatives are always *constant* in a linear function – and all higher-order derivatives are zero.

A *nonlinear* function (explained further below), as its name implies, is any function of the decision variables which is not linear, i.e. which cannot be written in the algebraic form shown above – and its partial derivatives are *not* constant. Examples would be = 1/C1, =LOG(C1), =C1^2 or =C1*C2 where both C1 and C2 are decision variables. If the objective function or any of the constraints are nonlinear functions of the variables, then the problem cannot be solved with an LP Solver.

Testing for a Linear Model

What if you have already created a complex spreadsheet model without using functions like SUMPRODUCT, and you aren't sure whether your objective function and constraints are linear or nonlinear functions of the variables? If you have Analytic Solver, you can easily find out by pressing the Analyze button in the Task Pane. Moreover, you can easily obtain a report showing exactly which cells contain formulas that are nonlinear.

You can try solving the model with the standard LP/Quadratic Solver. If the problem contains nonlinear functions of the variables, you will (in virtually all cases) receive the message "The linearity conditions required by this Solver engine are not satisfied." You can then ask the Solver to produce a Linearity Report, which shows whether the objective and each of the constraints is a linear or nonlinear function of the variables. This report also shows which variables occur linearly, and which occur nonlinearly in your model – another way of summarizing the same information. You should next look closely at the objective or constraint formulas that the Linearity Report indicates are nonlinear, and decide whether (or not) the formula can be written in linear form.

Quadratic Functions

The last two examples of nonlinear functions above, =C1^2 or =C1*C2, are simple instances of *quadratic* functions of the variables. A more complex example is:

=2*C1^2+3*C2^2+4*C1*C2+5*C1

A quadratic function is a sum of terms, where each term is a (positive or negative) constant (again called a *coefficient*) multiplied by a single variable or the product of two variables. In linear algebra notation, we can write $x^TQx + cx$ where x is a vector of *n* decision variables, Q is an *n* x *n* matrix of coefficients, and c is an *n* vector of linear coefficients. The QUADPRODUCT function computes values of exactly this form. If we put the constant 5 in A1, 0 in B1, 2 in A2, 4 in B2, 0 in A3 and 3 in B3, then we could write the above example as:

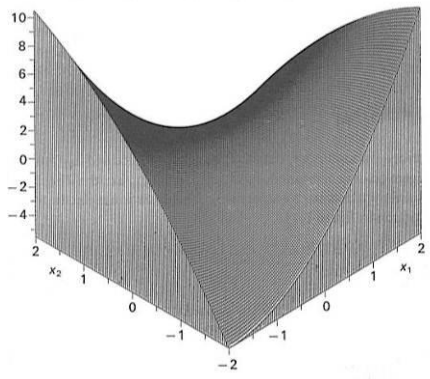
=QUADPRODUCT(C1:C2,A1:B1,A2:B3)

Common uses for quadratic functions are to compute the mean squared error in a curve-fitting application, or the variance or standard deviation of security returns in a portfolio optimization application.

As explained below in the section "Derivatives, Gradients, Jacobians and Hessians," the coefficients that multiply single variables in a quadratic function are the first partial derivatives of the function with respect to those variables; the coefficients that multiply the *products* of two variables are the *second* partial derivatives of the function, with respect to those two variables. In a quadratic function, these first and second order derivatives are always *constant*, and higher order derivatives are zero. The matrix Q of second partial derivatives is called the *Hessian* of the function.

Convex, Concave and Non-Convex Quadratics

A quadratic function of at least two variables may be convex, concave, or non-convex. The matrix Q in the general form x^TQx has a closely related algebraic property of *definiteness*. If the Q matrix is *positive definite*, the function is convex; if the Q matrix is *negative definite*, the function is concave. You can picture the graph of these functions as having a "round bowl" shape with a single bottom (or top). If the Q matrix is *semi-definite*, the function has a bowl shape with a "trough" where many points may have the same objective value, but it is still convex or concave. If the Q matrix is *indefinite*, the function is **non-convex**: It has a "saddle" shape, but its true minimum or maximum is not found in the "interior" of the function but on its boundaries with the constraints, where there may be many locally optimal points. Below is a plot of an example non-convex quadratic $x_1^2 + 2x_1x_2 - ½ (x_2^2 - 1)$:



A problem with **convex** quadratic functions is easily solved to global optimality up to very large size, but a problem with **non-convex** quadratic functions is a difficult global optimization problem that, in general, will require solution time that grows *exponentially* with the number of variables. The way that the Solver handles such functions is explained further below under "Quadratic Programming."

Nonlinear and Smooth Functions

A *nonlinear* function is any function of the variables that is not linear, i.e. which cannot be written in the algebraic form:

$a_1x_1 + a_2x_2 + ... + a_nx_n$

Examples, as before, are =1/C1, =LOG(C1), and =C1^2, where C1 is a decision variable. All of these are called *continuous* functions, because their graphs are curved but contain no "breaks." =IF(C1>10,D1,2*D1) is also a nonlinear function, but it is "worse" (from the Solver's viewpoint) because it is *discontinuous*: Its graph contains a "break" at C1=10 where the function value jumps from D1 to 2*D1. At this break, the rate of change (i.e. the derivative) of the function is undefined. As explained below in the section "Derivatives, Gradients, Jacobians and Hessians," most Solver algorithms rely on derivatives to seek improved solutions, so they may have trouble with a Solver model containing functions like =IF(C1>10,D1,2*D1). The Interval Global Solver does not accept discontinuous functions at all.

If the graph of the function's *derivative* also contains no breaks, then the original function is called a *smooth* function. If it does contain breaks, then the original function is *non-smooth*. Every discontinuous function is also non-smooth. An example of a continuous function that is non-smooth is =ABS(C1) – its graph is

an unbroken "V" shape, but the graph of its derivative contains a break, jumping from –1 to +1 at C1=0. Many nonlinear Solver algorithms rely on second order derivatives of at least the objective function to make faster progress, and to test whether the optimal solution has been found; they may have trouble with functions such as =ABS(C1). The Interval Global Solver does not accept any non-smooth functions.

As explained below in the section "Derivatives, Gradients, Jacobians and Hessians," general nonlinear functions have first, second, and sometimes higher order derivatives that *change* depending on the point (i.e. values of the decision variables) at which the function is evaluated.

Convex, Concave and Non-Convex Smooth Functions

A general nonlinear function of even one variable may be convex, concave or non-convex. A function can be convex but non-smooth: =ABS(C1) with its V shape is an example. A function can also be smooth but non-convex: = SIN(C1) is an example. But the "best" nonlinear functions, from the Solver's point of view, are both *smooth* and *convex* (concave for the objective if you are maximizing).

If a smooth function's second derivative is always nonnegative, it is a *convex* function; if its second derivative is always nonpositive, it is a *concave* function. This property extends to any number of 'dimensions' or variables, where the second derivative becomes the Hessian and "nonnegative" becomes "positive semidefinite."

Discontinuous and Non-Smooth Functions

Microsoft Excel provides a very rich formula language, including many functions that are discontinuous or non-smooth. As noted above, discontinuous functions cause considerable difficulty, and non-smooth functions cause some difficulty for most nonlinear Solvers; such functions are not accepted by the Interval Global Solver. Some models can only be expressed with the aid of these functions; in other cases, you have a degree of choice in how you model the real-world problem, and which functions you use. Even when you have a "full arsenal" of Solver engines available, as you do with Analytic Solver Comprehensive and its subset products, you'll get better results if you try to use the most "Solver-friendly" functions in your model.

By far the most common discontinuous function in Excel is the IF function where the conditional test depends on the decision variables, as in the example =IF(C1>10,D1,2*D1). Here is a short list of common *discontinuous* Excel functions:

IF, CHOOSE
LOOKUP, HLOOKUP, VLOOKUP
COUNT
INT, ROUND
CEILING, FLOOR

Here is a short list of common *non-smooth* Excel functions:

ABS
MIN, MAX

Formulas involving relations such as <=, = and >= (on the worksheet, not in constraints) and logical functions such as AND, OR and NOT are discontinuous at their points of transition from FALSE to TRUE values. Functions such as

SUMIF and the database functions are discontinuous if the criterion or conditional argument depends on the decision variables.

If you aren't sure about a particular function, try graphing it (by hand or in Microsoft Excel) over the expected range of the variables; this will usually reveal whether the function is discontinuous or non-smooth. If using Analytic Solver, just create a model using the function, and use the Analyze button to automatically diagnose the model type.

Analytic Solver Comprehensive, Analytic Solver Optimization, Analytic Solver Upgrade and Analytic Solver Basic can **automatically transform** a model that uses IF, AND, OR, NOT, ABS, MIN and MAX, and relations <, <=, >= and > to an equivalent model where these functions and relations are replaced by additional binary integer and continuous variables and additional constraints, that have the same effect – for the purpose of optimization – as the replaced functions. This powerful facility may be able to transform your non-smooth model into a smooth or even linear model with integer variables. An example is shown in the EXAMPLE5 worksheet of the **StandardExamples.xls** workbook, which is normally installed into C:\Program Files\Frontline Systems\Analytic Solver Platform\Examples.

Derivatives, Gradients, Jacobians, and Hessians

To find feasible and optimal solutions, most optimization algorithms rely heavily on derivatives of the problem functions (the objective and constraints) with respect to the decision variables. First derivatives indicate the direction in which the function is increasing or decreasing, while second derivatives provide curvature information.

The partial derivatives of a function $f(x_1,x_2,...,x_n)$ with respect to each variable are denoted $\partial f/\partial x_1$, $\partial f/\partial x_2$, …, $\partial f/\partial x_n$. They give the rate of change of the function in each dimension. For a linear function $a_1x_1 + a_2x_2 + ... + a_nx_n$, the partial derivatives are the coefficients: $\partial f/\partial x_1 = a_1$, $\partial f/\partial x_2 = a_2$, and so on.

To recap the comments about derivatives made in the sections above:

- Linear functions have *constant* first derivatives – the coefficients a_i – and all higher order derivatives (second, third, etc.) are zero.
- Quadratic functions have *constant* first and second derivatives, and all higher order (third, etc.) derivatives are zero.
- Smooth nonlinear functions have first and second derivatives that are *defined*, but not constant – they change with the point at which the function is evaluated.
- Non-smooth functions have second derivatives that are *undefined* at some points; discontinuous functions have first derivatives that are undefined at some points.

The *gradient* of a function $f(x_1,x_2,...,x_n)$ is the vector of its partial derivatives:

$$[\ \partial f/\partial x_1,\ \partial f/\partial x_2,\ \ldots,\ \partial f/\partial x_n\ ]$$

This vector points in the direction (in n-dimensional space) along which the function increases most rapidly. Since a Solver model consists of an objective and constraints, all of which are functions of the variables $x_1,x_2,...,x_n$, it is often useful to collect these gradients into a matrix, where each row is the gradient vector for one function:

$$\begin{vmatrix} \partial f_1/\partial x_1, & \partial f_1/\partial x_2, & \ldots, & \partial f_1/\partial x_n \\ \partial f_2/\partial x_1, & \partial f_2/\partial x_2, & \ldots, & \partial f_2/\partial x_n \\ \ldots & & & \\ \partial f_m/\partial x_1, & \partial f_m/\partial x_2, & \ldots, & \partial f_m/\partial x_n \end{vmatrix}$$

This matrix is called the *Jacobian* matrix. In a linear programming problem, this is the LP coefficient matrix, and all of its elements (the a_is) are constant.

The second partial derivatives of a function $f(x_1,x_2,\ldots,x_n)$ with respect to each pair of variables x_i and x_j are denoted $\partial^2 f / \partial x_i \partial x_j$. There are n^2 second partial derivatives, and they can be collected into an n x n matrix:

$$\begin{vmatrix} \partial^2 f/\partial x_1\partial x_1, & \partial^2 f/\partial x_1\partial x_2, & \ldots, & \partial^2 f/\partial x_1\partial x_n \\ \partial^2 f/\partial x_2\partial x_1, & \partial^2 f/\partial x_2\partial x_2, & \ldots, & \partial^2 f/\partial x_2\partial x_n \\ \ldots & & & \\ \partial^2 f/\partial x_n\partial x_1, & \partial^2 f/\partial x_n\partial x_2, & \ldots, & \partial^2 f/\partial x_n\partial x_n \end{vmatrix}$$

This matrix is called the *Hessian* matrix. It provides second order (curvature) information for a single problem function, such as the objective. The Hessian of a linear function would have all zero elements; the Hessian of a quadratic function has all *constant* elements; and the Hessian of a general nonlinear function may change depending on the point (values of the decision variables) where it is evaluated.

When reading the next section, "Optimization Problems and Solution Methods," bear in mind that the different classes of Solver problems, and the computing time required to solve these problems, is directly related to the nature of the derivatives (constant, changing, or undefined) of their problem functions, as outlined above.

For example, because the first derivatives of linear functions are *constant*, they need be computed only once – and second derivatives (which are zero) need not be computed at all. For quadratic functions, the first and second derivatives can be computed only once, whereas for general nonlinear functions, these derivatives may have to be computed many times.

A major difference between the Analytic Solver products versus Excel Solver, is the method used to compute derivatives. The Polymorphic Spreadsheet Interpreter in Analytic Solver can supply fast, accurate derivatives to Solver engines via a process called *automatic differentiation*.

What if your optimization problem requires the use of non-smooth or discontinuous functions? With Analytic Solver, you have several choices. First, for common non-smooth functions such as ABS, MAX and MIN, and even for some IF functions, the nonlinear GRG, Large-Scale GRG and Large-Scale SQP Solvers often yield acceptable results, though you may need to use multistart methods to improve the chances of finding the optimal solution. Second, you can use the Evolutionary Solver (which does not require any derivative values) to find a "good" solution, though you'll have to give up guarantees of finding an optimal solution, and it's likely to take considerably more computing time to find a solution. Third, you can use the automatic transformation feature to replace many of these functions with additional variables and linear constraints; if all discontinuous or non-smooth functions in the model are automatically

replaced, the problem should be solvable with the nonlinear Solvers, or even with the linear Solvers in some cases. Fourth, you can manually reformulate your model with binary integer variables and associated constraints. You can then use the nonlinear GRG Solver, or even the LP/Quadratic Solver, in combination with the Branch & Bound method, to find the *true optimal solution* to your problem. These ideas are explored further in the chapter "Best Practices for Building Large-Scale Models."

Optimization Problems and Solution Methods

A model in which the objective function and all of the constraints (other than integer constraints) are linear functions of the decision variables is called a *linear programming* (LP) problem. (The term "programming" dates from the 1940s and the discipline of "planning and programming" where these solution methods were first used; it has nothing to do with computer programming.) As noted earlier, a linear programming problem is always **convex**.

If the problem includes integer constraints, it is called an *integer linear* programming problem. A linear programming problem with some "regular" (continuous) decision variables, and some variables that are constrained to integer values, is called a *mixed-integer programming* (MIP) problem. Integer constraints are **non-convex**, and they make the problem far more difficult to solve; see below for details.

A *quadratic programming* (QP) problem is a generalization of a linear programming problem. Its objective is a **convex** *quadratic* function of the decision variables, and all of its constraints must be *linear* functions of the variables. A problem with linear and convex quadratic *constraints*, and a linear or convex quadratic objective, is called a *quadratically constrained* (QCP) problem.

A model in which the objective function and all of the constraints (other than integer constraints) are smooth nonlinear functions of the decision variables is called a *nonlinear programming* (NLP) or *nonlinear optimization* problem. If the problem includes integer constraints, it is called an *integer nonlinear* programming problem. A model in which the objective or any of the constraints are non-smooth functions of the variables is called a *non-smooth optimization* (NSP) problem.

Linear Programming

Linear programming (LP) problems are intrinsically easier to solve than nonlinear (NLP) problems. First, they are convex, where a general nonlinear problem is often non-convex. Second, since all constraints are linear, the globally optimal solution always lies at an "extreme point" or "corner point" where two or more constraints intersect. (In some problems there may be multiple solutions with the same objective value, all lying on a line between two corner points.) This means that an LP Solver needs to consider many fewer points than an NLP Solver, and it is always possible to determine (subject to the limitations of finite precision computer arithmetic) that an LP problem (i) has no feasible solution, (ii) has an unbounded objective, or (iii) has a globally optimal solution.

Problem Size and Numerical Stability

Because of their structural simplicity, the main limitations on the size of LP problems that can be solved are time, memory, and the possibility of numerical "instabilities" which are the cumulative result of the small errors intrinsic to finite precision computer arithmetic. The larger the model, the more likely it is that numerical instabilities will be encountered in solving it.

Most large LP models are *sparse* in nature: While they may include thousands of decision variables and constraints, the typical constraint will depend upon only a few of the variables. This means that the Jacobian matrix of partial derivatives of the problem functions, described earlier, will have many elements that are *zero*. Such sparsity can be exploited to save memory and gain speed in solving the problem.

The Simplex Method

LP problems are most often solved via the Simplex method. The standard Microsoft Excel Solver uses a straightforward implementation of the Simplex method to solve LP problems, when the Assume Linear Model box is checked in the Solver Options dialog. Analytic Solver Comprehensive, Analytic Solver Optimization, Analytic Solver Upgrade and Analytic Solver Basic use a far more sophisticated implementation of the Simplex method which exploits sparsity in the LP model and uses techniques such as presolving, matrix factorization using the LU decomposition , a fast, stable LU update, and dynamic Markowitz refactorization.

The Large-Scale LP/QP Solver and MOSEK Solver engines use even more powerful implementations of the methods mentioned above. They have been used to solve LP problems with millions of variables and constraints.

The Large-Scale SQP Solver engine includes a powerful linear programming Solver that uses "active set" methods (closely related to the Simplex method). It is practical for problems up to 100,000 variables and constraints. This same Solver engine also handles large-scale QP and NLP problems very efficiently.

The Gurobi Solver and XPRESS Solver engine are Frontline's fastest and most powerful Solvers for linear programming and especially *mixed-integer* linear programming problems. Their advanced primal and dual Simplex and Barrier methods, combined with state-of-the-art Branch and Cut methods for integer problems, yield solutions in record time.

Quadratic Programming

Quadratic programming problems are more complex than LP problems, but simpler than general NLP problems. They have only one feasible region with "flat faces" on its surface (due to their linear constraints), but the optimal solution may be found anywhere within the region or on its surface. Since a QP problem is a special case of an NLP problem, it *can* be solved with the standard nonlinear GRG Solver, but this may take considerably more time than solving an LP of the same size. The LP/Quadratic Solver in Analytic Solver Comprehensive and Analytic Solver Optimization solves QP problems using a variant of the Simplex method to determine the feasible region, and special methods based on the properties of quadratic functions to find the optimal solution.

Most quadratic programming algorithms are specialized to handle only positive definite (or negative definite) quadratics. The LP/Quadratic Solver, however, can also handle semi-definite quadratics; it will find one of the equivalent

(globally) optimal solutions – which one depends on the starting values of the decision variables. When applied to an indefinite quadratic objective function, the LP/Quadratic Solver provides only the guarantees of a general nonlinear Solver: It will converge to a locally optimal solution (either a saddle point in the interior, or a locally optimal solution on the constraint surface).

The Large-Scale LP/QP Solver, Large-Scale GRG Solver, Large-Scale SQP Solver, Knitro Solver, Gurobi Solver, MOSEK Solver, and XPRESS Solver engines can all be used to efficiently solve large QP problems.

Quadratically Constrained Programming

A problem with linear and convex quadratic *constraints*, and a linear or convex quadratic objective, is called a *quadratically constrained* (QCP) problem. Such a problem is more general than a QP or LP problem, but less general than a convex nonlinear problem. The Simplex-based methods used in the LP/Quadratic Solver, the Large-Scale LP/QP Solver, and the XPRESS Solver Engine handle only quadratic objectives, not quadratic constraints. But QCP problems – since they are **convex** – can be solved efficiently to global optimality with Barrier methods, also called Interior Point methods.

The SOCP Barrier Solver uses a Barrier method to solve LP, QP, and QCP problems. The MOSEK Solver Engine uses an even more powerful Barrier method to solve very large scale LP, QP, and QCP problems, as well as smooth convex nonlinear problems. Both of these Solvers form a logarithmic "barrier function" of the constraints, combine this with the objective, and take a step towards a better point on each major iteration. Unlike the Simplex method, which moves from one corner point to another on the *boundary* of the feasible region, a Barrier method follows a path – called the *central path* – that lies strictly *within* the feasible region.

A Barrier method relies heavily on second derivative information, specifically the Hessian of the Lagrangian (combination of the constraints and objective) to determine its search direction on each major iteration. The ability of the Poly-morphic Spreadsheet Interpreter to efficiently compute this second derivative information is key to the performance of this method.

Second Order Cone Programming

Second order cone programming (SOCP) problems are a further generalization of LP, QP, and QCP problems. An SOCP has a linear objective and one or more linear or *second order cone* (SOC) constraints. As explained earlier, a second order cone constraint such as "A1:A5 = conic" specifies that the vector formed by the decision variables A1:A5 must lie within the second-order cone (also called the Lorentz cone) of dimension 5. Algebraically, the constraint specifies that $a_1 \geq \| a_2{:}a_5 \|_2$. SOCPs are always **convex**; the SOCP Barrier Solver and the MOSEK Solver Engine are both designed to solve SOCP problems, efficiently to global optimality.

Any convex quadratic constraint can be converted into an SOC constraint, with several steps of linear algebra. A convex quadratic objective $x^TQx + cx$ can be handled by introducing a new variable *t*, making the objective minimize *t*, adding a constraint $x^TQx + cx <= t$, and converting this constraint to SOC form. The SOCP Barrier Solver and the MOSEK Solver Engine both make these transformations automatically; in effect they solve all LP, QP, QCP and SOCP problems in the same way. Second order cone programming can be viewed as

the *natural generalization of linear programming*, and is bound to become more popular in the future.

You can also solve an SOCP with the GRG Nonlinear Solver or the Large-Scale GRG, Large-Scale SQP, or Knitro Solver engines. Although these Solvers do not recognize SOC constraints directly, Analytic Solver products will compute values and derivatives for SOC constraints, based on their algebraic form shown above. Hence, these general nonlinear Solvers handle SOC constraints like other general nonlinear constraints. Using these Solvers, you can find optimal solutions for problems containing a mix of linear, general nonlinear, and SOC constraints – bearing in mind that such problems may be non-convex.

Nonlinear Optimization

As outlined above, nonlinear programming (NLP) problems are intrinsically more difficult to solve than LP, QP, QCP or SOCP problems. They may be **convex** or **non-convex**, and since their second derivatives are not constant, an NLP Solver must compute or approximate the Hessians of the problem functions many times during the course of the optimization. Since a non-convex NLP may have multiple feasible regions and multiple locally optimal points within such regions, there is no simple or fast way to determine with certainty that the problem is infeasible, that the objective function is unbounded, or that an optimal solution is the "global optimum" across all feasible regions. But some NLP problems *are* convex, and many problems include linear or convex quadratic constraints in addition to general nonlinear constraints. Frontline's field-installable nonlinear Solver engines are each designed to take advantage of NLP problem structure in different ways, to improve performance.

If you use the GRG Nonlinear Solver – the only choice for NLPs in the standard Excel Solver and Analytic Solver Upgrade – bear in mind that it applies the *same* method to *all* problems, even those that are really LPs or QPs. If you don't select another Solver engine from the Task Pane Engine tab dropdown list box (or, in the standard Microsoft Excel Solver, if you don't check the Assume Linear Model box in the Solver Options dialog), this Solver will be used – and it may have difficulty with LP or QP problems that could have been solved easily with one of the other Solvers. Analytic Solver Comprehensive can automatically determine the type of problem, and select only the "good" or "best" Solver engine(s) for that problem.

The GRG Method

Analytic Solver includes the enhanced GRG Solver while the Excel Solver uses the Generalized Reduced Gradient method as implemented in Lasdon and Waren's GRG2 code. The GRG method can be viewed as a nonlinear extension of the Simplex method, which selects a basis, determines a search direction, and performs a line search on each major iteration – solving systems of nonlinear equations at each step to maintain feasibility. This method and specific implementation have been proven in use over many years as one of the most robust and reliable approaches to solving difficult NLP problems.

As with the Simplex method, the GRG method in the standard Excel Solver uses a "dense" problem representation, and its memory and solution time increases with the number of variables *times* the number of constraints. It is also subject to problems of numerical instability, which may be even more severe than for LP and QP problems. The GRG Solver engine uses sparse storage methods and better numerical methods for nonlinear models, such as matrix condition testing and degeneracy handling, to solve much larger NLP problems.

The SQP Method

The Large-Scale SQP Solver engine for Analytic Solver Comprehensive and Analytic Solver Optimization uses a Sequential Quadratic Programming (SQP) method to solve nonlinear optimization problems. This method forms and solves a QP subproblem, with a quadratic merit function and linearized constraints, on each major iteration. Because it includes a highly efficient QP solver, a powerful linear programming solver using "active set" methods, and sparsity-exploiting matrix factorization, updating and refactorization methods, the Large-Scale SQP Solver engine is very fast in solving all types of LP, QP and NLP problems. However, the SQP method typically follows a path of *infeasible* trial points until it finds the solution that is both feasible and optimal. Hence, if you stop the Solver before it reports an optimal solution, the GRG method is far more likely than the SQP method to return a feasible solution as its "best point so far."

Interior Point and SLQP Methods

The Knitro Solver engine for Analytic Solver Comprehensive and Analytic Solver Optimization uses a Barrier or Interior Point method, specialized for **non-convex** problems, to solve general nonlinear optimization problems. As with the SOCP Barrier and MOSEK Solvers, this method forms a logarithmic "barrier function" of the constraints, combines this with the objective, and takes a step towards a better point on each major iteration. (The actual process of taking a step and the path followed are more complex, because Knitro assumes that the problem may be non-convex.) The Knitro Solver uses the PSI Interpreter to efficiently compute second derivative information, but it also has options to work with only first derivative information.

The Knitro Solver engine also includes a new, high performance Sequential Linear-Quadratic (SLQP) method, which is an "active set" method similar to the SQP method. On highly constrained problems, notably those with equality constraints, this method typically outperforms the Interior Point method. On loosely constrained or unconstrained problems, the Interior Point method can greatly outperform SQP and GRG methods, solving problems much larger than either of these methods. Benchmark studies in the academic literature have demonstrated exceptionally good performance for the Knitro Solver, on a wide range of test problems.

The GRG, SQP and Interior Point methods are all subject to the intrinsic limitations cited above for nonlinear optimization problems: For smooth **convex** nonlinear problems, they will (subject to the limitations of finite precision computer arithmetic) find the globally optimal solution; but for **non-convex** problems, they can only guarantee a locally optimal solution. To have a reasonable chance – let alone a guarantee – that you'll find the globally optimal solution to a non-convex problem, you must use special methods for global optimization.

Global Optimization

Analytic Solver Comprehensive and its subset products include powerful tools to help you find the globally optimal solution for a smooth nonlinear **non-convex** problem. These tools include *multistart methods*, which can be used with the nonlinear GRG Solver, the Large-Scale GRG Solver, the Large-Scale SQP Solver, and the Knitro Solver; the Interval Global Solver offers powerful interval methods for global optimization in a commercial software product; and

the Evolutionary Solver, for global solutions of smooth and non-smooth problems.

The Multistart Method

The basic idea of the multistart method is to automatically run a nonlinear Solver from different starting points, reaching different locally optimal solutions, then select the best of these as the proposed globally optimal solution. Both *clustering* and *topographic search* multistart methods are included in Analytic Solver and its subset products.

The multistart method operates by generating candidate starting points for the nonlinear Solver (with randomly selected values between the bounds you specify for the variables). These points are then grouped into "clusters" – through a method called *multi-level single linkage* – that are likely to lead to the same locally optimal solution, if used as starting points for the Solver. The nonlinear Solver is then run repeatedly, once from (a representative starting point in) each cluster. The process continues with successively smaller clusters that are increasingly likely to capture each possible locally optimal solution. A Bayesian test is used to determine whether the process should continue or stop.

For many smooth nonlinear problems, the multistart method has a limited guarantee that it will "converge in probability" to a globally optimal solution. This means that as the number of runs of the nonlinear Solver increases, the probability that the globally optimal solution has been found also increases towards 100%. (To attain convergence for constrained problems, an exact penalty function is used in the process of "clustering" the starting points.) For most nonlinear problems, this method will at least yield very good solutions. As discussed below, the multistart method, like the Evolutionary Solver, is a *nondeterministic* method, which by default may yield different solutions on different runs. (To obtain the *same* solution on each run, you can set a Random Seed option for either of these solution algorithms, as discussed in the chapter "Solver Engine Option Reference" in the Frontline Solvers Reference Guide.)

As discussed below, the Evolutionary Solver has been enhanced with "filtered local search" methods that offer many of the benefits of multistart methods – making the Evolutionary Solver even more effective for global optimization problems.

The multistart method can be used on smooth nonlinear problems that also contain integer variables and/or "alldifferent" constraints. But this can take a great deal of solution time, since the multistart method is used for each subproblem generated by the Branch & Bound method for integer problems, and it can also impact the Solver's ability to find feasible integer solutions. If you have many integer variables, or alldifferent constraints, try the Evolutionary Solver as an alternative to the multistart method.

The Interval Branch & Bound Method

In contrast to the multistart methods and the Evolutionary Solver's methods, which are *nondeterministic* methods for global optimization that offer no firm guarantees of finding the globally optimal solution, the Interval Global Solver in uses a *deterministic* method: An *Interval Branch & Bound* algorithm that will find the globally optimal solution – given enough time, and subject to some limitations related to roundoff error, as discussed in the Frontline Solvers Reference Guide.

The Interval Branch & Bound algorithm processes a list of "boxes" that consist of bounded intervals for each decision variable, starting with a single box

determined by the bounds that you specify. On each iteration, it seeks lower and upper bounds for the objective and the constraints in a given box that will allow it to discard all or a portion of the box (narrowing the intervals for some of the variables), by proving that the box can contain no feasible solutions, or that it can contain no objective function values better than a known best bound on the globally optimal objective. Boxes that cannot be discarded are subdivided into smaller boxes, and the process is repeated. Eventually, the boxes that remain each enclose a locally optimal solution, and the best of these is chosen as the globally optimal solution.

Several methods are used to obtain good bounds on the values of the objective and constraints within a box or region. *Classic interval methods* rely on the ability of the PSI Interpreter to evaluate Excel functions over intervals and interval gradients. Local constraint propagation methods (also known as *hull consistency* methods) are used to narrow intervals at each stage of evaluation of the problem functions. *Second-order methods* rely on the Interpreter's ability to compute interval Hessians of Excel functions, and use a variant of the *Interval Newton* method to rapidly minimize function values within a region. Innovative *linear enclosure* methods – implemented for the first time in the Interval Global Solver – bound each problem function with a linear approximation that can be used in a Simplex method-based test for feasibility and local optimality.

The Interval Global Solver also has a unique ability to find *all real solutions* for a system of nonlinear equations – which can be listed in the Solutions Report. It can also find an "inner solution" for a system of nonlinear inequalities – a region or "box" (bounds on the variables) within which *all* points satisfy the inequalities. These capabilities are summarized in the chapter "Getting Results: Optimization."

Non-Smooth Optimization

The most difficult type of optimization problem to solve is a non-smooth problem (NSP). Such a problem may not only have multiple feasible regions and multiple locally optimal points within each region – because some of the functions are non-smooth or even discontinuous, derivative or gradient information generally cannot be used to determine the direction in which the function is increasing (or decreasing). In other words, the situation at one possible solution gives very little information about where to look for a better solution.

In all but the simplest problems, it is impractical to exhaustively enumerate all of the possible solutions and pick the best one, even on a fast computer. Hence, most methods rely on some sort of controlled random search, or sampling of possible solutions – combined with deterministic (non-random) methods for exploring the search space. The Evolutionary Solver, based on genetic algorithms, relies fairly heavily on controlled random search, whereas the OptQuest Solver Engine, based on tabu search and scatter search, relies more heavily on deterministic search methods.

A drawback of these methods is that a solution is "better" only in comparison to other, presently known solutions; both the Evolutionary and OptQuest Solvers normally *have no way to test whether a solution is optimal*. This also means that these methods must use heuristic rules to decide *when to stop*, or else stop after a length of time, or number of iterations or candidate solutions, that you specify.

Genetic and Evolutionary Algorithms

A non-smooth optimization problem can be attacked – though not often solved to optimality – using a genetic or evolutionary algorithm. (In a genetic algorithm the problem is encoded in a series of bit strings that are manipulated by the algorithm; in an "evolutionary algorithm," the decision variables and problem functions are used directly. Most commercial Solver products are based on evolutionary algorithms.)

An evolutionary algorithm for optimization is different from "classical" optimization methods in several ways. First, it relies in part on random sampling. This makes it a *nondeterministic* method, which may yield different solutions on different runs. (To obtain the *same* solution on each run, you can set a Random Seed option for the Evolutionary Solver.)

Second, where most classical optimization methods maintain a single best solution found so far, an evolutionary algorithm maintains a *population* of candidate solutions. Only one (or a few, with equivalent objectives) of these is "best," but the other members of the population are "sample points" in other regions of the search space, where a better solution may later be found. The use of a population of solutions helps the evolutionary algorithm avoid becoming "trapped" at a local optimum, when an even better optimum may be found outside the vicinity of the current solution.

Third – inspired by the role of mutation of an organism's DNA in natural evolution – an evolutionary algorithm periodically makes random changes or *mutations* in one or more members of the current population, yielding a new candidate solution (which may be better or worse than existing population members). There are many possible ways to perform a "mutation," and the Evolutionary Solver actually employs five different mutation strategies. The result of a mutation may be an infeasible solution, and the Evolutionary Solver attempts to "repair" such a solution to make it feasible; this is sometimes, but not always, successful.

Fourth – inspired by the role of sexual reproduction in the evolution of living things – an evolutionary algorithm attempts to combine elements of existing solutions in order to create a new solution, with some of the features of each "parent." The elements (e.g. decision variable values) of existing solutions are combined in a *crossover* operation, inspired by the crossover of DNA strands that occurs in reproduction of biological organisms. As with mutation, there are many possible ways to perform a "crossover" operation – some much better than others – and the Evolutionary Solver actually employs multiple variations of four different crossover strategies.

Fifth – inspired by the role of natural selection in evolution – an evolutionary algorithm performs a *selection* process in which the "most fit" members of the population survive, and the "least fit" members are eliminated. In a constrained optimization problem, the notion of "fitness" depends partly on whether a solution is feasible (i.e. whether it satisfies all of the constraints), and partly on its objective function value. The selection process is the step that guides the evolutionary algorithm towards ever-better solutions.

Hybrid Evolutionary and Other Algorithms

You might imagine that better results could be obtained by combining the strategies used by an evolutionary algorithm with the "classical" optimization methods used by the nonlinear GRG and LP/Quadratic Solver. Frontline Systems has done just that.

The Evolutionary Solver operates as described above, but it also employs classical methods in two situations: First, when the evolutionary algorithm generates a new best point, a local search is conducted to try to improve that point. This step can use a "random local search" method, a gradient-free, deterministic direct search method, a gradient-based quasi-Newton method, or a "linearized local gradient" method. Second, when the evolutionary algorithm generates an infeasible point, the Solver can use "repair methods", a quasi-Newton method, or even a specialized Simplex method (for subsets of the constraints that are linear) to transform the infeasible point into a feasible one.

The Evolutionary Solver takes advantage of the diagnostic information available from the PSI Interpreter: It automatically applies genetic algorithm methods to non-smooth variable occurrences (where classical methods cannot be used) and classical methods to smooth and linear variable occurrences. In the local search phase, it can either fix non-smooth variables, or allow them to vary. And it can automatically select the most appropriate local search method, based on linearity and smoothness of the problem functions.

The Evolutionary Solver uses a "distance filter" and a "merit filter" to determine whether to carry out a local search when the genetic algorithm methods find an improved starting point. The "distance filter" plays a role similar to "clustering" in the multistart methods described earlier; both filters contribute to the excellent performance of the Evolutionary Solver on global optimization problems.

The "Achilles' heel" of most evolutionary algorithms is their handling of constraints – they are typically unable to handle more than a few inequalities, or any equality constraints at all. In contrast, the hybrid Evolutionary Solver has been able to find good solutions to non-smooth problems with many – even hundreds – of constraints.

Tabu Search and Scatter Search

The OptQuest Solver Engine for Analytic Solver Comprehensive and Analytic Solver Optimization is based on the principles of tabu search and scatter search. These methods have strong analogies with – and actually predate – genetic algorithm methods, but they rely less heavily on random choice. They work with a population of solutions, which are modified and combined in different ways, then subjected to a selection process. Scatter search methods can sample the space of possible solutions, avoid becoming "trapped" in regions close to local optima, and adaptively diversify or intensify the search. Tabu search uses memory of past search steps to avoid repeated steps and improve future searches. Use of the OptQuest Solver is described in more depth in the **Frontline Solvers Engine User Guide**.

Integer Programming

When a Solver model includes integer constraints (for example A1:A10 = integer, A1:A10 = binary, A1:A10 = semicontinuous, or A1:A10 = alldifferent), it is called an *integer programming* problem. Integer constraints make a model **non-convex**, and finding the optimal solution to an integer programming problem is equivalent to solving a global optimization problem. Such problems may require *far* more computing time than the same problem without the integer constraints.

The standard Microsoft Excel Solver uses a basic Branch & Bound method, in conjunction with the linear LP/Quadratic or nonlinear GRG Solver, to find

optimal solutions to problems involving general integer or binary integer variables. Analytic Solver Upgrade and Analytic Solver Basic use a much more sophisticated Branch & Bound method that is extended to handle alldifferent constraints, and that often greatly speeds up the solution process for problems with integer variables. In Analytic Solver Comprehensive and Analytic Solver Optimization, the LP/Quadratic Solver uses improved pseudocost-based branch and variable selection, reduced cost fixing, primal heuristics, cut generation, Dual Simplex and preprocessing and probing methods to greatly speed up the solution of *integer linear* programming problems.

The Evolutionary Solver handles integer constraints, in the same form as the other Solver engines (including alldifferent constraints), but it does not make use of the Branch & Bound method; instead, it generates many trial points and uses "constraint repair" methods to satisfy the integer constraints. (The constraint repair methods include classical methods, genetic algorithm methods, and integer heuristics from the local search literature.) The Evolutionary Solver can often find good solutions to problems with integer constraints, but where the Branch & Bound algorithm can *guarantee* that a solution is optimal or is within a given percentage of the optimal solution, the Evolutionary Solver cannot offer such guarantees.

The Branch & Bound Method

The Branch & Bound method begins by finding the optimal solution to the "relaxation" of the integer problem, ignoring the integer constraints. If it happens that in this solution, the decision variables with integer constraints already have integer values, then no further work is required. If one or more integer variables have non-integral solutions, the Branch & Bound method chooses one such variable and "branches," creating two new subproblems where the value of that variable is more tightly constrained. For example, if integer variable A1 has the value 3.45 at the solution, then one subproblem will have the additional constraint A1 <= 3 and the other subproblem will add the constraint A1 >= 4. These subproblems are solved and the process is repeated, "branching" as needed on each of the integer decision variables, until a solution is found where all of the integer variables have integer values (to within a small tolerance).

Hence, the Branch & Bound method may solve many subproblems, *each one* a "regular" Solver problem. The number of subproblems may grow *exponentially*. The "bounding" part of the Branch & Bound method is designed to eliminate sets of subproblems that do not need to be explored because the resulting solutions cannot be better than the solutions already obtained.

Cut Generation

The LP/Quadratic Solver, the Large-Scale LP/QP Solver, Large-Scale SQP Solver, MOSEK Solver, Gurobi Solver, and XPRESS Solver all make use of "cut generation" methods to improve performance on integer linear programming problems. Cut generation derives from so-called "cutting plane" methods that were among the earliest methods applied to integer programming problems, but they combine the advantages of these methods with the Branch & Bound method to yield a highly effective approach, often referred to as a "Branch & Cut" algorithm.

A *cut* is an automatically generated linear constraint for the problem, in addition to the constraints that you specify. This constraint is constructed so that it "cuts off" some portion of the feasible region of an LP subproblem, without

eliminating any possible integer solutions. Many cuts may be added to a given LP subproblem, and there are many different methods for generating cuts. For example, *Gomory cuts* are generated by examining the reduced costs at an LP solution, while *knapsack cuts*, also known as *lifted cover inequalities*, are generated from constraints involving subsets of the 0-1 integer variables. Cuts add to the work that the LP solver must perform on each subproblem (and hence they do not always improve solution time), but on many problems, cut generation enables the overall Branch & Cut algorithm to more quickly discover integer solutions, and eliminate branches that cannot lead to better solutions than the best one already known.

The Alldifferent Constraint

In Analytic Solver Comprehensive and its subset products, a constraint such as A1:A5 = alldifferent specifies that the variables A1:A5 must be integers in the range 1 to 5, with each variable different from all the others at the solution. Hence, A1:A5 will contain a *permutation* of the integers from 1 to 5, such as 1,2,3,4,5 or 1,3,5,2,4.

To solve problems involving alldifferent constraints, Analytic Solver employs an extended Branch & Bound method that handles these constraints as a native type. Whenever variables in an "alldifferent group" have non-integral solution values, or integral values that are not all different, the Branch & Bound method chooses one such variable and "branches," creating two new subproblems where the value of that variable is more tightly constrained.

The nonlinear GRG Solver, Large-Scale GRG Solver, Large-Scale SQP Solver, and Knitro Solver engines use this extended Branch & Bound method to solve problems with integer and alldifferent constraints.

The Large-Scale LP/QP Solver, MOSEK Solver, Gurobi Solver, and XPRESS Solver use their own Branch & Cut methods. They transform alldifferent constraints into equivalent sets of binary integer variables and additional linear constraints, then apply their preprocessing, probing and cut generation methods to these variables and constraints.

The Evolutionary Solver uses methods from the genetic algorithm literature to handle alldifferent constraints as permutations, including several mutation operators that preserve the "alldifferent property," and several crossover operators that generate a "child" permutation from "parents" that are also permutations.

Since Solver engines use quite different methods to handle the alldifferent constraint, you'll want to try a variety of Solver engines to see which one performs best on your model. This is especially true if your model uses smooth nonlinear or – even better – linear functions aside from the alldifferent constraint.

Looking Ahead to Models with Uncertainty

If you've read through this chapter, **congratulations** – you've learned a *great deal* about the nature of optimization problems, and how they are solved! But as we said in "Elements of Solver Models" at this chapter's beginning, we've assumed that all parameters of the model are *certain*. The chapter "Mastering Stochastic Optimization Concepts" will cover situations where the parameter values are *uncertain* – and the problems are called *stochastic optimization*

problems. In these problems, it's ***more important than ever*** to know how the objective and constraints depend on the decision variables.

We'll see that **stochastic linear programming** problems can be transformed and solved to optimality far more easily and quickly than **stochastic nonlinear, non-convex** problems. We'll also see that certain ways of summarizing the **uncertainty** involved in the model, in chance constraints and expected-value and risk-measure objectives, allow us to form a **convex** optimization model, that can be solved quickly and 'scaled up' to large size. We'll see that even one **decision-dependent uncertainty** usually makes a model non-convex and non-smooth, and far more difficult to solve – but we can still find *good* solutions for such a model, using high-speed simulation optimization in Analytic Solver.

We explained in this chapter that it's usually a mistake to apply a *general-purpose* Solver to a problem that has a simpler structure – for example, applying the GRG Solver or Evolutionary Solver to a linear programming problem: Solution times are much longer than necessary, solutions are less reliable, and the problem typically cannot be scaled up to large size and still solved by these methods.

In a similar way, we'll see that it's usually a mistake to apply a general-purpose *stochastic optimization method* to a problem that has a simpler structure – for example, applying **simulation optimization** (which requires a general-purpose Solver) to a stochastic linear programming problem. Again solution times will be *much* longer than necessary, solutions are *much* less reliable, and the problem typically cannot be scaled up to large size and still solved by these methods.

Mastering Simulation and Risk Analysis Concepts

Introduction

To build a Monte Carlo simulation model in Excel, you begin with a conventional spreadsheet model, designed for 'what-if' analysis. Next, you identify the *inputs* to your model that are uncertain, and use PSI Distribution functions to describe the uncertainty. Then, you identify the *outputs* of special interest (such as Net Profit), and use PSI Statistics functions to examine or summarize how they behave in light of the uncertainty.

This User Guide assumes you have some experience building conventional spreadsheet models, and you almost certainly have experience using such models to ask 'what if' questions, by manually changing input values on the spreadsheet. **The key step in risk analysis is to think in terms, not of just one 'what if' scenario at a time, but of a *range of scenarios, considered at once*.** Think of your spreadsheet cells as representing not just single numbers, that you change once in a while to explore alternatives, but *arrays* of numbers that cover the range of possibilities.

Although you can usually visualize the range of values for one *input* value at a time, it is very difficult to foresee – without computer assistance – the range of outcomes for an *output* value that depends on *several* interacting inputs, each one subject to uncertainty. But Analytic Solver Comprehensive, Analytic Solver Simulation and Analytic Solver Basic (in both the Desktop and Cloud apps) *automatically* compute the full range of outcomes for every cell in your spreadsheet model, and enables you to quickly see statistics such as the mean, standard deviation, or 10^{th} and 90^{th} percentiles of the range of outcomes.

What Happens During Monte Carlo Simulation

You'll find it easier to understand simulation results if you have a good grasp of the Monte Carlo simulation process. At its heart, this process is very simple. It consists of the following steps:

1. Generate a **random sample** for the **uncertain variables** in your model. If you specify (say) 1,000 Monte Carlo trials per simulation, then 1,000 randomly chosen values will be generated for *each* uncertain variable.
2. For each of 1,000 Monte Carlo trials, **recalculate** your model, with the right sample values in each uncertain variable cell. When Excel is used to recalculate, the PSI Distribution function in each uncertain variable cell returns the correct sample value for that trial. When the PSI Interpreter is used (as is always the case in Analytic Solver Cloud), this is done internally (much faster) by Analytic Solver.
3. On each Monte Carlo trial, monitor and save the calculated value of each **uncertain function** in your model. (Recall that any formula cell containing a call to PsiOutput(), or referenced in the first argument of PsiOutput() or a

PSI Statistics function, is monitored as an uncertain function cell.) For 1,000 trials, there will be 1,000 saved values for *each* uncertain function.

When the simulation process is complete, Analytic Solver Simulation uses the 1,000 saved values of each uncertain function to calculate statistics and percentiles, draw frequency distributions, scatter plots and other charts, and compute values for each PSI Statistic function call in your model.

Random Number Generation and Sampling

On each Monte Carlo trial, *sample values* are drawn from the probability distributions represented by the PSI Distribution functions in your model. Sample values are computed by first *drawing* a "random number" between 0 and 1, then *transforming* this uniform random sample value into a sample value that:

- Constrains the samples drawn to obtain better coverage of the sample space, where each PSI Distribution function is a 'dimension' of that space
- Ensures that the frequency distribution of samples drawn properly reflects the shape and parameters of the PSI Distribution function
- Ensures that the samples drawn for multiple PSI Distribution functions properly reflect the correlation of distributions with each other

Random Number Generator

Analytic Solver Simulation includes an advanced set of random number generation capabilities. In common applications, any good random number generator is sufficient – but for challenging applications (for example in financial engineering) that involve many uncertain variables and many thousands of trials, the advanced features of Analytic Solver Simulation can make a real difference.

Computer-generated numbers are never truly "random," since they are always computed by an algorithm – they are called *pseudorandom* numbers. A random number generator is designed to quickly generate sequences of numbers that are as close to statistically independent as possible. Eventually, an algorithm will generate the same number seen sometime earlier in the sequence, and at this point the sequence will begin to repeat. The *period* of the random number generator is the number of values it can generate before repeating.

A long period is desirable, but there is a tradeoff between the length of the period and the degree of statistical independence achieved within the period. Hence Analytic Solver Simulation offers a choice of four random number generators:

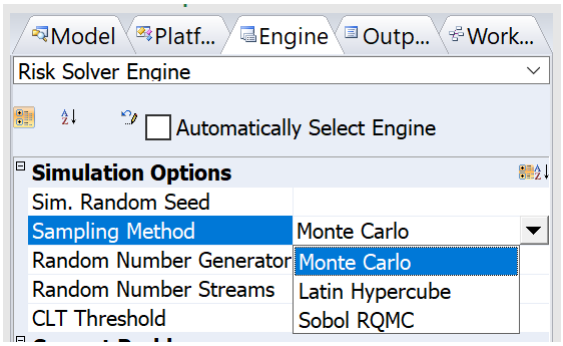
- **Park-Miller** "Minimal" Generator with Bayes-Durham shuffle and safeguards. This generator has a period of 2^{31}-2. Its properties are good, but the following choices are usually better.
- Combined Multiple Recursive Generator (**CMRG**) of L'Ecuyer. This generator has a period of 2^{191}, and excellent statistical independence of samples within the period.
- Well Equidistributed Long-period Linear (**WELL1024**) generator of Panneton, L'Ecuyer and Matsumoto. This very new generator combines a long period of 2^{1024} with very good statistical independence.

- **Mersenne Twister** generator of Matsumoto and Nishimura. This generator has the longest period of 2^{19937}-1, but the samples are not as "equidistributed" as for the WELL1024 and CMRG generators.

Random Number Seeds

As explained in the chapter "Getting Results: Simulation," the **seed**, or initial value, of the random number generator determines whether your results are *exactly reproducible* when you re-run a simulation, or whether your results are *similar but not identical* because a different random sample was drawn.

You can set a seed for the entire simulation run using the **Sim. Random Seed** option – the first option on the Task Pane Engine tab when you select **Risk Solver Engine** (the simulation engine) from the dropdown list. Any positive integer sets a specific seed; 0 means the seed will be *different* on every run.



You can also set a seed for any specific uncertain variable, using the Seed option in the Uncertain Variable dialog, or by supplying a **PsiSeed()** property function as an argument to the PSI Distribution function call. This means the uncertain variable will have its own independent stream of random numbers starting from the given seed, whether or not you've set a seed for the whole simulation run.

Sampling Method

In standard Monte Carlo sampling, numbers generated by the chosen random number generator are used directly to obtain sample values for the uncertain variables (PSI Distribution functions) in the model. With this method, the variance or *estimation error* in computed samples for uncertain functions is inversely proportional to the square root of the number of trials; hence to cut the error in half, four times as many trials are required.

Analytic Solver Simulation provides two other sampling methods than can significantly improve the 'coverage' of the sample space, and thus reduce the variance in computed samples for output functions. This means that you can achieve a given level of accuracy (low variance or error) with fewer trials. You choose this via the **Sampling Method** option on the **Engine tab**, shown above.

Latin Hypercube Sampling. Latin Hypercube sampling begins with a stratified sample in each dimension (one for each uncertain variable), which constrains the random numbers drawn to lie in a set of subintervals from 0 to 1. Then these one-dimensional samples are combined and randomly permuted so that they 'cover' a unit hypercube in a stratified manner. This often reduces the variance of uncertain functions.

Sobol numbers (Randomized QMC). Sobol numbers are an example of so-called "Quasi Monte Carlo" or "low-discrepancy numbers," which are generated with a goal of coverage of the sample space rather than "randomness"

and statistical independence. Analytic Solver adds a "random shift" to Sobol numbers, which improves their statistical independence. Sobol numbers are frequently used in quantitative finance applications, where they are often effective at reducing variance.

Random Number Streams

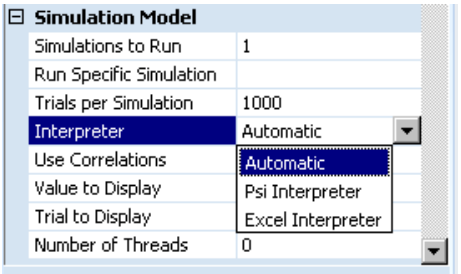
Most Monte Carlo simulation tools generate a *single* sequence of random numbers, taking values consecutively from this sequence to obtain samples for each of the distributions in a model. This introduces a subtle dependence between the samples for all distributions in one trial. Analytic Solver Comprehensive and Analytic Solver Simulation allow you to specify that an independent random number sequence (stream) should be used for each distribution in the model – using the **Random Number Streams** option on the **Engine tab**, as shown on the previous page. This capability works for Monte Carlo sampling and Latin Hypercube sampling; it does not apply to Sobol numbers.

In many applications, the difference between a single stream and multiple strams is very small – but in some cases, found in financial engineering and other demanding applications, better results are obtained if independent random number sequences (streams) are used.

The PSI Interpreter and Simulation

Analytic Solver Desktop can use either Excel, or its own *Polymorphic Spreadsheet Interpreter* (PSI Technology) to perform Monte Carlo simulation trials at high speed – often 100 times faster or more than performing the trials by allowing Microsoft Excel to recalculate the spreadsheet. (Analytic Solver Cloud *always* uses PSI Technology.) Normally, you'll want to use the PSI Interpreter for simulation trials, since it is designed to compute the same values as Excel does, but much faster than the Excel Interpreter.

However, there are a few features of Excel formulas and functions that the PSI Interpreter does not handle; if you use these features in your model, you'll see an error message when you try to run a simulation. If your model requires the use of Excel features that are not supported by the PSI Interpreter, you may have to use the Excel Interpreter instead. To do this, change the Task Pane Platform tab Simulation Model group **Interpreter** option, as shown below.



Note: Functions not supported by the PSI Interpreter are: Call(), Cell(), CubeX(), EuroConvert(), GetPivotData(), HyperLink(), Info(), RegisterID(), and SqlRequest().

More About the PSI Interpreter

So, how does the PSI Interpreter work, and how can it be so much faster than Excel alone for simulation? To answer this, we must look at how Excel itself computes values for your formulas.

Microsoft Excel is an *interpreter* for spreadsheet formulas. When you enter a formula such as =A1+A2*(A3-4) in cell B1, Excel first scans and *parses* the formula, storing the results in a coded internal form. It also maintains storage for A1, A2, A3 and thousands of other cells. When you change a number and recalculate, Excel refers to the coded internal form, looks up the values of A1, A2 and A3 and fetches the constant 4, performs the arithmetic, and saves the result in storage reserved for B1. *Only a small part of the time is spent on the actual arithmetic* – most of the time goes into processing the encoded formula, and looking up and saving cell values.

PSI stands for ***Polymorphic Spreadsheet Interpreter***. PSI is also an *interpreter* for spreadsheet formulas, that accepts the same formula syntax and built-in functions as Microsoft Excel. But where Excel evaluates formulas only for one datatype – single numbers, PSI can evaluate formulas for many different datatypes. (The word "polymorphic" comes from object-oriented programming, where it has essentially the same meaning.)

One of the special PSI datatypes is Monte Carlo trials, where each number is replaced by a vector of 1,000 or more trial values. The heart of PSI speed comes from the fact that it processes the encoded formula *once*, fetches 1,000 data values *at once*, and performs the arithmetic for all 1,000 values *at once*. Hence, the "overhead" of the interpreter is incurred *once* rather than 1,000 times; *most of the time is spent doing the actual arithmetic*. PSI is so fast because it is *specialized* for simulation (and optimization).

Uncertain Functions, Statistics, and Risk Measures

Once a Monte Carlo simulation is complete, what statistics should you use to evaluate the outputs of special interest in your model? The answer depends on your application, but some general guidelines can be given.

Descriptive statistics are usually classified into measures of central tendency, and measures of variation or dispersion. You should look at both kinds of measures, and at some kind of *quantile* measure, to assess almost any output in your model.

Measures of Central Tendency

Analytic Solver provides several measures of central tendency:

- **PsiMean**, the average of all the values
- **PsiPercentile** for the median or 50th percentile
- **PsiMode**, the most frequently occurring single value

Measures of Variation

Analytic Solver provides several standard measures of variation:

- **PsiVariance**, which describes the *spread* of the distribution of values
- **PsiStdDev** for standard deviation, the square root of variance

- **PsiSkewness**, which describes the *asymmetry* of the distribution of values
- **PsiKurtosis**, which describes the *peakedness* of the distribution of values
- **PsiMin**, **PsiMax**, and **PsiRange** for the minimum and maximum values, and the difference between them

Risk Measures

Analytic Solver also provides several risk measure functions that are most often used in quantitative finance applications, but may be used in any model.

- **PsiAbsDev** for 'MAD', which measures *absolute* deviations from the mean
- **PsiSemiVar** for semivariance or lower partial moment, which measures and weights *negative* deviations from the mean
- **PsiSemiDev** for semideviation, the square root of semivariance (*q*th root for the lower partial moment)

PsiSemiVar and PsiSemiDev are useful in situations where 'upward' variation – for example, higher stock prices or increased profits – is desirable, but 'downward' variation – lower prices or losses – is undesirable.

Quantile Measures

To get a complete grasp of the range of outcomes, it's essential to look at *quantile* measures, such as percentiles and Value at Risk, in addition to measures of central tendency and variation. Quantile measures allow you to answer questions such as 'How much money might we lose, with 5% or 10% probability?" or "What is the probability that we'll make at least $100,000?" based on your simulation model. Analytic Solver provides:

- **PsiPercentile**, which provides percentile values from 1% to 99%
- **PsiTarget**, which returns the proportion of values less than or equal to a target value
- **PsiBVaR**, which measures standard ('Basel') Value at Risk
- **PsiCVaR**, which measures Conditional Value at Risk

Confidence Intervals

Every Monte Carlo simulation uses a *sample* of the possible values of your uncertain variables; hence any statistic resulting from the simulation involves some degree of sampling error. For the mean and standard deviation of an output value, Analytic Solver Simulation provides functions that help you assess this error, and estimate the range or interval in which you can be *confident* that the true mean or standard deviation lies, at a confidence level that you specify:

- **PsiMeanCI**, which returns a confidence interval for the mean
- **PsiStdDevCI**, which returns a confidence interval for the standard deviation
- **PsiCITrials**, which returns the number of simulation trials needed to obtain a confidence interval of a given size, at a given confidence level

Uncertain Variables and Probability Distributions

For experienced spreadsheet modelers, the most challenging task in creating a Monte Carlo simulation model is usually not identifying the key inputs and outputs, but selecting an appropriate probability distribution and parameters to model the uncertainty of each input variable.

Analytic Solver provides over 40 analytic probability distributions – which one should you use? Again the answer depends on your application, but some general guidelines can be given.

If a **Certified Distribution** (see below under "Probability Management Concepts") is available for an uncertain variable – for example, your company's estimate of the range and probabilities for prices of certain chemical feedstocks, or a service provider's estimate of the range and probabilities for stock or bond prices – you can simply use the Certified Distribution.

Discrete Vs. Continuous Distributions

If you must choose or create your own distribution, the first step is to determine whether to use a **discrete** or **continuous** form. If there are a small number of possible values for the uncertain variable, you may be able to use a discrete analytic distribution, or construct a discrete custom distribution. If the underlying physical process involves discrete, countable entities – such as the number of customers arriving at a service window – you can use a discrete distribution. If the possible values are highly divisible – such as most prices, volumes, interest rates, exchange rates, weights, distances, etc. – you will likely use a continuous distribution. In some cases, you may use a continuous distribution to *approximate* a discrete distribution.

Bounded Vs. Unbounded Distributions

Another characteristic that distinguishes input distributions is the range of sample values they can generate. Some distributions are intrinsically **bounded** – samples are guaranteed to lie between a known minimum and maximum value. Examples are the Uniform, Triangular, Beta, and Binomial distributions. Other analytic distributions are **unbounded** – sample values may cluster around the distribution's mean, but may sometimes have extreme negative or positive values. Examples are the Normal, Logistic, and Extreme Value distributions. Still other distributions are **partially bounded**, with a known minimum such as zero, but no maximum value. Examples are the Exponential, Poisson, and Weibull distributions.

At times, you may find that the most appropriate distribution (say the Normal) is unbounded, but you know that the realistic values of the physical process are bounded, or your model is designed to handle values only up to some realistic limit. You can impose bounds on any distribution using Analytic Solver Simulation's Uncertain Variable dialog. For information about "cutoff bounds" and "censor bounds" (both may be used), consult the Frontline Solvers Reference Guide.

Analytic Vs. Custom Distributions

A third characteristic of input distributions is whether they are analytic (also called parametric) or custom (sometimes called non-parametric) distributions. An **analytic** distribution has a form derived from certain theoretical assumptions

about the problem. For example, a Poisson distribution is derived from an assumption that events are *independent* and occur at a known *average rate*, and an Exponential distribution is derived from an assumption of a *constant rate* of decay in some process. A **custom** distribution has a form dictated by either past data or expert opinion about the range and frequency of sample values. Analytic Solver offers five general-purpose functions – PsiCumul, PsiDiscrete, PsiDisUniform, PsiGeneral and PsiHistogram – to help you model custom distributions. Generally speaking, you should choose an analytic distribution if – and *only* if – the theoretical assumptions truly apply in your situation.

Creating your Own Distributions When Past Data is Available

If you have, or you can collect **data on the past performance** of the uncertain variable – and if you believe that 'past performance' is likely to be representative of future performance – you have three options:

- If you can **fit the data** (past observations) to a specific type of analytic distribution and its parameters, and if there is reason to believe that the underlying process that the uncertain variable is measuring is *consistent* with the *assumptions* from which the analytic distribution is derived, you can use this distribution (for example PsiNormal, PsiWeibull, etc.) for the variable. See "Using the Fit Feature" section below. *Note: Data used in fitting a distribution should be independent.*
- If you have a reasonably **large number** of observations of past performance of the variable, compared to the number of simulation trials you want to run, you can use the *past data itself* for simulation trials, in the form of a SIP (Stochastic Information Packet) or a DIST (Distribution String), and use the PsiSip() or PsiSlurp() distribution function for the uncertain variable. See "Probability Management Concepts" and, for DISTs, "Stochastic Libraries: SIPs and SLURPs" below.
- If – as is often the case – you have a relatively **small number** of observations of past performance compared to the number of trials you want to run, you may be better off *resampling* the past performance data. To do this, store the past data in a cell range or SIP, and use the PsiDisUniform() function (single values) or the PsiResample() function (multiple values). The difference is that, instead of using all of the past observations (one per simulation trial), you *randomly sample* the past observations on each trial.

You can use the Analytic Solver GUI to find the best-fitting analytic distribution. Both discrete and continuous distributions can be fitted to data; 29 common distributions (out of the 40+ available) are used for fitting. You can also call the Distribution object Fit and AutoFit methods in your VBA code, as described in the chapter "VBA Object Model Reference" within the Frontline Solvers Reference Guide.

When Past Data is Not Available

If you *don't* have, and you cannot easily collect data on the past performance of the uncertain variable – or if past performance is not likely to be representative of future performance – you must tackle the problem in a different way:

- Consult the **literature for your industry**, if available, to find examples of applications like yours where simulation models were built. Find out – by

contacting the authors if necessary – what kinds of distributions were used for the uncertain variables, and the rationale for choosing them.

- If you cannot find reports on industry-specific applications like yours, consult the **publications of professional societies** like INFORMS, where simulation applications are reported. One rich source is the past proceedings of the Winter Simulation Conference (www.wintersim.org).
- In the chapter **PSI Function Reference**, read the descriptions of the different PSI Distribution functions, which include brief comments on the types of applications where each distribution has been used in the past. See the books listed at the beginning of that chapter for further information.

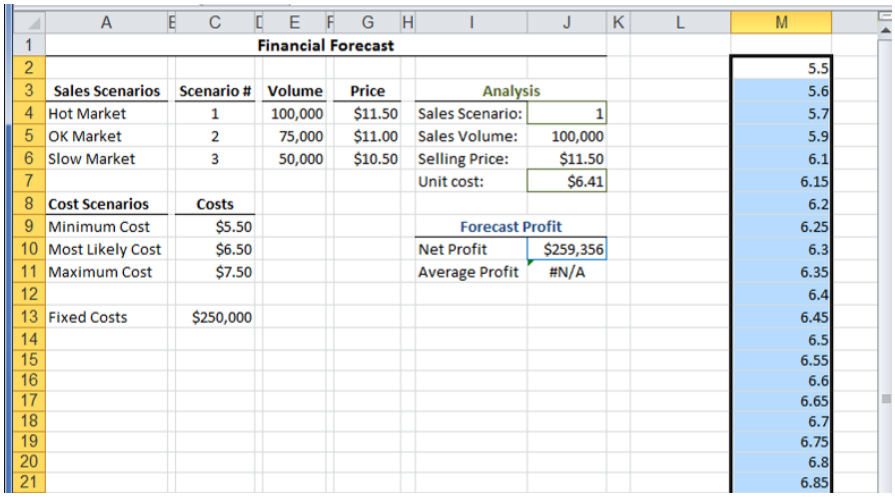
You are well-advised to *keep it simple!* Many physical, social and biological phenomena are well described by the Normal distribution, or – *if* the possible values are *equally likely* to occur, as in a coin flip or single die – the Uniform distribution. Bear in mind that when any set of distributions are summed, the result (quickly) tends towards the Normal distribution.

Applications that involve *queuing* – customers arriving or departing, parts awaiting assembly, etc. – have been well studied, so you can often find appropriate distributions in the literature. Applications that use the Project Evaluation and Review Technique (PERT) can often use the PsiPert() function to model uncertainty.

Using the Fit feature

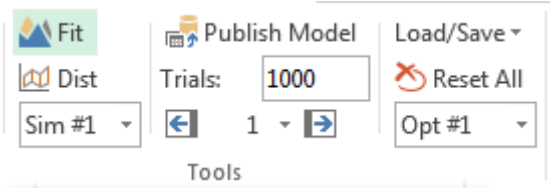
To fit a series of data using the Fit tool in Analytic Solver follow the following steps:

1. Select the range of data you want to fit. In this example, we've selected data in Column M.

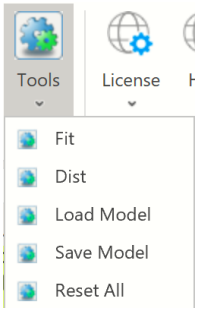


	A	C	E	G	I	J	M
1	Financial Forecast						
2							5.5
3	Sales Scenarios	Scenario #	Volume	Price	Analysis		5.6
4	Hot Market	1	100,000	$11.50	Sales Scenario:	1	5.7
5	OK Market	2	75,000	$11.00	Sales Volume:	100,000	5.9
6	Slow Market	3	50,000	$10.50	Selling Price:	$11.50	6.1
7					Unit cost:	$6.41	6.15
8	Cost Scenarios	Costs					6.2
9	Minimum Cost	$5.50			Forecast Profit		6.25
10	Most Likely Cost	$6.50			Net Profit	$259,356	6.3
11	Maximum Cost	$7.50			Average Profit	#N/A	6.35
12							6.4
13	Fixed Costs	$250,000					6.45
14							6.5
15							6.55
16							6.6
17							6.65
18							6.7
19							6.75
20							6.8
21							6.85

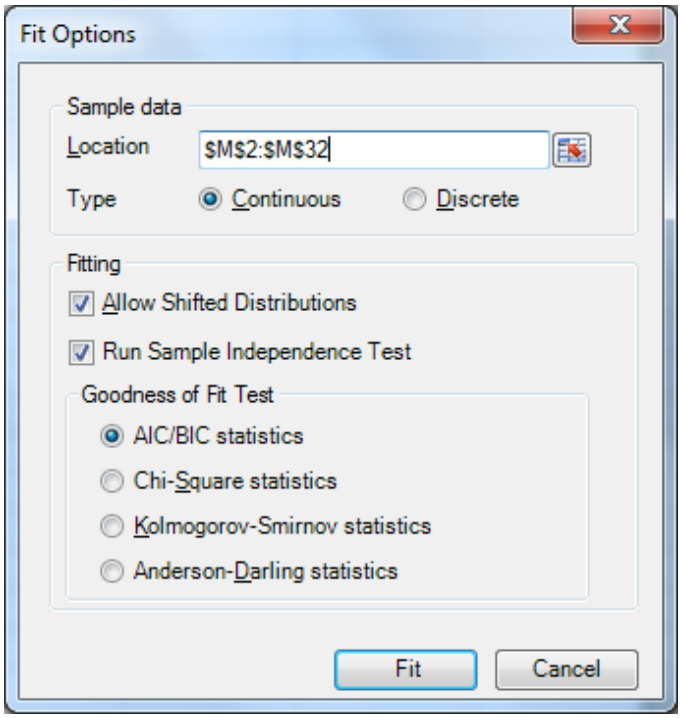
2. Select the "Fit" icon on the Ribbon in Analytic Solver Desktop,



In Analytic Solver Cloud, select Fit on the Tools ribbon.



3. Make any changes to the default settings on the Fit Options dialog.



For the **Type**, select **Continuous** if the uncertain variable's values are highly divisible – such as most prices, volumes, interest rates, exchange rates, weights, and distances – or **Discrete** if the underlying physical process involves discrete, countable entities.

The checkbox **Allow Shifted Distributions** allows Analytic Solver to shift the center of analytic distribution (equivalent to using the PsiShift() property function) to better fit the sample data; sometimes this is not desirable, so the box may be unchecked.

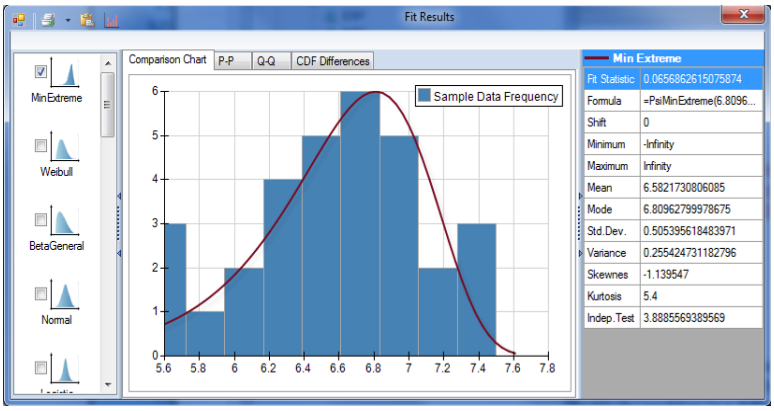
When fitting a sample to a distribution, it is important that the trial values are not in any way correlated with each other. In other words it is important that each trial is independent. If the checkbox **Run Sample Independence Test** is checked, the Psi Interpreter will run an independence test and will report an error if the trial values are found to be dependent.

Note: This option is not included in Analytic Solver Cloud. In the Cloud app, this feature is always on.

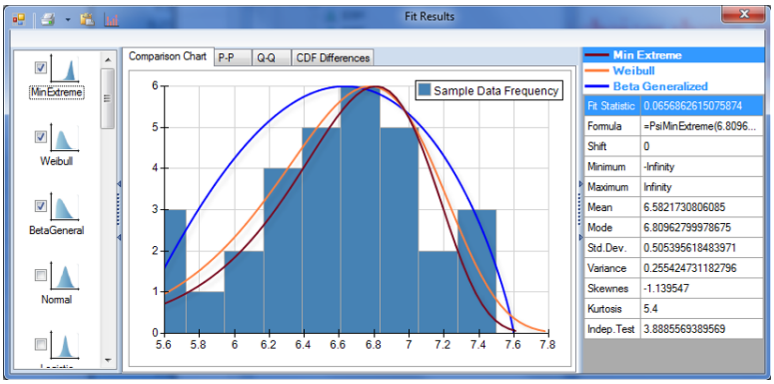
For Continuous data, you can choose to rank the fitted distributions by **AIC/BIC**, **Chi Square**, **Kolmogorov-Smirnoff**, or **Anderson-Darling** statistics. For Discrete data, only the Chi Square statistic is meaningful (and may be selected). For more information on these options, see the Analytic Solver Reference Guide.

Analytic Solver computes and displays a ranked list of candidate fitted distributions, as shown below. Initially, the distribution with the best fit statistic (selected in the above dialog) is shown in a chart that overlays the sample data.

4. Review and accept or modify the results



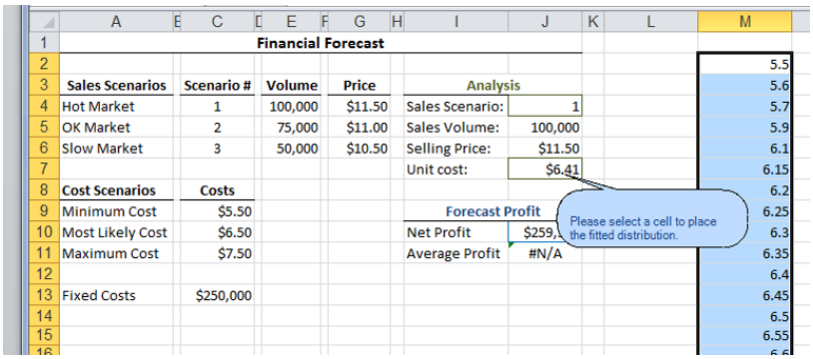
On the left of the dialog is a list of fit choices shown in order of decreasing Goodness of Fit based on the test you chose. You can select multiple choices to see how they compare and choose the one you are most happy with. See the example shown on the next page.



You can also click on the P-P, Q-Q, CDF Differences tabs to get additional perspective on which distribution best fits.

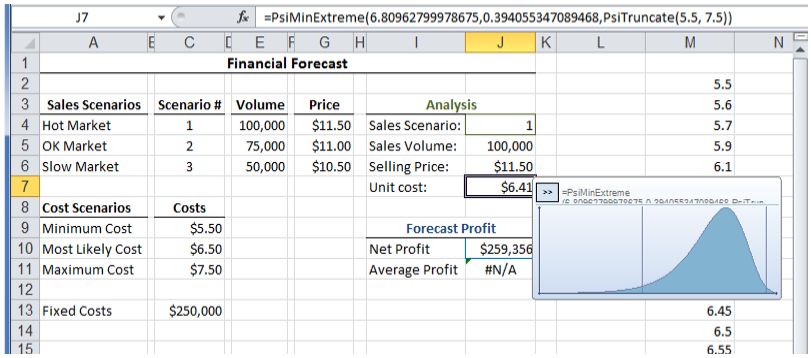
Tip: Once you have accepted the distribution you can open it back up and modify the lower and upper bounds, shift, etc.

5. In Desktop Analytic Solver, place the resulting distribution by clicking "X" at the top right of the menu, clicking on "Yes" in the resulting dialog to accept, and choosing where you want to place it in Excel.



In Analytic Solver Cloud, you'll be asked for the cell address. Simply type the cell address and then click OK.

You can see the new distribution where you placed it by clicking the cell. It will show up in the formula bar and if you leave the mouse over that cell a pop-up will show your distribution.



More Hints and Warnings

Using a Triangular Distribution

If you have only estimates of the minimum, maximum, and most likely values of an uncertain variable – and no other past data or literature references – you can create a **PsiTriangular** distribution from these three numbers. This is *unlikely* to be a highly accurate representation of the uncertainty, but it will allow you to get started, and it is *far* better than a single average value. If your 'minimum' and 'maximum' values are really low- and high-percentile *estimates* rather than the absolute lowest and highest values that can occur, consider using the **PsiTriangGen** distribution instead.

Define Each Uncertain Variable Only Once

Often, you'll need to use the same uncertain variable in several different formulas in your model. A very common error is to enter the same distribution function, with the same parameters (say PsiNormal(100, 10)), *several times* in a model – in a belief that these instances will yield the same results on each trial. This is *incorrect* – by doing this, you've actually defined *several independent* uncertain variables that may well sample *different values* on each trial. You should instead enter =PsiNormal(100, 10) in a cell such as A1, and use A1 in each cell formula where the variable is needed.

Compute Statistics Only on Final Outputs

Another common error is to use formulas in your model to compute a statistic across two or more uncertain variables, and then *use this statistic* in further calculations that are part of the same simulation model.

For example, suppose you have two uncertain variables, =PsiUniform(0,10) in cell A1 and =PsiUniform(0,20) in B1. You want to know the mean or average value of these two variables, across the trials of the simulation. The *wrong* way to do this is to put = (A1+B1)/2 or =AVERAGE(A1,B1) in cell C1. This takes the average of A1 and B1 *on each trial* – the result will be a distribution that tends to the Normal, with a different (larger) mean than you probably intended. The right way to do this is to put =PsiDisUniform(A1,B1) in cell C1. Now the distribution of cell C1 is "flat:" On each trial only one of A1 or B1 is selected.

David Vose, principal of Vose Consulting, offers his ***cardinal rule of risk analysis modeling***: "Every trial of a risk analysis model must be a scenario that could actually occur." To ensure that this is true, you may need to specify *correlations* between your uncertain variables, as described in the next section.

Dependence and Correlation

Unless you specify otherwise, Monte Carlo simulation assumes that each of your uncertain variables is *independent* of all the other uncertain variables. When two variables are independent, the value of one variable on a given trial conveys no information about the value of the other variable. When two variables are *dependent*, there is a statistical relationship between them: On average, the value of one variable on a given trial *does* convey information about the value of the other variable on that trial.

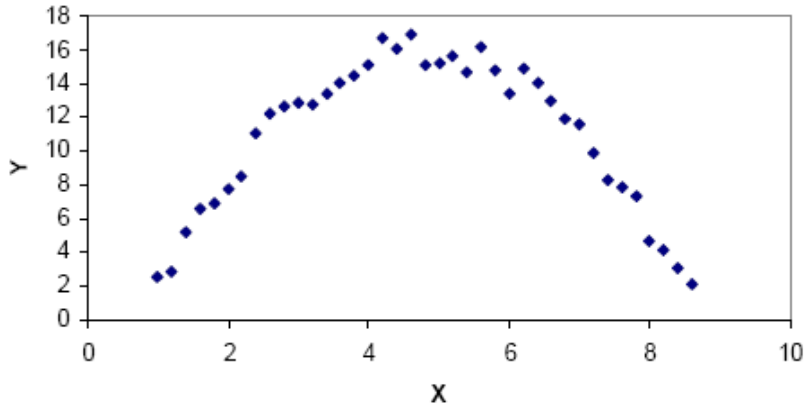
Measuring Observed Correlation

Correlation is a statistical measure of the degree to which one variable is related to another. When we observe that two variables are correlated, it may be that one variable is dependent on the other, or that both variables are dependent on a third variable, *or* that the correlation appeared by chance and there is no real dependence of one variable on the other.

The most common parametric measure of correlation is the **Pearson product moment correlation coefficient**. You can use the **PsiCorrelation** function to compute this correlation coefficient, across the trials of a simulation, for any pair of uncertain functions or variables in your model. The value of a product moment correlation coefficient can range from -1 to +1.

A correlation coefficient captures a simple *linear* relationship between two variables; it cannot capture all of the ways one variable may depend on another. A low or zero correlation coefficient between two uncertain variables or functions does *not* necessarily mean that the variables or functions are *independent* – the two variables or functions might have a strong relationship, but one that cannot be captured by a single correlation coefficient.

The figure below is a scatter plot of two variables X and Y. There is an obvious relationship between these two variables – when X is 1, Y is about 2, when X is 5, Y is about 15, when X is 9, Y is about 2, and so on – yet the Pearson product moment correlation coefficient between X and Y is zero.



More complex relationships among variables can be expressed in several ways including *newly supported copulas* or a very general way using SLURPs (Stochastic Library Units, Relationships Preserved). For more information on copulas, see below. For more information SLURPs, see below under "Probability Management Concepts."

Inducing Correlation Among Uncertain Variables

If you can compute a value for A1 with a formula based on an uncertain variable B1, then certainly A1 is dependent on B1. But in many modeling situations, both A1 and B1 are *uncertain* variables, you have no way to directly compute one from the other, yet A1 may *statistically depend* on B1. For example, mortgage interest rates depend on bond market interest rates (since mortgages are pooled and sold as securities in the bond market), and both rates depend on inflation expectations, but it is quite difficult to specify a formula that relates these variables.

In cases like these, you'll need to specify the statistical dependence between uncertain variables using PSI Property functions, supplied as arguments to PSI Distribution functions. This is called *inducing correlation* between uncertain variables, that would otherwise be considered independent. For example, you can write =PsiNormal (100, 10, **PsiCorrIndep("MyCorr")**) in cell B1 and write =PsiUniform(0, 100, **PsiCorrDepen("MyCorr", 0.9)**) in cell A1 to specify that A1 depends heavily on B1. "MyCorr" is an arbitrary string name.

The number 0.9 in the example above is a **Spearman rank order correlation coefficient**. This is a *nonparametric* measure of correlation that is computed from a rank ordering of the trial values drawn for both variables. It can be used to induce correlations between *any* two uncertain variables, whether they have the same or different analytic distributions, or even custom distributions. Like the product moment correlation coefficient, its value can range from -1 to +1.

Meaning of Rank Correlation Coefficients

- A correlation coefficient of +1 forces the sampled values of the uncertain variables to be exactly positively correlated, meaning that the p^{th} percentile value from one distribution will be sampled on the same trial as the p^{th} percentile value from the other distribution. Coefficients from 0 to +1 will produce varying degrees of positive correlation.
- A correlation coefficient of -1 forces the sampled values of the uncertain variables to be exactly negatively correlated, meaning that the p^{th} percentile

value from one distribution will be sampled on the same trial as the (100-p^{th}) percentile value from the other distribution. Coefficients from 0 to -1 will produce varying degrees of negative correlation.

- A correlation coefficient of 0 means there is no induced relationship between the variables. In practice, one usually uses coefficients less than +1 or -1, and uses 0 only in a correlation matrix that defines relationships among several variables (see below).

Computing Rank Correlations from Sample Data

If you have sufficient data on the past performance of two uncertain variables where the observations occurred at the same time for each variable, you can compute the Spearman rank correlation coefficient *r* as follows, where ΔR is the difference between the ranks of corresponding observations of the two variables:

$$r = 1 - \frac{6\sum_{i=1}^{n} \Delta R_i^2}{n\left(n^2 - 1\right)}$$

$$\Delta R_i = \Delta R_{i1} - \Delta R_{i2}$$

ΔR_i is the difference between the ranks of observation i for the two variables

ΔR_{ij} is the rank of observation i for variable j, $j = 1, 2$

You can easily compute this value on a spreadsheet, using Excel's RANK function, which returns the rank of a given cell value within a range of values. Suppose that A1:A100 contains trial values for uncertain variable A, and B1:B100 contains trial values for uncertain variable B. In C1 enter the formula =RANK(A1, $A$1:$A$100,1), in D1 enter =RANK(B1,$B$1:$B$100,1), and in E1 enter the formula =(C1-D1)^2. Then copy C1:E1 down to row 100. Then the rank order correlation coefficient is =1-(6*SUM(E1:E100)/(100*(100^2-1)).

If you don't have data on past performance of the uncertain variables, you will have to use judgment to estimate rank correlation coefficients.

Using a Rank Correlation Matrix for Several Variables

What if you have three, four, or more uncertain variables that should all be correlated with each other? You can create a small table or matrix of rank correlation coefficients in a cell range on the worksheet, and use this cell range in the PSI Property function **PsiCorrMatrix**. Below is an example of a 3x3 correlation matrix:

	A	B	C
1	1	0.8	0.5
2	0.8	1	0.2
3	0.5	0.2	1

You pass PsiCorrMatrix (*matrix cell range*, *position*) as an argument to the PSI Distribution function, for example =PsiNormal (10,5,PsiCorrMatrix(A1:C3,1)) for the first uncertain variable covered by the correlation matrix. You'd pass PsiCorrMatrix(A1:C3,2) to the PSI Distribution function for the second variable, and PsiCorrMatrix(A1:C3,3) for the third. This specifies that the first variable

has a rank correlation coefficient of 0.8 with the second variable, and 0.5 with the third variable. The second and third variables are correlated with each other, with a rank correlation coefficient of 0.2.

Note that a correlation matrix must always have 1's on the diagonal, because an uncertain variable is always perfectly correlated with itself. Also, the matrix must be symmetric: If row 2, column 1 contains 0.8, then row 1, column 2 must also contain 0.8. Finally, the correlation coefficients must be consistent with each other: For example, if uncertain variable 1 is strongly positively correlated with variable 2, and variable 2 is strongly positively correlated with variable 3, then variable 1 cannot be negatively correlated with variable 3. Formally, the matrix must be *positive semidefinite* – it cannot have any negative eigenvalues. Analytic Solver tests for this condition, and displays #N/A in the PSI Distribution cells for the uncertain variables that refer to an inconsistent correlation matrix.

To learn more about rank correlation and its uses in Monte Carlo simulation, consult the book *Risk Analysis: A Quantitative Guide* by David Vose, mentioned in the Introduction.

Modeling Correlation Using Copulas

Analytic Solver includes copulas to improve the method of defining the correlation or dependence between two or more uncertain variables. Copulas offer more flexibility over the rank order correlation method, and are able to capture complex correlations between multiple uncertain variables. In recent years, the popularity of copulas in finance and insurance risk models has skyrocketed.

An n – dimensional copula C is a multi-variate probability distribution where the marginal probability distribution of each variable follows the Uniform(0,1) distribution. A major benefit of copulas is that they allow two or more uncertain variables to be correlated without changing the shape of the original uncertain variable distributions.

For some copula C, a multi-variate distribution F with distributions of F_1, F_2, … F_n can be written as:

$$\mathbf{F(x_1, \ldots, x_n) = C(F_1(x_1), F_2(x_2), \ldots, F_n(x_n))}$$

Analytic Solver Desktop supports five types of copulas: three Archimedean copulas (clayton, frank, and gumbel) and two elliptical copulas (Gauss and Student). Analytic Solver Cloud supports one type: Gaussian.

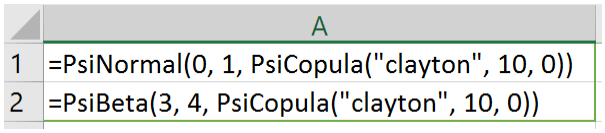
Each of these copulas may be bi-variate (correlating only two uncertain variables), or multi-variate (correlating more than two uncertain variables). Each copula type has its own parameter domain and method of calculation. The signatures for each copula are the same, except that multi-variate Archimedean copulas lack the "reflection" argument. For details regarding Archimedian copulas, see the following sections. For a complete discussion of the theory behind all five copula types, see the section *Psi Property Functions* in the *Frontline Solvers Reference Guide*.

Archimedean Copulas

Archimedean copulas can be bi-variate (correlating two uncertain variables) or multi-variate (correlating more than two uncertain variables). A bi-variate copula has a density function associated with it, which is similar to the

probability density of a bi-variate distribution. Archimedean Copulas are not supported in Analytic Solver Cloud.

To create a bi-variate Archimedean copula, enter two uncertain variable distributions into two Excel cells, and then use the PsiCopula property as an argument to both. See the screenshot below for an example.



Cell A1 contains an uncertain variable that follows the PsiNormal distribution with mean = 0 and standard deviation = 1. Cell A2 contains an uncertain variable following the PsiBeta distribution with shape parameters equal to 3 and 4. The PsiCopula property is passed as the third argument to each uncertain variable. All three Archimedean copulas use the same signature.

```
PsiCopula(type, param, [reflection], [instance])
```

`Type`: As previously mentioned, Analytic Solver supports three types of Archimedean copulas: clayton, frank, and gumbel. The copula type should be passed in quotes as, "clayton", "frank", or "gumbel". In this example, "clayton" is passed. The two elliptical copulas have their own Psi property names: PsiCopulaGauss and PsiCopulaStudent. See the example below for their signatures.

`Param`: The parameter of a copula determines the strength of the correlation. In this example, a parameter equal to 10 is passed. See the following parameter restrictions for each Archimedean copula type.

Clayton:

- Bi-variate: param >= -1, param ≠ 0.
- Muilti-variate: param > 0

Gumbrel

- Bi-variate or Multi-variate: param >= 1

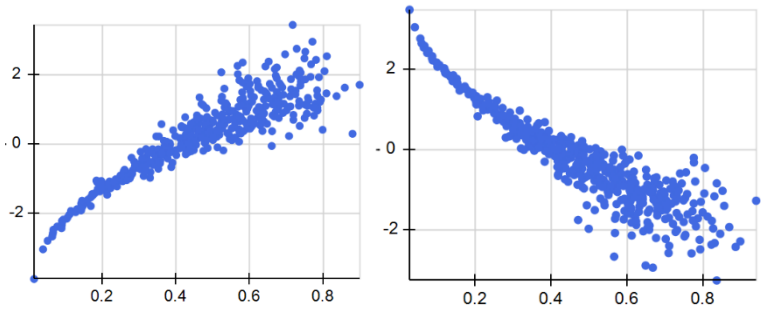
Frank

- Bi-variate: param ≠ 0.
- Muilti-variate: param > 0

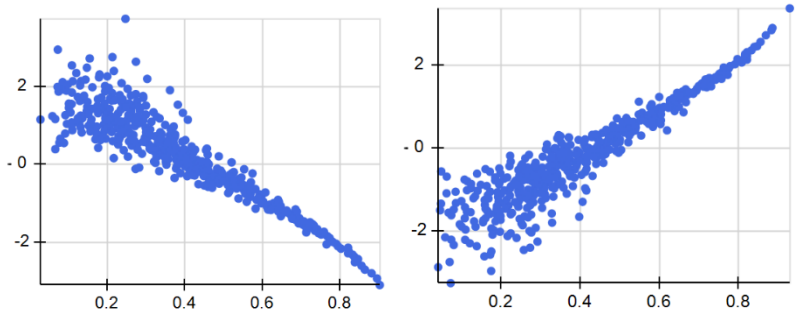
Note: Param = 0 for a multi-variate Archimedean copula is supported, but indicates no correlation between the uncertain variables.

`Reflection`: (Optional) Analytic Solver allows you to control the direction of a bi-variate Archimedean copula using an optional reflection parameter. This argument may take on values of 0, 1, 2, or 3, which control the reflection of no variables using the value of 0, the first variable using the value of 1, the second variable using the value of 2 or both variables using the value of 3. By default, the reflection option is set to 0, which indicates no reflection. In this example, a 0 is passed for the reflection argument to illustrate how this parameter should be passed. In practice, a value of 0 need not be present.

The scatter plots below illustrate the four different positions of a clayton copula correlating two uncertain variables with distributions PsiNormal(0,1) and PsiBeta(3,4).

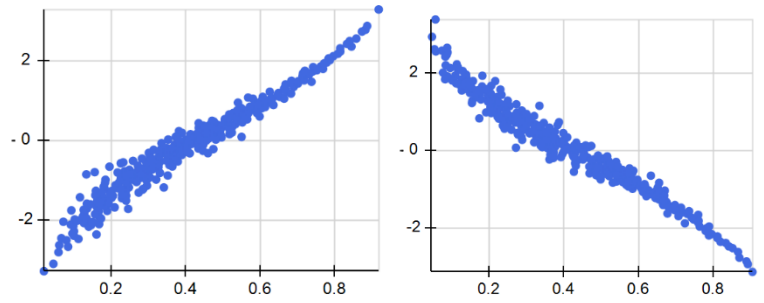


Reflection = 0 Reflection = 1

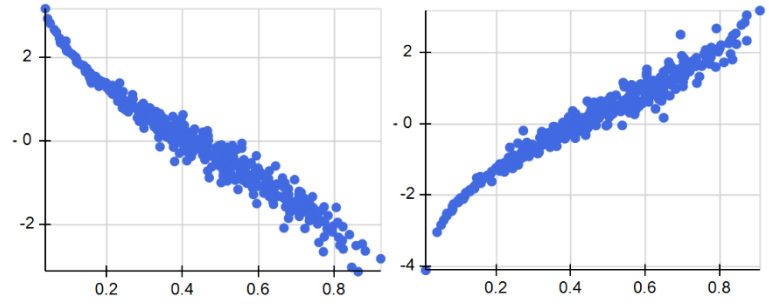


Reflection = 2 Reflection = 3

The scatter plots below illustrate the four different positions of a type gumbel copula correlating two uncertain variables with distributions PsiNormal(0,1) and PsiBeta(3,4).



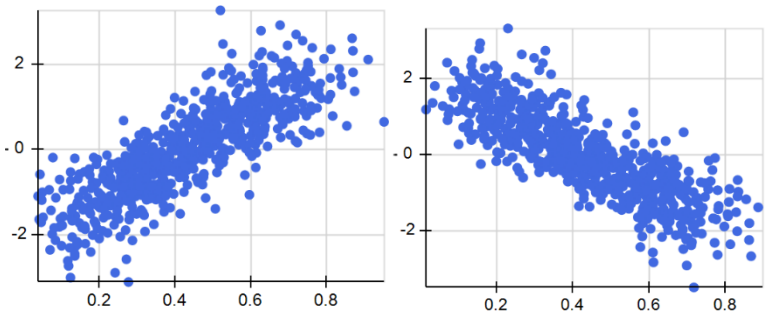
Reflection = 0 Reflection = 1



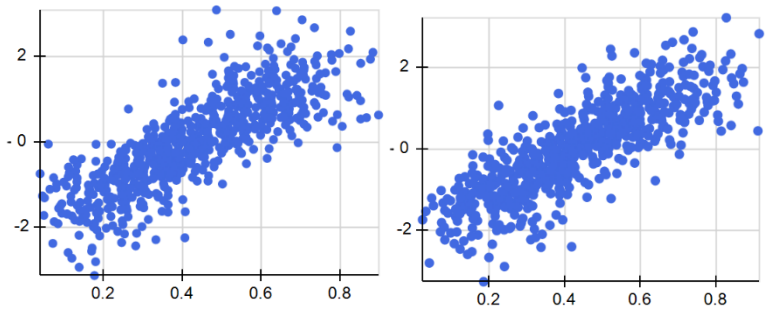
Reflection = 2 Reflection = 3

The scatter plots below illustrate the four different positions of a type frank copula correlating two uncertain variables with distributions PsiNormal(0,1) and

PsiBeta(3,4). Note: Since the Frank copula is symmetric, this type of copula has only one reflection.



Reflection = 0 Reflection = 1



Reflection = 2 Reflection = 3

`Instance`: (Optional) Instance is the string name given to the copula. An Archimedean copula is explicitly identified by the Instance argument, and implicitly identified by its argument values. When multiple copulas are present in the same workbook, it is considered "best practice" to use this argument.

In this example, we correlate the two uncertain variables using the PsiCopula property, =PsiCopula("clayton", 10, 0). Since the Instance property is missing, the copula is identified *implicitly* by its unique set of arguments, in this case "clayton" and "10". *When not passing the Instance property, the PsiCopula property within each uncertain variable signature, MUST use the same arguments.* Otherwise, the correlation between the uncertain variables will not be invoked.

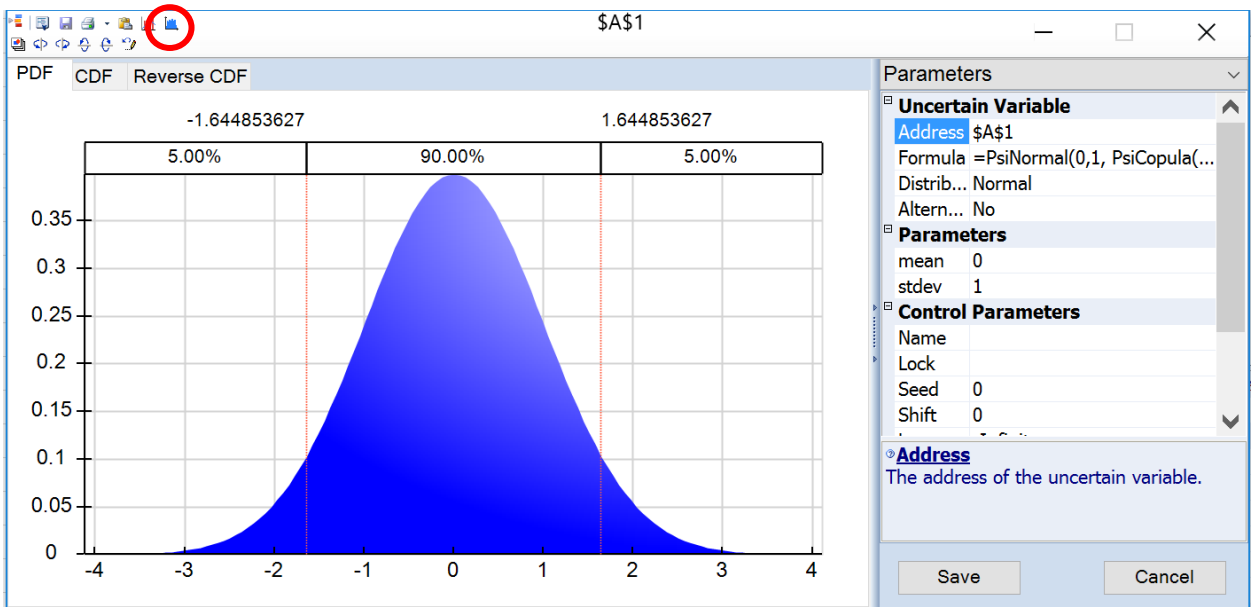
Note: PsiCopula("clayton", 10) and PsiCopula("clayton", 10, 0) is considered as the same copula since 0 is the default for Reflection argument.

To correlate a new group of uncertain variables using a second copula, such as PsiCopula("clayton", 12) or PsiCopula("frank", 10), the Instance argument is still not required since either copula is identified by its unique parameters of "clayton" and "12" or "frank" and "10". However, if correlating this same new group of uncertain variables with a copula using the same arguments of "clayton" and "10", we MUST pass a unique name to the Instance argument, for example, "copula2".

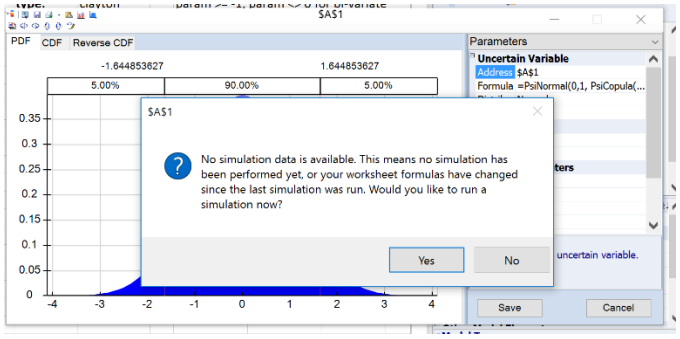
Finally, to view the output of the copula, we must make each uncertain variable an uncertain function. We can easily do so by clicking cell A1, then **Results – Output -- Referred** on the Analytic Solver ribbon. Next, select an empty Excel cell, say C1. The formula, =PsiOutput(A1), is inserted into this cell. Perform similar steps to make cell A2 an output function. (See the screenshot below for an example.)

	A	B	C
1	=PsiNormal(0, 1, PsiCopula("clayton", 10, 0))		=PsiOutput(A1)
2	=PsiBeta(3, 4, PsiCopula("clayton", 10, 0))		=PsiOutput(A2)

Double-click cell A1 to open the Uncertain Variable dialog, then click the Show Results icon.



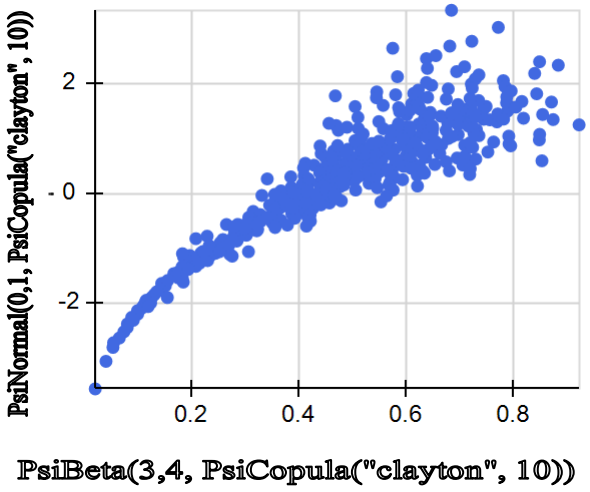
When Analytic Solver Simulation prompts you to perform a simulation, click **Yes**.



Instantly, a simulation with 1,000 trial values is executed. Excel cells A1 and A2 return 1,000 trial values from the sampled distribution, generating the pattern of correlation defined by the copula.

Click the Scatter Plots tab to view the results of the copula. In this example, a copula of type "clayton" is created correlating two uncertain variables with distributions of PsiNormal(0,1) and PsiBeta(3, 4). The distribution generated for the first uncertain variable will still follow the Normal(0,1) distribution, and the distribution generated for the second variable will still follow the Beta(3,4) distribution. The scatter plot below displays the copula correlating the two uncertain variables using a parameter of 10.

Note: If the copula is multi-variate, the associated scatter plots will be 2-D projections.



Elliptical Copulas

Analytic Solver Comprehensive supports two elliptical copulas that can be either bi-variate or multi-variate: Gaussian and Student. Each elliptical copula has its own signature. Student copulas are not supported in Analytic Solver Coud.

To create a multi-variate Student copula, enter three or more uncertain variable distributions into three (or more) different Excel cells, and then use the PsiCopulaStudent() property as an argument to each. See the screenshot below for an example.

	A
1	=PsiNormal(0, 1, PsiCopulaStudent(N2:P4, 1, 1, "mycop"))
2	=PsiBeta(3, 4, PsiCopulaStudent(N2:P4, 2, 1, "mycop"))
3	=PsiNormal(0, 1, PsiCopulaStudent(N2:P4, 3, 1, "mycop"))

Cells A1 and A3 contain an uncertain variable that follows the PsiNormal distribution with mean equal 0 and standard deviation = 1. Cell A2 contains an uncertain variable following the PsiBeta distribution with shape parameters equal to 3 and 4. The PsiStudentCopula property is passed as the third argument to each uncertain variable. The PsiCopulaStudent property uses the following signature. Note: The signature for PsiCopulaGauss() is the same minus the "df" argument.

```
PsiCopulaStudent(number_range, position, df,
[instance])
```

`Number range`: If bi-variate, a number between -1 and 1; if multi-variate, the Excel cell range where the correlation matrix is located in the Excel spreadsheet. In this instance, the copula is multi-variate, so the correlation matrix in cells N2:P4 is passed.

	L	M	N	O	P
1		**Correlation**	$A$1	$A$2	$A$4
2		$A$1	1	0.5	0.6
3		$A$2	0.5	1	0.7
4		$A$4	0.6	0.7	1

`Position`: Specifies the uncertain variable index in the correlation matrix. For example, the "2" passed in the formula, =PsiBeta(3, 4, PsiCopulaStudent(N2:P4, **2**, 1, "mycop") specifies that the correlation coefficients in the second column of the correlation matrix in cells N2:P4 will be applied to the PsiBeta() uncertain variable.

`df`: Enter an integer greater than 1. This parameter specifies the degrees of freedom for the PsiCopulaStudent function. In this example, 1 degree of freedom is used. (Note: The formula for PsiCopulaGauss() does not include this argument.)

`Instance`: (Optional) Instance is the string name given to the copula. An elliptical copula is explicitly identified by the Instance argument and implicitly identified by the location of the correlation matrix. PsiCopulaStudent and PsiCopulaGauss support multiple copulas using the same correlation matrix. If passing the same type of elliptical copula using the same correlation matrix within the same workbook, this argument **must** be present. If the workbook contains multiple copulas of different types, then this argument may be omitted. When multiple copulas are present in the same workbook, it is considered "best practice" to use this argument.

In this example, we correlate the three uncertain variables using the PsiCopulaStudent property, =PsiCopulaStudent(N2:P4, 1, 1, "mycop"). Since the Instance property is present, the copula is identified *explicitly* by the name given in the last argument, "mycop". *When not passing the Instance property, the PsiCopulaStudent property within each uncertain variable signature, MUST use the same correlation matrix.* Otherwise, the correlation between the uncertain variables will not be invoked.

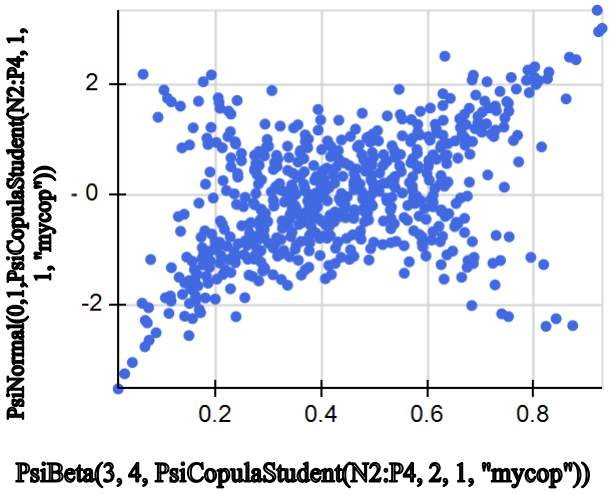
To view the output of the copula, we must make each uncertain variable an uncertain function. We can easily do so by clicking cell A1, and then **Results – Output -- Referred** on the Analytic Solver ribbon. Next, select an empty Excel cell, say C1. The formula, =PsiOutput(A1), is inserted into this cell. Perform similar steps to make cells A2 and A3 output functions. (See the screenshot below for an example.)

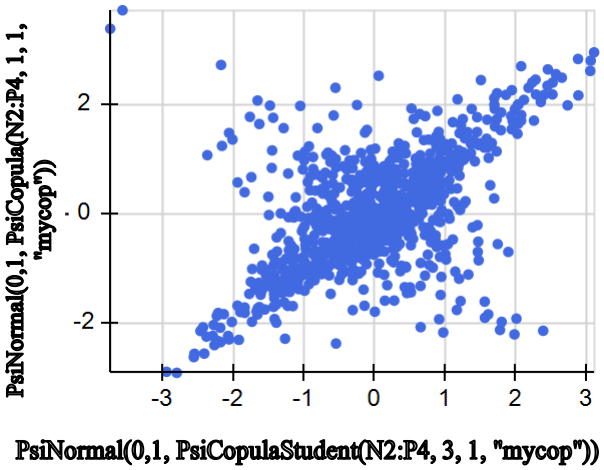
	A	B	C
1	=PsiNormal(0, 1, PsiCopulaStudent(N2:P4, 1, 1, "mycop"))		=PsiOutput(A1)
2	=PsiBeta(3, 4, PsiCopulaStudent(N2:P4, 2, 1, "mycop"))		=PsiOutput(A2)
3	=PsiNormal(0, 1, PsiCopulaStudent(N2:P4, 3, 1, "mycop"))		=PsiOutput(A3)

On the Analytic Solver ribbon, click the down arrow under Simulate, then select Run Once from the menu. Instantly, a simulation with 1000 trial values is executed. The result is a correlated uncertain function following the Uniform(0,1) distribution. Excel cells A1, A2 and A3 return 1000 trial values from the sampled distribution generating the pattern of correlation defined by the copula.

In this example, a copula of type "student" is created correlating three uncertain variables with distributions of PsiNormal(0,1) and PsiBeta(3, 4). The

distributions generated for the first and third uncertain variables will still follow the Normal(0,1) distribution and the distribution generated for the second variable will still follow the Beta(3,4) distribution. The scatter plots below show plots from the PsiNormal(0,1) distribution, the PsiBeta(3,4) distribution and the copula correlating the three uncertain variables.





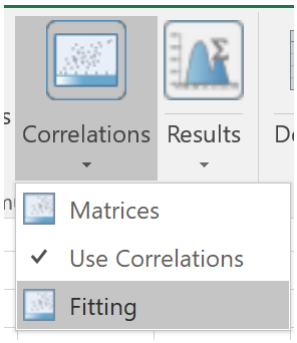
Correlation Fitting

The previous chapter, "Getting Results: Simulation", discussed how to fit a distribution to simulation results. Recall that, in this chapter, the simulation results from the BusinessForecast(Sim).xlsx model were fit to the Min-Extreme uncertain variable distribution. Analytic Solver calculated the parameters of several distributions from the data within the example model and listed the distributions with the best fit, with Min-Extreme at the top of the list.

Similarly, the goal of correlation fitting is to find the parameters of the correlation function that match the existing (but unknown) correlation between two or more samples of historical data. Each sample is assumed to come from an independent uncertain variable. Analytic Solver offers correlation fitting using 6 correlation types: rank, clayton, gumbel, frank, gauss and student. It is up to the user to determine which correlation type results in the best fit to the data. Note: Rank is not a copula correlation, but rather a stand-alone type of correlation.

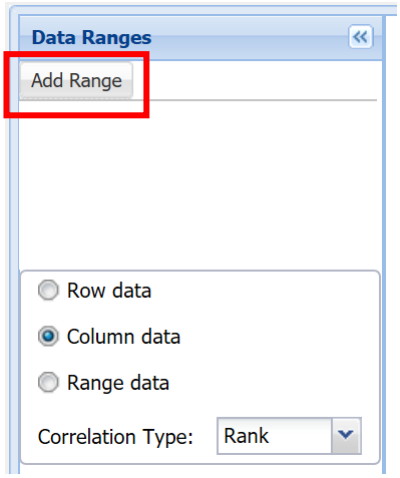
For example, if a scatter plot is drawn from two independent samples resembling a tilted ellipse, one can assume that the correlation will be a "Gauss" correlation. If the correlation is fit, using the Gauss fitting algorithm, one rank-correlation coefficient will be returned. If more than 2 samples are drawn, the fitting algorithm will return a correlation matrix of size n.

Analytic Solver users can fit a correlation using the Copula Fit dialog which can be opened from the Analytic Solver ribbon by clicking the down arrow beneath the Correlations icon and selecting Fitting.

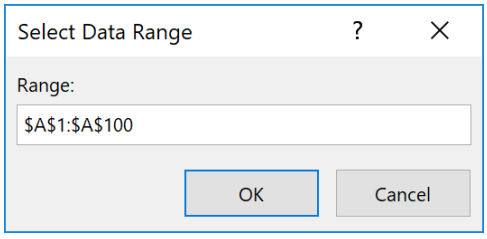


Two or more Excel cell ranges containing independent samples can be added to the Copula Fit dialog by clicking Add Range. Data may exist in row form, column form, or in a matrix. For example, if you had two independent samples located in cells A1:A100 and B1:B100 you would select Column Data, then click Add Range on the Copula Fit dialog.

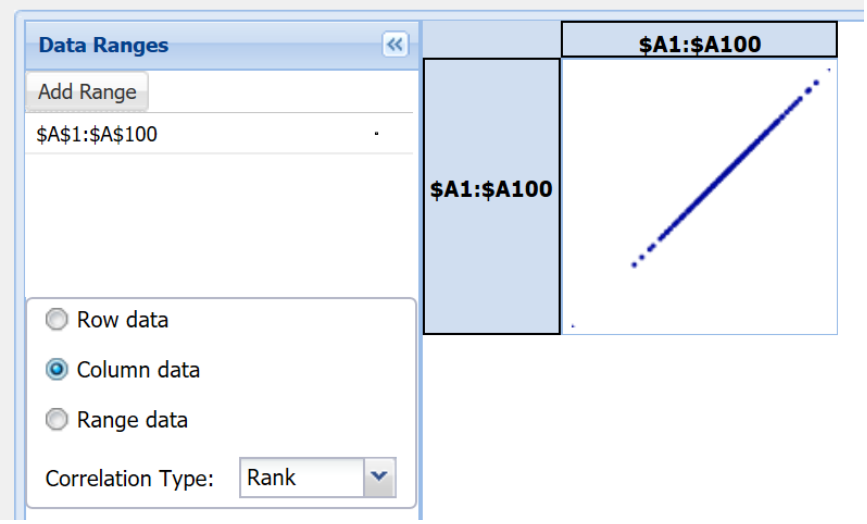
If the data were contained by row, then you would select Row data and if data were contained in, say, a 10 x 10 matrix in cells A1:J10, then you would select Range data.



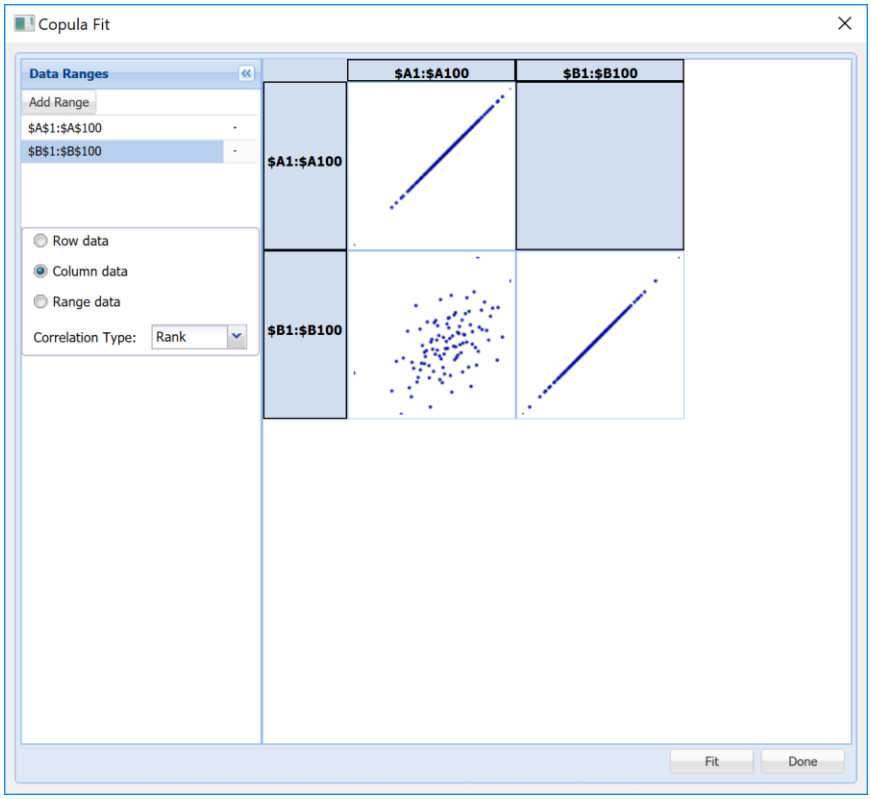
Then either select or enter A1:100 on the Select Data Range dialog.



After you click OK, the data range will appear under Data Ranges and a scatter plot will appear on the right of the dialog.



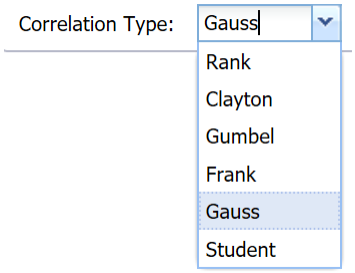
To enter the 2nd range, keep Column Data selected, then click Add Range again, enter the Excel range, B1:B100, then click OK to add the data range to the Copula Fit dialog.



Notice that the scatter plot that has been drawn for the two ranges resembles an ellipse. From this scatter plot, we can assume that the copula correlation type for fitting is "Gauss". A shape resembling a star points to a Student copula for Correlation Type and a shape resembling a funnel would indicate a Clayton copula. Although a complete discussion of the definition of copulas is beyond the scope of this guide, see the previous section, "Modeling Correlation Using

Copulas" for a brief introduction of each type of copula defined in the Correlation Type drop down menu.

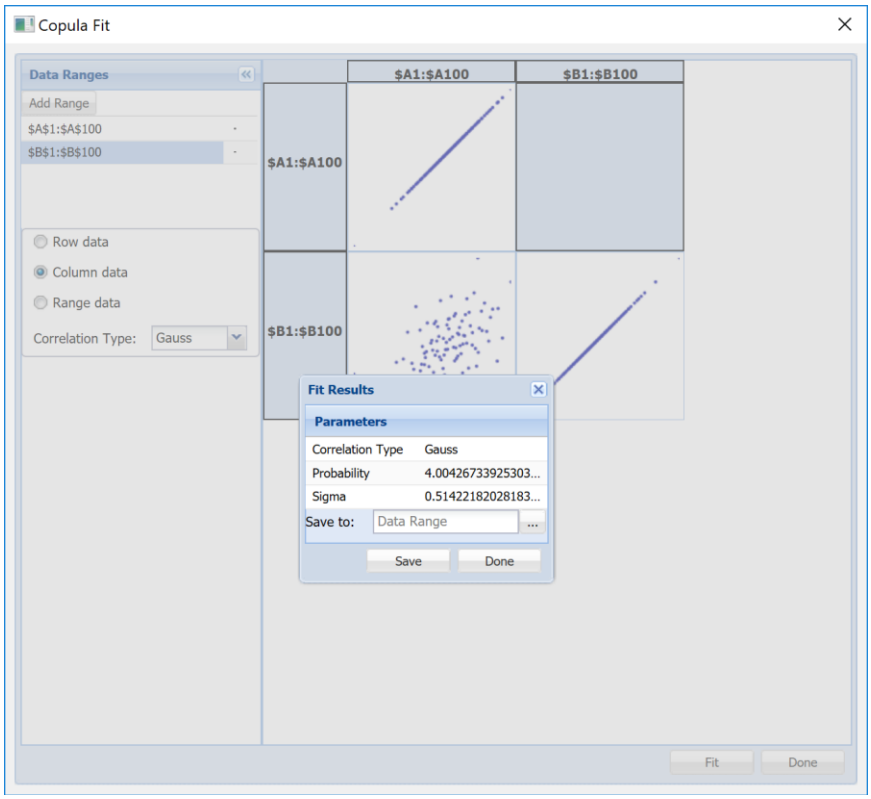
Select Gauss as Correlation Type…



…then click Fit at the bottom of the Copula Fit dialog to fit the correlation.

The Fit Results Parameters dialog opens to display the Correlation Type (Gauss) and the Probability and Sigma fitting parameters. Select a blank cell, say D1, to save the fitting parameters to the worksheet, then click Save.

Note: The cell entered for "Save to" on the Fit Results dialog will become the top left corner of the data range on the Excel sheet. Any value or text contained in this cell or in any cell used to save the Fit Results Parameters, will be overwritten.



Then click Done to close the Copula Fit dialog and return to the worksheet. Notice that the information from the Fit Results dialog has been saved to the Excel range, D1:E3. The size of this range will vary depending on the Correlation Type and number of Data Ranges present in the Copula Fit dialog.

	A	B	C	D	E
1	-0.42418	-0.21635		Correlation Type	Gauss
2	-0.408	0.677854		Probability	4E-07
3	-0.1467	-1.08687		Sigma	0.514222
4	0.359818	-0.39609			

Using the Correlations Dialog

The Correlation dialog offers an easy way to create, edit, and remove correlation matrices in your model. It appears when you click the Correlations button on the Ribbon.

You use a correlation matrix to *induce* a statistical correlation among two or more uncertain variables. When you do this, the trial values of these variables in a Monte Carlo simulation will tend to be drawn from related percentiles of their distributions on each trial. Starting with V2016-R2, the numbers in a correlation matrix may be **Spearman rank order correlation coefficients** or specifying an **Archimedean** or **Elliptical copula.** For more information on correlation matrices, see "Inducing Correlation Among Uncertain Variables" in the Dependence and Correlation section above.

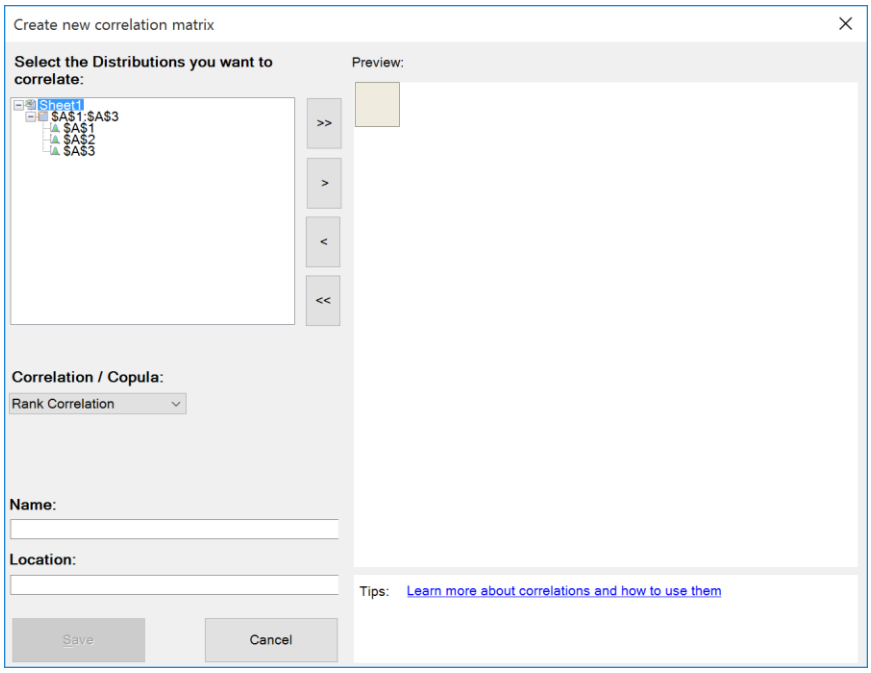
A correlation matrix is stored in a contiguous cell range, with an equal number of columns and rows. To correlate *N* variables together, you need a matrix of *N* columns and *N* rows. Here's an example of a 3x3 correlation matrix:

1	0.8	0.5
0.8	1	0.2
0.5	0.2	1

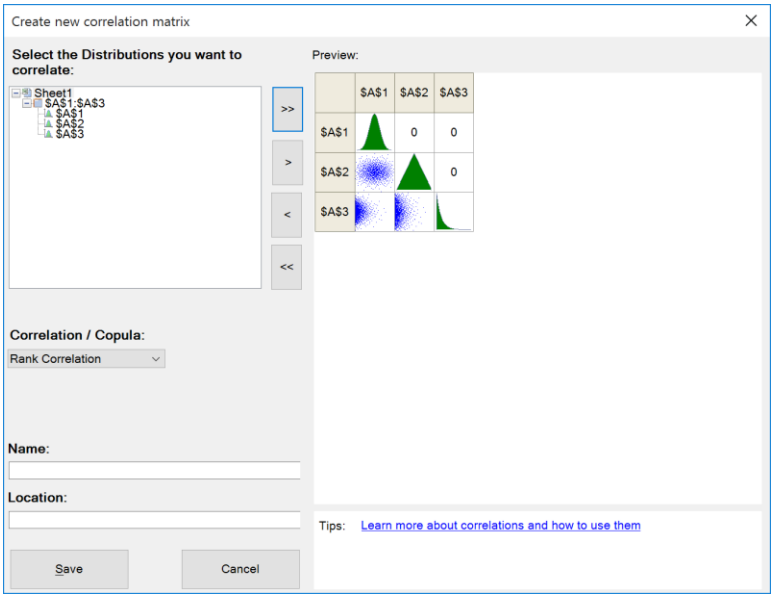
You can type in values for a correlation matrix directly on the Excel worksheet, and then reference this matrix in the PsiCorrMatrix() property function, passed as an argument to PSI Distribution functions for each of the correlated variables. But it is easier to use the Correlation Dialog to create the matrix for you.

Creating a Correlation Matrix

When you first click the Correlations button on the Ribbon, the Correlation dialog appears with an empty matrix area, and a left pane (similar to the Task Pane displayed by the Model button) that lists the uncertain variables in the model:



You can either choose the specific cells for the uncertain variables you want to correlate (press Ctrl or Shift and click for more than one) and then click the ">" button to include them in the matrix, or you can click the ">>" button to include all of them. The initial matrix with correlation values set to zero will display similar to the example below:

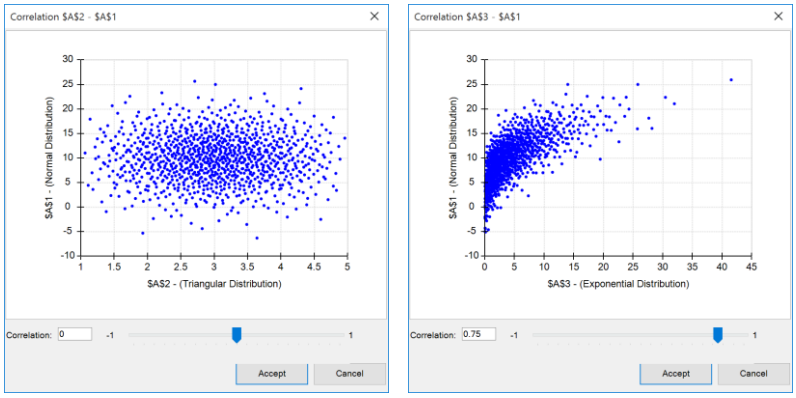


The preview for the correlation Matrix has three parts:

1. Black numerical values for each correlation in the top right of the matrix. In this case we have three values initially set with a zero correlation which you can edit. Since correlation matrices have to be symmetrical (the correlation between A1 and A2 must be the same as the correlation between A2 and A1) we only show one value. Note: Both values are shown in Analytic Solver Cloud.

2. Green graphical representations of each distribution diagonally from top left to bottom right. In this example, we used a Normal distribution in our worksheet in cell A1 (show here in the top left part of the matrix), a Triangular distribution in cell A2, and a LogNormal distribution in cell A3. Note: Graphical representations are not currently available in Analytic Solver Cloud.

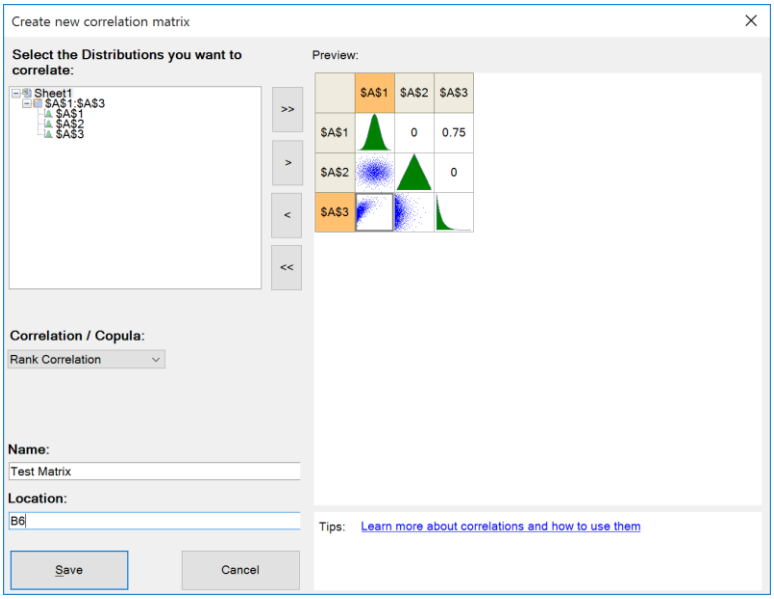
3. Blue scatterplots reflecting the current correlations between the distributions. When you edit the values of each correlation, these will automatically update giving you a visual representation of the updated correlation. Note, you can click on any scatterplot here and a dialog will come up where you can more clearly see the scatterplot and how the scatterplot changes as you adjust the correlation (see below). In the example on the left the correlation is set to zero while on the right we have adjusted it (either directly typing in 0.75 into the Correlation field or adjusting the slider. Note: Scatterplots are not currently available in Analytic Solver Cloud.



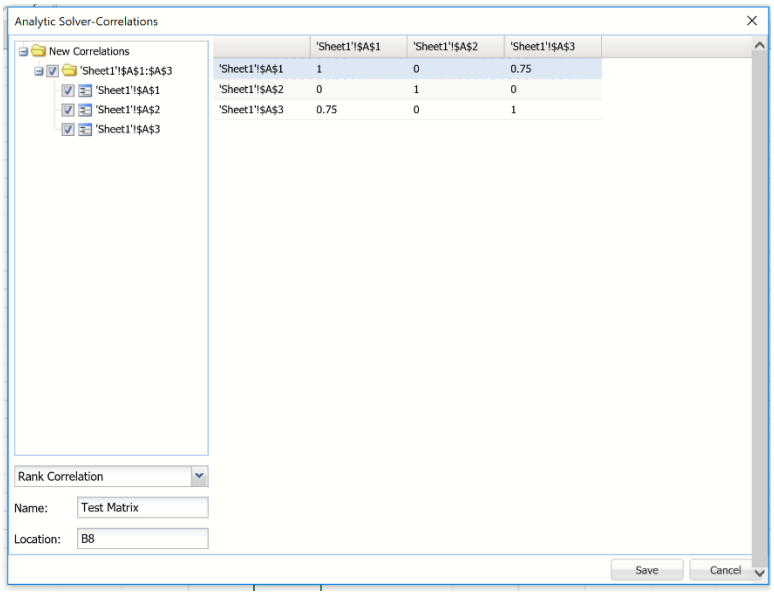
Once you click "Accept" you are taken back to the initial dialog and it shows the updated correlation matrix.

At this point you can name your correlation matrix and then choose the location you want to place it in your worksheet. While optional, naming your matrix is recommended, and is important if you want to use the same matrix several times. To place your matrix, simply click your cursor in the location field and click where you want to place the matrix on your worksheet.

Analytic Solver Desktop

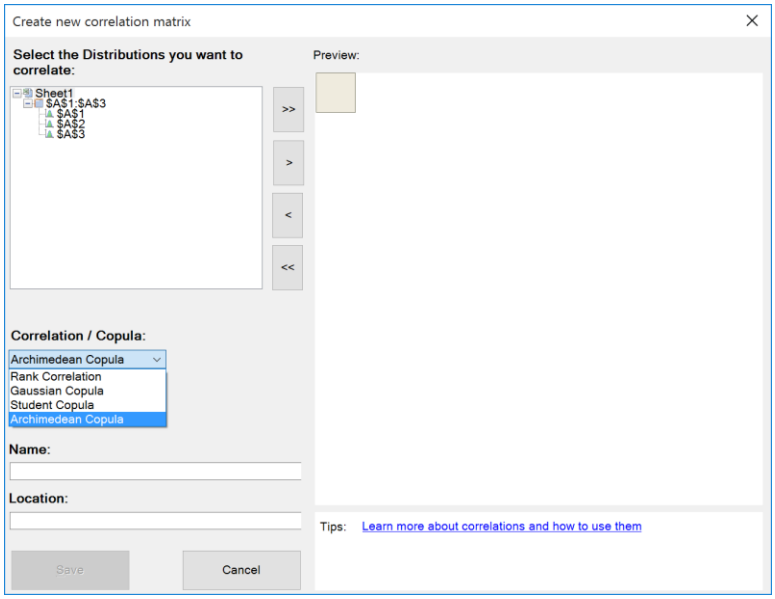


Analytic Solver Cloud



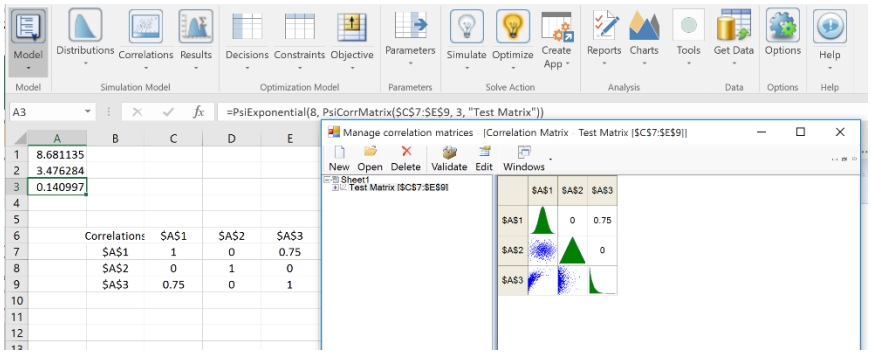
Managing Copulas

Analytic Solver includes the ability to correlate uncertain variables using Gaussian, Student or Archimedean Copulas. To correlate the three uncertain variables in cells A1, A2, and A3 using an Archimedian Copula, select Archimedian Copula from the Correlation/Copula drop down menu. Note: Only Rank Order and Gaussian Copulas are supported in Analytic Solver Cloud.



Once the Copula type is selected, three more fields will be enabled, Type, Parameter, and Reflection. Using these three parameters you may choose the type of Archimedean copula (Clayton, Frank, or Gumbel), specify the copula parameter, and choose a Reflection type. If Gaussian Copula is selected, no additional parameters are required. If Student Copula is selected, one additional parameter is required, Degrees of Freedom. For more information on copulas and copula parameters, see "Inducing Correlation Among Uncertain Variables" in the Dependence and Correlation section above.

Lastly, click "Save" to complete the process. Your new correlation matrix will then be saved and placed on your worksheet (in this case in cell B6) and the Manage Correlation Matrices Dialog will show in place of the Create New Correlation Matrix dialog. This dialog lists all the matrices you have set up on the left side of the dialog, and when you double-click on a particular matrix it will show on the right side.



As the matrix is created, Analytic Solver Simulation also edits the PSI Distribution function formulas for the uncertain variables (at A1, A2, & A3 in the example above) to include the property function **PsiCorrMatrix(C7:E9, *n*)**, where *n* is 1 for A1, 2 for A2, and 3 for A3. During a Monte Carlo simulation, when trial values are drawn for the uncertain variables A1, A2 and A3, Analytic Solver will use the correlation matrix at C7:E9 to adjust the 'draws' so that the values are properly correlated across all the simulation trials.

The matrix C7:E9 now appears in the left pane of the Manage Correlation Matrices dialog. If you close and later reopen the Correlation dialog, this matrix

will reappear in the lower left pane. If you create a correlation matrix 'by hand' on the Excel worksheet, and insert the PsiCorrMatrix() calls yourself into the PSI Distribution function calls for the variables, the matrix you create will also appear in this left pane the next time you open the Correlation dialog. You can double-click on each matrix to display and edit that matrix.

Removing a Correlation Matrix

To remove a correlation matrix from your model, in the Manage Correlation Matrices dialog click on the matrix you want to remove and then click on the "Delete" icon in the dialog's ribbon menu. The matrix will disappear from the Correlations dialog, and the PsiCorrMatrix() property function formula referencing this matrix will be removed from the PSI Distribution function calls for the corresponding uncertain variables. However, the cell range on the worksheet where the matrix elements were written is left undisturbed – you can either delete them in Excel worksheet mode, or re-use them later.

To remove a correlation matrix in Analytic Solver Cloud, simply select the matrix in the Model task pane, then click the red X to delete.

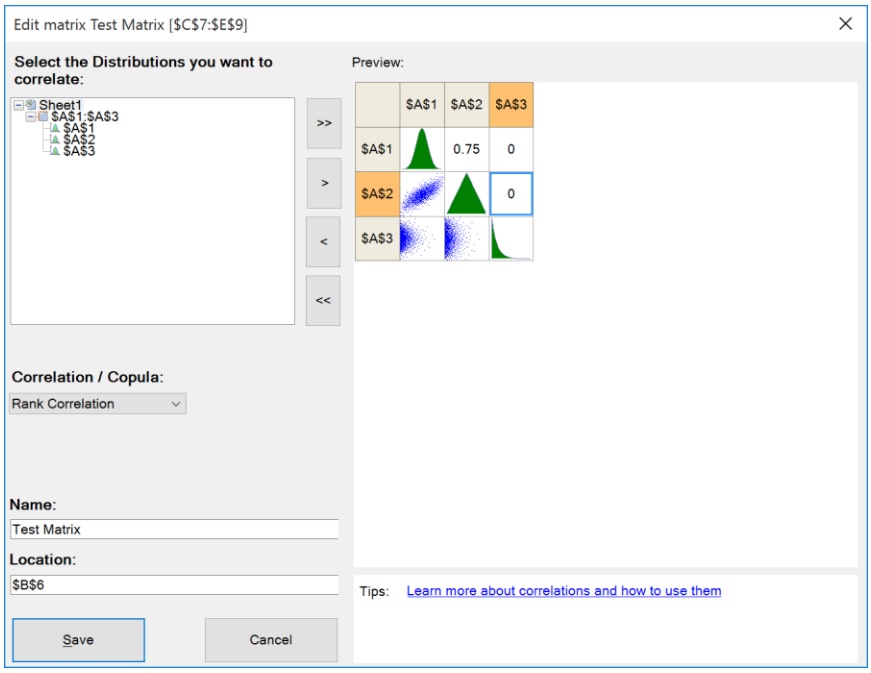
Editing a Correlation Matrix

As shown in the both the Create Correlations and Manage Correlations dialogs, the value of each correlation is numerically shown in the top right portion of the matrix. To edit the value of a correlation you can simply click on the correlation you wish to edit and enter a new value from -1 (exactly negatively correlated) to +1 (exactly positively correlated). The default value of 0 means the two variables have zero correlation.

When you are finished, click the "X" button in the top right of the dialog to close it and your change(s) will be saved. Importantly, we will automatically check to make sure your matrices are valid (Positive Semi-Definite; see "Making a Matrix Consistent" below) and if they are not will offer help to correct them.

Alternatively, you can click on the Edit button on the Manage Correlations Ribbon to go to the Edit Matrix Dialog. The Edit Matrix dialog (see below) will appear, which looks very similar to the Create Matrix dialog. At this point you can change the name and location of the matrix, add or remove uncertain variables, and change correlation values. When done, simply hit **Save**.

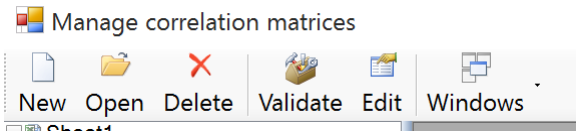
In Analytic Solver Cloud, double click the correlation matrix in the Model task pane to edit. Click save when finished.



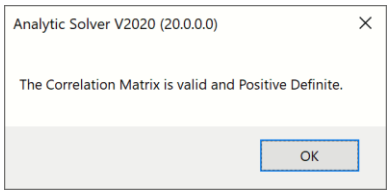
Making a Matrix Consistent

A correlation matrix must be not just symmetrical, but ***consistent***. This means for example that if variable A has a high positive correlation with variable B, and B has a positive correlation with C, then variable A cannot have a high negative correlation with C. In mathematical terms, the correlation matrix must be *positive semidefinite*. This property depends on all of the elements of the matrix. If the matrix you create by hand does not satisfy this property (the example matrix above does not), Analytic Solver can automatically adjust the matrix elements so that the matrix is positive semidefinite.

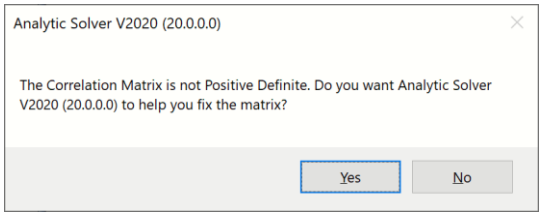
To check whether the matrix you've entered is positive semidefinite, in the Manage Correlations dialog simply click the Validate icon in the dialog's ribbon menu:



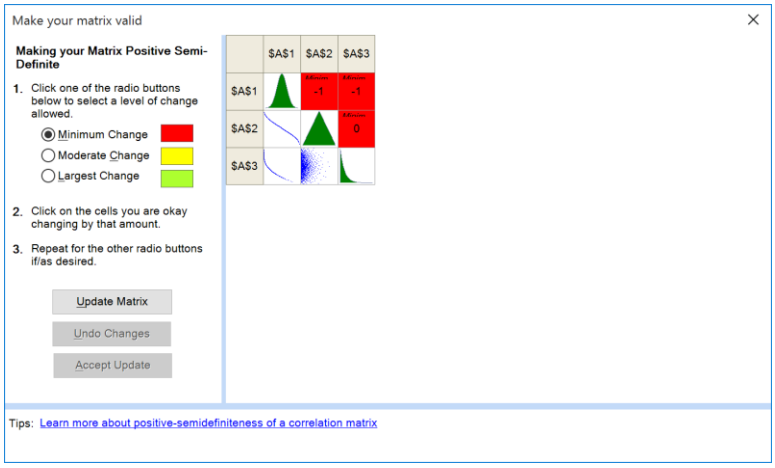
In our example, the matrix is valid so the following message is displayed and no action is needed:



If, for example, we set all our correlations to be -1, we would have a matrix which could not be valid and you will see the following message instead:



If you click No, the matrix remains as-is. If you click Yes, a new dialog appears:

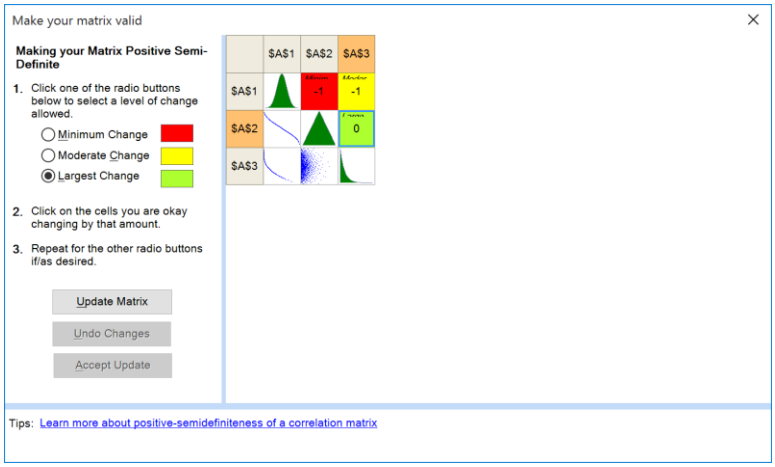


In this dialog, we can simply click the Update Matrix button to allow Analytic Solver to adjust the matrix to be consistent (positive semidefinite). This may involve changing all of the elements of the matrix, by various amounts. But Analytic Solver can do more than this.

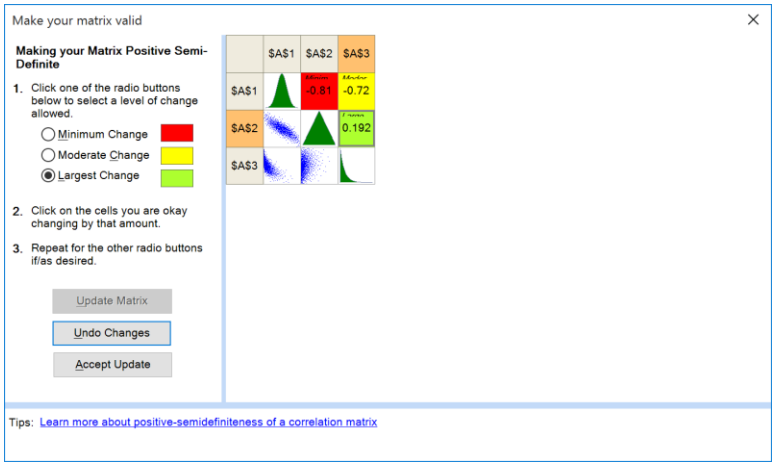
In many applications, you can determine 'good' values for correlations between certain pairs of variables, but for other pairs you have no special information. Analytic Solver Simulation can adjust the matrix to make it positive semidefinite while minimizing changes to the matrix elements you care about, and making greater changes in the elements you don't care about.

In the example above, let's say we feel very confident there is a strong negative correlation between A1 and A2 but are less sure about A1 and A3 and very uncertain about any correlation between A2 and A3. We can click first on the radio button on the left relating to the amount of change we are comfortable with and then click on the cell(s) we want changed by that general amount.

Using the information above we would click on the "Moderate Change" radio button and then click on the correlation for A1 and A3 and then click on the "Largest Change" radio button followed by clicking on the correlation for A2 and A3. Our Matrix will now look like the following:

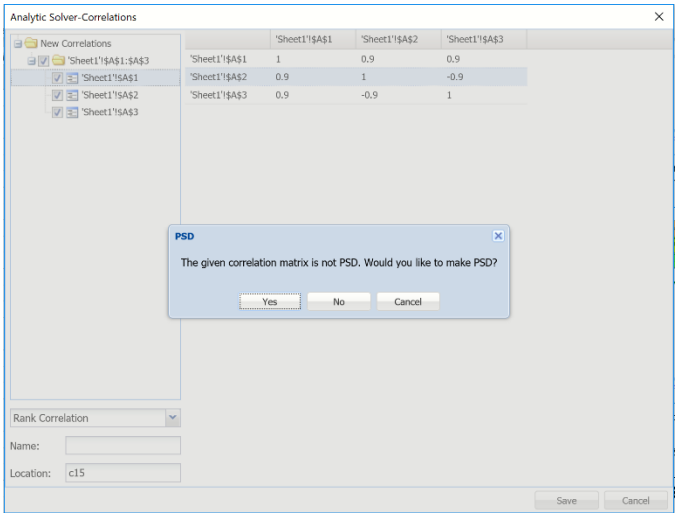


At this point we just click the "Update Matrix" button and our matrix is updated to be consistent (Positive Semi-Definite) with new correlation values as shown below:



We can now accept the update or undo the changes. We can of course further refine our correlation values if/as we wish.

In Analytic Solver Cloud, each time the Save button is clicked on the Correlations dialog, the matrix is checked for consistency (positive semi-definite). If the matrix is not consistent, you will be asked if you would like Analytic Solver to modify the matrix. Click yes, to accept Analytic Solver's modifications. Click No to save the matrix without any modifications. Click Cancel to go back to the matrix.



Probability Management Concepts

In the February and April 2006 issues of the publication *OR/MS Today*, Dr. Sam Savage and coauthors Stefan Scholtes (University of Cambridge) and Daniel Zweidler (Shell Global Exploration) advance a series of ideas called "Probability Management." They argue for much broader use of risk analysis methods in planning and management, especially in large enterprises, based on three ideas:

- Interactive Simulation
- Stochastic Libraries
- Certification Authority

Probability Management calls for an up-front investment in the creation of standardized Certified Distributions, created or reviewed by an expert authority, and distributed to simulation modelers, often in the form of Stochastic Libraries. The payoffs of Probability Management include:

- Much easier creation of new simulation models
- Ability to capture complex dependencies – beyond what's possible with correlation coefficients
- 'Apples-to-apples' comparison of simulation model results
- Valid 'roll-ups' of simulation models from different groups

Analytic Solver Comprehensive is the first product designed to support the concepts of Probability Management. In addition to best-in-class support for *Interactive Simulation*, it provides direct support for creating, 'publishing' and using *Certified Distributions* and *Stochastic Libraries*, as discussed in this chapter.

Analytic Distributions

As described above, and documented in the Reference Guide, Analytic Solver provides a wide range of analytic probability distributions – more than 40 distributions are available, from **PsiBernoulli()** to **PsiWeibull()**. Given knowledge and experience, you can choose and use these distributions in your simulation models. But as discussed above, this is often the most challenging

part of creating a Monte Carlo simulation model, especially for users with spreadsheet modeling expertise, but limited math and statistics background.

Moreover, when different end user modelers choose their own analytic distributions and parameters, they will often create models that cannot be compared or combined ('rolled up'), because the relationships between uncertain variables and functions would not be preserved. In large firms especially, where different business units must take into account common uncertainties, a better approach is needed.

Certified Distributions and Stochastic Libraries

A Certified Distribution is a custom probability distribution, created and/or reviewed by an expert, that is made available to end user modelers as a 'prepackaged unit.' These modelers need only the *name* of the Certified Distribution; they need not choose, or even be aware of, its analytic form, parameters or correlations.

An analytic Certified Distribution can be given its own random number seed, which overrides a user-specified seed for the model. This ensures that end user modelers employing the Certified Distribution will use the same *samples* (sequence of Monte Carlo trials) each time they run a simulation – as long as they use the same simulation software package and version.

Given the capacity of modern computers and networks, an even better idea is to create and distribute Certified Distributions in the form of **Stochastic Libraries**. Such libraries contain *pre-generated trial data* for a group of (potentially statistically dependent) distributions. The sequence of trials is predetermined, so that if two or more end users develop and run simulation models using the same Stochastic Library, their model results can be compared and combined, on a trial-by-trial basis if necessary.

Analytic Solver Desktop supports the use of both analytic distributions and Stochastic Libraries as Certified Distributions. But since they contain pre-generated trial data, the use of Stochastic Libraries can *guarantee* that models will be run with exactly the trial data intended, regardless of the software (or version thereof) installed on end user modelers' PCs – as long as it accepts Stochastic Libraries. *This functionality is not currently supported in Analytic Solver Cloud.*

Publishing and Using Certified Distributions

Certified Distributions can be prepared and tested using a variety of tools. One of these tools is Analytic Solver Desktop itself, as illustrated below. When creating a Stochastic Library, any good Monte Carlo simulation software package can be used, inside or outside of Excel, as long as it offers a way to save all the Monte Carlo trials. Once prepared, Certified Distributions should be approved and 'published' in a form where they can be made available to end user modelers.

Analytic Solver Simulation provides a property function **PsiCertify()** that you can use to name and "certify" a distribution as ready for publication. It also provides a distribution function **PsiCertified()** that end user modelers can use to access the Certified Distribution using only its name.

Certified Distributions can be physically distributed or made accessible in a variety of ways: On CDs or DVDs, via a network file share, or via email or

Web download. The data for Monte Carlo trials may be easily stored in a relational database or a multidimensional data warehouse.

Analytic Solver Simulation, with its *Interactive Simulation* facilities, is the ideal 'client' tool for end user modelers using Certified Distributions. It provides an easy way to access Certified Distributions by *name*, using Microsoft Excel as a "universal data access client" to access distributions and Stochastic Libraries.

Analytic Solver Simulation makes it easy for an expert or CPO to create an Excel workbook, separate from any end user's simulation model workbook, where Certified Distributions are defined. This may be a **standard workbook** or an Excel **add-in workbook**; the latter provides certain advantages, since it is normally hidden from display and loaded automatically when Excel starts.

For example, it is straightforward to create an Excel add-in workbook that defines a Certified Distribution that draws its trial data from a Stochastic Library (see below) that is actually stored in a relational database or data warehouse. When the add-in workbook is (automatically) opened, either Excel data access functions or VBA code can be used to query the database for the trial data.

Stochastic Libraries: SIPs and SLURPs

As described by Dr. Savage in *OR/MS Today*, the simplest element of a coherent Stochastic Library is a *Stochastic Information Packet* or SIP, which is just a list of trial values for a single uncertain variable. An example might be 1,000 sample values, in a specific sequence, for the future price of oil at some point or interval of time. In a Monte Carlo simulation, trials will be drawn from the SIP ***in the order in which they were generated***.

If the SIPs for several different uncertain variables are generated as a group, in a manner that preserves the statistical dependence between them, they may be combined into a Stochastic Library Unit, Relationships Preserved, or SLURP. A SLURP is a table of trial values, where each column represents a specific uncertain variable, and each row represents a distinct trial. The SLURP's uncertain variables may be dependent in ways not measured by traditional correlation. But if a Monte Carlo simulation draws trials in the specific order given by the SLURP, this dependence will be reflected in the simulation model results.

On an Excel spreadsheet, a SIP is naturally represented by a column of cell values, and a SLURP is most easily represented by a two-dimensional table of cell values. As noted above, the data for this table of cell values may be easily drawn from a relational database or multidimensional data warehouse, or it may be created and maintained directly in Excel.

Analytic Solver provides two PSI Distribution functions, **PsiSip()** and **PsiSlurp()**, that make it easy to define distributions using SIPs and SLURPs. PsiSip() takes one argument: a cell range (normally a column) containing the trial values for one uncertain variable. PsiSlurp() takes two arguments: a two-dimensional cell range containing the SLURP data, and a column index (starting from 1) for the uncertain variable whose trials should be returned by the PsiSlurp() function. You'll want to ensure that the number of rows in the first argument range is at least as large as the number of simulation trials to be run.

PsiSip() and PsiSlurp(), like other PSI Distribution functions, can be used directly in simulation models to return sample values from a SIP or SLURP. But they are especially powerful when you name and publish a Certified Distribution based on them. Doing this is as simple as including a **PsiCertify()**

function call as an argument to PsiSip() or PsiSlurp() – as described below in the section "Creating and Using Certified Distributions."

Creating Stochastic Libraries

Of course, a Stochastic Library must first be created before it can be used. In some cases, you may have a data source from which you can draw SLURP data directly. For example, if you are working with demographic data such as age, family size, income, and taxes paid, you might be able to use a representative sample directly as a SLURP. But in many cases, an expert (perhaps like you) will have to select appropriate analytic probability distributions and their parameters, determine whether and how they should be correlated, and then generate the trial data through a Monte Carlo process.

Analytic Solver is a great tool for *creating* Stochastic Libraries, as well as using them. It supports a wide range of analytic distributions, shifting and truncation of distributions, and rank order correlation of different distributions. When you run a simulation, the trial data is generated, and with the PsiData() function, you can easily save the trial data in a column on the spreadsheet – this will create a SIP. Several PsiData() functions in adjacent spreadsheet columns will create a SLURP. To see an example, open the simulation example workbook **Creating aSlurp(Sim).xls** (normally installed into C:\Program Files\Frontline Systems\Analytic Solver Platform\Examples), pictured below.

13				SLURP	#VALUE!					
14				Market Type Distribution	0.4269			Sales Volume	Sales Price	Unit Cost
15				Unit Cost Distribution	6.5022			50,000	$11.00	$6.50
16										
17	Trial	Volume	Sales	Cost				Volume	Sales	Cost
18	1	#N/A	#N/A	#N/A				50,000	$11.00	$5.91
19	2	#N/A	#N/A	#N/A				50,000	$11.00	$6.67
20	3	#N/A	#N/A	#N/A				50,000	$11.00	$6.57
21	4	#N/A	#N/A	#N/A				100,000	$8.00	$7.04
22	5	#N/A	#N/A	#N/A				100,000	$8.00	$6.75
23	6	#N/A	#N/A	#N/A				50,000	$11.00	$6.86
24	7	#N/A	#N/A	#N/A				50,000	$11.00	$6.83
25	8	#N/A	#N/A	#N/A				50,000	$11.00	$6.01
26	9	#N/A	#N/A	#N/A				100,000	$8.00	$5.85
27	10	#N/A	#N/A	#N/A				100,000	$8.00	$6.37
28	11	#N/A	#N/A	#N/A				100,000	$8.00	$6.08
29	12	#N/A	#N/A	#N/A				50,000	$11.00	$6.86
30	13	#N/A	#N/A	**#N/A**				100,000	$8.00	$6.25
31	14	#N/A	#N/A	#N/A				100,000	$8.00	$6.50
32	15	#N/A	#N/A	#N/A				100,000	$8.00	$6.14
33	16	#N/A	#N/A	#N/A				100,000	$8.00	$5.78
34	17	#N/A	#N/A	#N/A				50,000	$11.00	$6.33
35	18	#N/A	#N/A	#N/A				50,000	$11.00	$6.64
36	19	#N/A	#N/A	#N/A				100,000	$8.00	$6.34
37	20	#N/A	#N/A	#N/A				100,000	$8.00	$6.57
38	21	#N/A	#N/A	#N/A				100,000	$8.00	$7.05
39	22	#N/A	#N/A	#N/A				100,000	$8.00	$6.32
40	23	#N/A	#N/A	#N/A				50,000	$11.00	$6.77
41	24	#N/A	#N/A	#N/A				50,000	$11.00	$6.37
42	25	#N/A	#N/A	#N/A				100,000	$8.00	$5.68

In this workbook, we generate SLURP data for the BusinessPlanPsi.xls model (also included as an example workbook). This model has three uncertain variables: Sales in units, Price per unit, and Unit cost. In cells E14 and E15 we have **PsiUniform()** and **PsiTriangular()** functions, and in cells H15, I15 and J15 we generate trial data as we did in the BusinessPlanPsi.xls model. For example, H15 contains the formula **=IF(E14>0.5,100000,50000)**.

In the cell range B18:B1017, we've array-entered the formula {=PsiData(H15)}. This will cause 1,000 trial values for H15 – a SIP for Sales in units – to be inserted in this cell range, each time a simulation is performed. Similarly, C18:C1017 contains {=PsiData(I15)}, and D18:D1017 contains {=PsiData(J15)}.

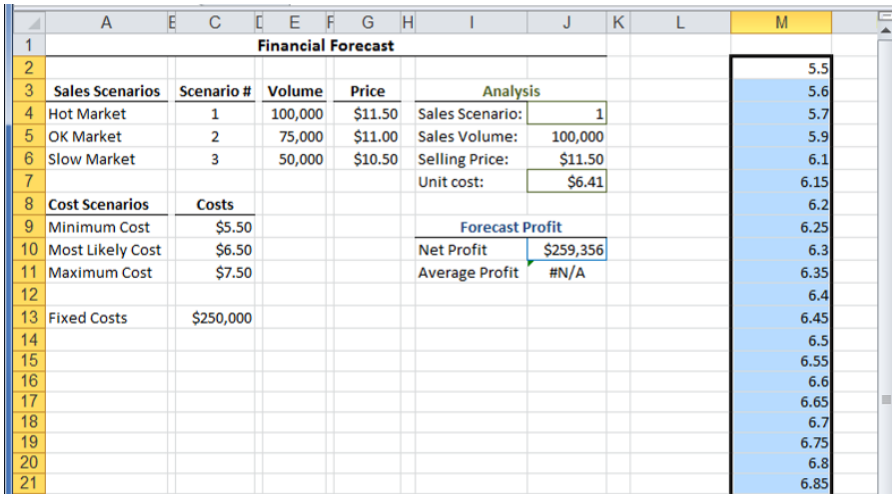
To create and save the SLURP, simply run a simulation, by pressing the Simulate button on the Analytic Solver ribbon. The SLURP data will appear starting at cells B18, C18 and D18. Also note that cell range B18:B1017 has the defined name 'Sales', B18:B1017 is named 'Price', and C18:C1017 is named 'UnitCost'. BusinessPlanSLURP.xls should then be saved. We've generated 1,000 trials for each uncertain variable, enough to match the number of trials in our simulation.

Then select cells B18:D1017, press CTRL + C to copy, then select cell H18 and press CTRL + V to paste the contents of cells B18:D1017 to the cell range H18:J1017.

Using the DIST Feature

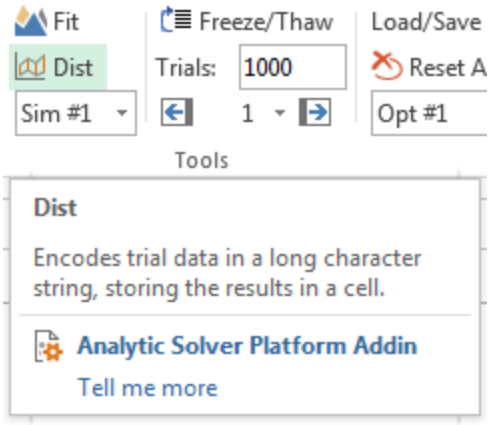
Another way to use historical data is to use the DIST feature. This tool allows you to encode your specific historical data as a distribution and then use the PsiSip function to sample that data during the simulation trials.

1. Select your data just as you did for the Fit process above.

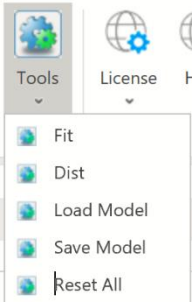


	A	C	E	G	I	J	M
1	Financial Forecast						
2							5.5
3	Sales Scenarios	Scenario #	Volume	Price	Analysis		5.6
4	Hot Market	1	100,000	$11.50	Sales Scenario:	1	5.7
5	OK Market	2	75,000	$11.00	Sales Volume:	100,000	5.9
6	Slow Market	3	50,000	$10.50	Selling Price:	$11.50	6.1
7					Unit cost:	$6.41	6.15
8	Cost Scenarios	Costs					6.2
9	Minimum Cost	$5.50			Forecast Profit		6.25
10	Most Likely Cost	$6.50			Net Profit	$259,356	6.3
11	Maximum Cost	$7.50			Average Profit	#N/A	6.35
12							6.4
13	Fixed Costs	$250,000					6.45
14							6.5
15							6.55
16							6.6
17							6.65
18							6.7
19							6.75
20							6.8
21							6.85

2. Click on the Dist button on the Analytic Solver Desktop ribbon.

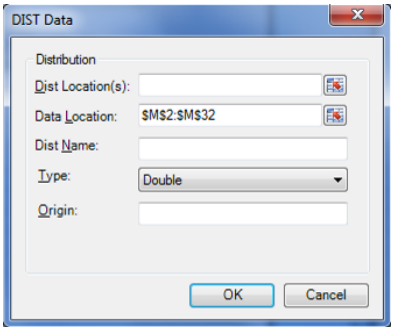


Or select Dist from the Analytic Solver Cloud Tools menu.



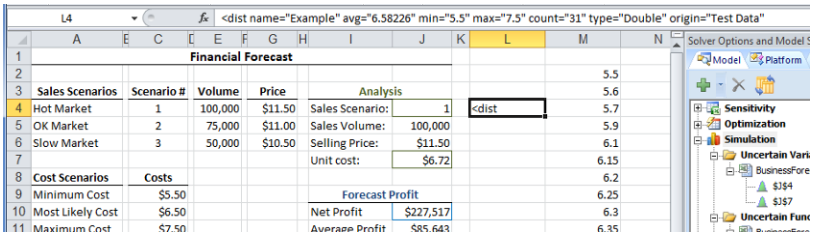
3. You will see a "Generate DIST from Data" Dialog. Click "OK".

4. The next dialog will allow you to choose where to place the DIST after it is generated as well as add information to it such as a name, comments on where the data came from, as well as the type of encoding.



Tip" The default encoding choice is "Double". If you have 0-10,000 data points you can use this setting. If you have 10,001 to 20,000 data points you should use "Single". If you have more than 20,000 data points you should use the Fit feature.

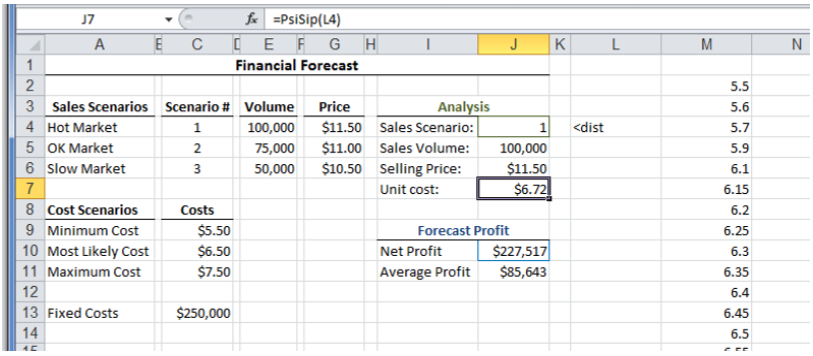
5. You can see the results after you hit "OK" below.



Note: In this case we chose cell L4 to place the data. You will see the DIST in the formula bar (only part of the DIST is visible above). The more data points you have the longer the DIST string will be.

Tip: The DIST you've created can now be copied and used in any spreadsheet. The data that created it no longer needs to be kept for it to work.

6. Use the PsiSip function to add the DIST to your model.



To use this DIST we enter "=PsiSip(L4)" in cell J7. Now our simulation model will use the DIST we just created.

Tip: When you run a simulation using a DIST you won't see the value in the cell containing it change as it will always show the first data point in your distribution and is working correctly.

Creating and Using Certified Distributions

As described above, Analytic Solver supports the use of both analytic distributions and Stochastic Libraries as Certified Distributions. It provides a property function **PsiCertify()** that you can use to name and certify a distribution as ready for publication. It also provides a distribution function **PsiCertified()** that end user modelers can use to access the Certified Distribution via its name.

Certified Distributions may be defined in an Excel workbook different from the end user modeler's workbook. This may be a **standard workbook** or an Excel **add-in workbook**; the latter provides certain advantages, since it is normally hidden from display and may be loaded automatically when Excel starts up.

***Note*:** The workbook that defines Certified Distributions must be a 'complete model' on its own: It must **define at least one output** by using a PSI Statistics function (PsiMean(), PsiOutput(), etc.) in a formula.

Publishing Distributions with PsiCertify

To name and certify an analytic distribution, you simply include the PsiCertify() property function in the formula that defines the distribution. For example:

=PsiNormal(0.1, 1, PsiTruncate(-2,2), PsiSeed(3), PsiCertify("MyDist",0.1))

will define a Certified Distribution named "MyDist" based on a Normal distribution with mean 0.1 and standard deviation 1, truncated so that its samples lie in the interval -2 to 2, and generated using a random number seed of 3 (this overrides any random seed specified in the end user's model). To use this distribution, the end user modeler enters **=PsiCertified("MyDist")** in his or her own workbook. When no simulation has been performed, the cell containing the PsiCertified() call will display the default value 0.1.

To name and certify a distribution based on trial data in a Stochastic Library, you also use the PsiCertify() property function in the formula defining the distribution. For example:

=PsiSip(A1:A1000, PsiCertify("MyDist",100))

will define a Certified Distribution named "MyDist" whose trials are drawn sequentially from the range A1:A1000, with default value 100 to be displayed when no simulation has been performed.

When (as is often the case) the SIPs for several different uncertain variables are generated as a group, in a manner that preserves the statistical dependence between them, they should be combined into a SLURP, i.e. a table of trial values where each column represents an uncertain variable, and each row represents a Monte Carlo trial. Analytic Solver allows you to place a character string name for each column (uncertain variable) in the first row of the SLURP data. You can then name and certify the entire SLURP, for example:

=PsiSlurp(A10:C1010, PsiCertify("MyPlan"))

where range A10:C10 contains labels such as "Sales", "Price" and "UnitCost", and A11:C1010 contains the SLURP trial data.

Now the end user modeler can write **=PsiCertified("MyPlan", "Sales")** to define an uncertain variable in a model whose samples will be sales figures.

The PsiCertify() function allows you to define more properties of the Certified Distribution than just its name. It is good practice to document the name, description, author, history of creation, and other relevant information about a Certified Distribution using PsiCertify(). The full set of arguments is:

=PsiCertify(***name, default value, short description, full description, version, author, copyright, trademark, history*****)**

Using Distributions with PsiCertified

To use a Certified Distribution, the end user modeler simply enters:

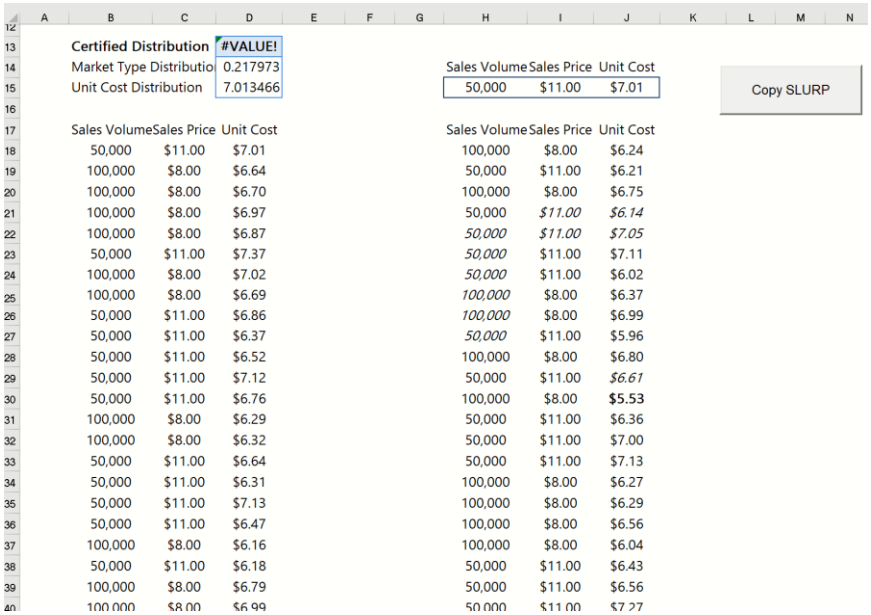
=PsiCertified(*name*) or **=PsiCertified(*slurp,sip*)**

in his or her own workbook, where *name* or *slurp* and *sip* are quoted strings. The user needs no knowledge of the form or parameters of the distribution, or of the name or folder path of the workbook that defines the distribution.

Analytic Solver scans the open workbooks (including regular workbooks and add-in workbooks) for distributions that include the **PsiCertify()** function, and adds the names found in PsiCertify() calls to the Certified dropdown gallery.

Certified Distributions may also be used with Risk Solver Engine, when the Analytic Solver GUI is not available. The PSI Interpreter matches calls to **=PsiCertified()** to the known Certified Distributions. If a named distribution is not found, the PsiCertified() call will return the error value #NAME?

To see an example of publishing and using Certified Distributions, open the simulation example workbook **BusinessForecastingCertified(Sim).xls** (normally installed into C:\Program Files\Frontline Systems\Analytic Solver Platform\Examples), shown on the next page. This example uses a regular workbook, rather than an add-in. Look for "Creating and Using a Certified Distribution" in the Cloud app. Click the **Certified Distributions** tab.



Certified Distribution	#VALUE!		
Market Type Distributio	0.217973		
Unit Cost Distribution	7.013466		

Sales Volume	Sales Price	Unit Cost
50,000	$11.00	$7.01

Copy SLURP

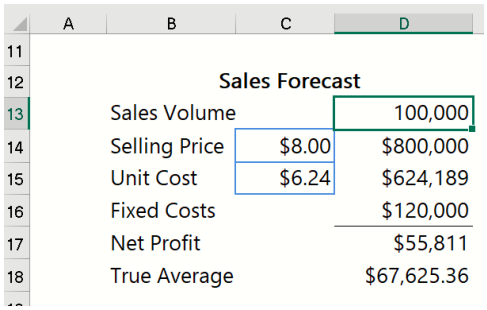
Sales Volume	Sales Price	Unit Cost
50,000	$11.00	$7.01
100,000	$8.00	$6.64
100,000	$8.00	$6.70
100,000	$8.00	$6.97
100,000	$8.00	$6.87
50,000	$11.00	$7.37
100,000	$8.00	$7.02
100,000	$8.00	$6.69
50,000	$11.00	$6.86
50,000	$11.00	$6.37
50,000	$11.00	$6.52
50,000	$11.00	$7.12
50,000	$11.00	$6.76
100,000	$8.00	$6.29
100,000	$8.00	$6.32
50,000	$11.00	$6.64
50,000	$11.00	$6.31
50,000	$11.00	$7.13
50,000	$11.00	$6.47
100,000	$8.00	$6.16
50,000	$11.00	$6.18
100,000	$8.00	$6.79
100,000	$8.00	$6.99

Sales Volume	Sales Price	Unit Cost
100,000	$8.00	$6.24
50,000	$11.00	$6.21
100,000	$8.00	$6.75
50,000	*$11.00*	*$6.14*
50,000	*$11.00*	*$7.05*
50,000	$11.00	$7.11
50,000	$11.00	$6.02
100,000	$8.00	$6.37
100,000	$8.00	$6.99
50,000	$11.00	$5.96
100,000	$8.00	$6.80
50,000	$11.00	*$6.61*
100,000	$8.00	**$5.53**
50,000	$11.00	$6.36
50,000	$11.00	$7.00
50,000	$11.00	$7.13
100,000	$8.00	$6.27
100,000	$8.00	$6.29
100,000	$8.00	$6.56
100,000	$8.00	$6.04
50,000	$11.00	$6.43
50,000	$11.00	$6.56
50,000	$11.00	$7.27

This worksheet contains the function call =PsiSlurp(H17:J1017,PsiCertify("ForecastDist")) in cell D13. This cell (D13) displays #VALUE! since there are labels rather than numbers in the first row of the SLURP range, but this doesn't affect use of the Certified Distribution.

To use the certified distribution, simply insert a function call =PsiCertified("ForecastDist") into the currently selected cell. That's all there is to it.

To see how this set of Certified Distributions can be used, click the Forecast using Certified Dist tab, shown on the next page.



	A	B	C	D
11				
12		Sales Forecast		
13		Sales Volume		100,000
14		Selling Price	$8.00	$800,000
15		Unit Cost	$6.24	$624,189
16		Fixed Costs		$120,000
17		Net Profit		$55,811
18		True Average		$67,625.36

This model uses **=PsiCertified ("ForecastDist", "Sales Volume")** in cell D13, **=PsiCertified ("ForecastDist", "Sales Price")** in C14, and **=PsiCertified ("ForecastDist", "Unit Cost")** in C15. It no longer requires an Excel 'external reference' to a specific folder path, workbook filename, or cell range. In fact, there might not *exist* a single cell range containing fixed trial data – the trials might be loaded from an external database, or generated dynamically from one or more analytic distributions – as illustrated below.

Packaging Analytic Distributions

As described above, you can use PsiCertify() to name and publish an analytic distribution, with a specific form and parameters and a pre-specified random number seed, as a Certified Distribution. Further, you can "package" several analytic distributions that are correlated through a rank correlation matrix in the form of Certified Distributions. You can place these definitions in a standard workbook, or in an add-in workbook that is automatically loaded when Excel starts, hiding a good deal of complexity from end users who simply need to use these Certified Distributions.

Mastering Stochastic Optimization Concepts

Introduction

Analytic Solver offers you one unified framework for modeling and solving optimization problems, with or without uncertainty. Models may include 'normal' decision variables, constraints and an objective, plus uncertainties, recourse decision variables, chance constraints, and recourse constraints. This chapter seeks to explain this framework, starting from the basics of Solver models. It assumes only a limited knowledge of optimization – but if you've first read the chapter "Mastering Conventional Optimization Concepts," you'll gain a much deeper understanding from reading this chapter.

Our goal is to find a ***solution*** – values for the ***decision variables*** in our model – that satisfies the ***constraints*** and that maximizes or minimizes the ***objective***. In computing the objective and constraints, we use ***parameters*** of the model – for example quantities, distances, shipping costs, interest rates, etc.

Certain and Uncertain Parameters

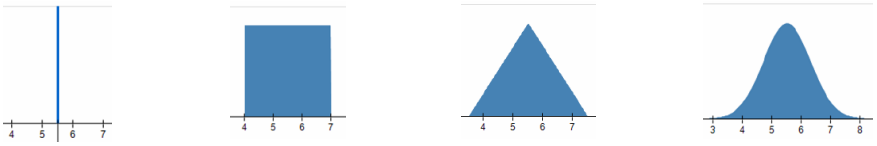
In conventional optimization, all the parameters are *assumed* to be numbers known with certainty. If estimation of a parameter involves uncertainty or noise, an average or other 'nominal' value is used. This is a simplification and *idealization* of the real world situation: In almost all business and engineering problems, there is at least some uncertainty in the values of the parameters.

In some models, the uncertainty or variation in the parameters may be small enough to be ignored. But in many models, it is large enough to be of concern. And in some models, the uncertainty is so large that it is a major feature of the problem, and much effort is (or should be) invested in modeling the uncertainty.

In the discussion to follow, by **uncertain parameter** we mean a parameter of your optimization model, such as an objective coefficient or constraint right hand side, that is subject to uncertainty. Such parameters might be *computed* from a "primitive uncertainty," such as a future interest rate or rainfall amount; we will call this an **uncertain variable**, and in Analytic Solver, we'll use the Uncertain Variable dialog to define and quantify this primitive uncertainty.

Realizations of Uncertain Parameters

Where a *certain* parameter has a *single*, known value, we can think of an *uncertain* parameter as having *many possible values.* We call each such value a *realization* of the uncertainty. Below, we've pictured one certain and three uncertain parameters.



An uncertain parameter might have an infinite number of possible realizations, but – as discussed near the end of this chapter – normally we can work with a finite ***sample*** of possible realizations. We just don't know *which one* of the sample values is the 'true' value, or closest to this true value.

Decision-Dependent Uncertainties

In many real-world problems, the uncertainties being modeled are ***independent* of the decision variables**. For example, in a crop planning model where the acres to plant of different crops are decision variables, and the rainfall in a future period is an uncertainty, the uncertainty is almost surely independent of the decisions.

In other real-world problems, the uncertain parameters being modeled are ***dependent* on the decision variables** – they change if the decisions change. For example, in a market response model that includes competitor actions in a future period, where your product prices are decision variables, and your competitors' product prices are uncertainties, it is quite likely that the uncertainties will depend on the decisions.

In portfolio models where one is investing in publicly traded, large capitalization stocks, a decision to purchase some number of shares is unlikely to affect the uncertain future returns on those stocks. On the other hand, a large institution investing in thinly traded small-capitalization stocks may find that decisions to purchase a large number of shares may move the market price and impact the uncertain future returns. So both types of problems arise in practice. As we'll see later, the presence of ***decision-dependent uncertainties*** has a **huge impact** on how, and even whether, our model can be solved.

Resolving Uncertainty and Recourse Decisions

In some real-world problems, we are uncertain about the value of a parameter today, and **we will remain uncertain about its value in the future**; we have to make decisions in the presence of this uncertainty. This often arises in engineering design models, where there is uncertainty about the exact strength of a steel girder or the exact resistance or capacitance of an electronic component. The uncertainty may be *irreducible* – perhaps inherent in nature – or it may be *reducible* through better data collection, measurement or calibration – but these steps may be impractical for us.

In other real-world problems, we are uncertain about the value of a parameter today, but **we will know its value with certainty at some point in the future**. This often arises in marketing and finance models, where a competitor's price or next year's commodity prices or interest rates are uncertain today, but will become known at some future date. We say that the uncertainty will be ***resolved*** at the future date; its *many possible values* will be reduced to a *single* value, and the uncertain parameter will become certain.

If we are dealing with uncertainty that will not be resolved, we must find values of the decision variables that yield feasible (or *nearly* feasible) solutions for many possible realizations of the uncertainty. On the other hand, if we are dealing with uncertainty that *will* be resolved at a future date, we can ask what decisions we must make 'here and now,' *before* the uncertainty becomes known, and what decisions we can make on a 'wait and see' basis, *after* the uncertainty is known. This leads to the concept of ***recourse decisions***, described below – and it has a **huge impact** on how our model should be formulated and solved.

Uncertainty and Conventional Optimization

The impact of uncertainty is *magnified* by conventional optimization. By its nature, optimization drives the decision variables to values that *just satisfy* certain constraints, while maximizing or minimizing the objective function. In doing so, optimization exploits any 'noise' or error, as well as the 'true value,' captured in the fixed numbers used in the model for uncertain parameters.

This effect is very evident in investment portfolio optimization, where the parameters of the model are estimated returns, variances, and covariances between securities. Practitioners often describe portfolio allocations from an optimizer as "unrealistic," and such allocations often do not perform well in practice. When the actual security returns, variances and covariances in future periods vary from the parameters used in the optimization, even by small amounts, the 'optimized' portfolio return often suffers by large amounts.

As shown by Ben-Tal and Nemirovski in a 2000 study of the NETLIB linear programming problems, "In real-world applications of linear programming, one cannot ignore the possibility that a small uncertainty in the data can make the usual optimal solution completely meaningless from practical viewpoint." Summarizing the effects of conventional investment portfolio optimization, Michaud wrote in a 1998 book "The result is that optimized portfolios are 'error maximized' and often have little, if any, investment value." ***Conventional optimization is not enough!***

Elements of Solver Models

We'll now describe all the elements of a Solver model with uncertainty. Again our goal is to find a ***solution*** – values for the ***decision variables*** in our model – that satisfies the ***constraints*** and that maximizes or minimizes the ***objective***. In computing the objective and constraints, we may use many ***parameters*** – some of which are computed from primitive ***uncertain variables***. In Excel, the decision variables and parameters are represented by worksheet cells; the objective and constraints are computed by formulas in other worksheet cells.

Uncertain Variables

A *certain* parameter is easy to model, in a worksheet cell containing a number. A primitive uncertainty requires a way to specify the range and 'shape' of the values it can assume. In Analytic Solver, we model primitive uncertainties as **uncertain variables** in worksheet cells that contain special add-in functions. For example:

=PsiUniform(0,1) – a uniform distribution ranging from 0 to 1

=PsiNormal(2,1.5) – a Normal distribution with mean 2, standard deviation 1.5

=PsiBeta(A1,B1) – a Beta distribution with shape parameters A1 and B1

=PsiSip(A1:A1000) – a 'Stochastic Information Packet' containing a range of user-supplied sample values, or realizations, for this uncertainty

Any of the 40-odd PSI Distribution functions that you can use for Monte Carlo simulation may also be used as uncertain variables for stochastic optimization.

You can think of the cell for an uncertain variable, containing a formula such as =PsiUniform(0,1), as holding an *array* of sample values, each one selected at random from the range 0 to 1 inclusive. Each value is one possible *realization*

of the uncertainty. Analytic Solver can generate such an array of sample values automatically, using Monte Carlo simulation 'behind the scenes'.

Looking ahead to the section "Functions of the Variables and Uncertainties," note that any formula cell that *depends* on an uncertain variable cell must also compute an *array* of sample values. Each value corresponds to one possible *realization* of all the uncertain variables on which the formula depends.

In the example **PsiBeta(A1,B1)**, it is important to know whether A1 or B1 is dependent on the decision variables. A model that includes such a ***decision-dependent uncertainty*** is *much* harder to solve, and will require the methods of simulation optimization. Analytic Solver can automatically diagnose your model and determine whether any uncertain variables depend – possibly through a chain of formula cells – on the decision variables.

Decision Variables

Conventional optimization deals with only one type of decision variable, which represents a decision that must be made 'here and now,' irrespective of any uncertainty in the model. We call this a normal or first-stage variable.

If we are dealing with uncertainty that will be resolved in the future, then at some point the *array* of sample values for the uncertainty is effectively replaced by a *single* value, the *realization* of the uncertainty as it actually occurs.

If the situation we are modeling allows us to make certain decisions *after* the uncertainty becomes known, on a 'wait and see' basis, we can model these decisions with recourse variables, also called second-stage variables. (At the 'second stage,' the uncertainty has become known.)

Normal or First-Stage Variables

A **normal variable** for a 'here and now' decision is represented by a worksheet cell – say A1 – containing a number; the Solver will replace this number with an optimal value, when the problem is solved. (The term 'normal' here is unrelated to a Normal distribution, which is one way to define an uncertain variable.)

Recourse or Second-Stage Variables

A **recourse variable** for a 'wait and see' decision is also represented by a worksheet cell – say A2 – containing a number. But at the time the optimization is performed, a single recourse variable effectively represents an *array* of solution values, one for each *realization* of the uncertainties in the model.

Functions of the Variables and Uncertainties

Any formula that participates (in the objective and constraints, see below) in your model will normally depend on the decision variables and the parameters.

As a simple example, the objective of the Product Mix model EXAMPLE1in the **Examples.xls** workbook, is SUMPRODUCT(D17:F17,D9:F9) which can also be written as D17*D9 + E17*E9 + F17*F9. Here, D17:F17 are parameters (the selling prices of the three products), and D9:F9 are decision variables (the amounts of each product to build). In this model, the parameters are assumed to be *certain.*

An objective or constraint might be computed, from the parameters and the decision variables, through a chain of several formula cells. For example, in the Gas Company Chance and Recourse models in **StochasticExamples.xls**,

illustrated in the chapter "Examples: Stochastic Optimization," the constraint at cell C23 is D15+D18-C8 >= 0, where D15 and D18 are decision variables (amounts of gas to purchase), C8 = 100+80*D5 (estimated demand next year), and D5 is an uncertain variable in the model.

Model Uncertainty and Optimization Methods

Recall that an uncertain variable effectively holds an *array* of sample values. For example, D5 =PsiUniform(0,1) represents an array of *realizations* of the uncertainty, each one selected at random from the range 0 to 1. If your objective or constraint (say C8 = 100+80*D5) depends on D5, it must also compute an *array* of sample values. Each value corresponds to one possible *realization* of all the uncertainties on which the formula depends.

Traditional Solver Engines cannot handle an objective or constraints that depend on uncertainty, and hence represent an array of sample values. To solve a problem with such an objective and constraints, we must choose one of three possible approaches:

1. Use the 'Stochastic Decomposition Engine' that *can* handle constraints that depend on uncertainty. *Note: This engine is not supported in Analytic Solver Cloud.*
2. *Transform* a model whose objective and/or constraints depend on uncertainty into a 'deterministic equivalent' or 'robust counterpart' model that may be much larger, but whose objective and constraints no longer depend on uncertainty. Then we can solve the transformed model using a traditional Solver Engine, and translate the results into a solution for the original model. To be transformed successfully, the original model must have only uncertainties that are *independent* of the decisions, and have an objective and constraints that are *linear* (or certain other) functions of the decision variables.
3. Ensure that all 'top-level' formula cells computing the objective and constraints represent only *single* values – statistical summaries of the arrays of sample values. We can do this manually, with formulas in top-level cells that call PSI Statistics functions such as PsiMean(), PsiVariance() or PsiPercentile() – or Analytic Solver can do this automatically and implicitly, when we define our objective and constraints as described in the next two sections. This choice is flexible, but it requires that we use simulation optimization – the most general, but also the slowest and least scalable optimization method.

In all these approaches, we must specify what it *means* to maximize or minimize an objective, or to satisfy a constraint that depends on uncertainty – implicitly or explicitly reducing an array of sample values to a single value. The next two sections explain how we can do this.

The Objective Function

The quantity you want to maximize or minimize is called the *objective function.* In Excel, the objective is calculated by a formula cell – say A1 – listed in the Task Pane Model tab or the Solver Parameters dialog, in the outline list box under **Objective**. This could be a calculated value for projected profits (to be maximized), or costs, risk, or error values (to be minimized).

If the objective function depends on uncertainties, we must specify how we want to 'optimize' this function. The most common practice is to maximize or minimize the *expected value* (informally, the mean value) of the objective, over

all realizations of the uncertainties. In Analytic Solver, you do this by selecting the objective in the Task Pane Model tab, and in the lower Properties area, selecting **Expected** from the Type dropdown list in the Stochastic group.

Instead of maximizing or minimizing the *expected value* of a function of the decision variables and uncertainties, you can maximize or minimize a *measure of the uncertainty* in a function. Analytic Solver converts the objective to the form max *t* or min *t*, where *t* is a new variable, and the model includes a *chance constraint* A1 >= *t* or A1 <= *t* with the measure of uncertainty that you specify.

Implicit and Explicit Forms for the Objective

When you select Expected from the Type dropdown list in the Stochastic group, Analytic Solver treats the objective cell as implicitly containing **E**[*objective*], or using sample realizations of the uncertainty PsiMean(*objective*). To make this *explicit* on the worksheet, you can direct Analytic Solver to automatically create a **PsiObj()** function call with an "Expected" argument – using either the "Use Psi Functions to Define Model" option, or the Save Model button. You can also manually enter a **PsiMean()** function call in the objective cell. Similar options apply to the constraints, as discussed below.

Constraints: Normal, Chance, Recourse

Constraints are relations such as $f(x_1, x_2 \ldots, x_n) <= b$, where $x_1, x_2 \ldots, x_n$ are decision variables. In Excel, each x_i corresponds to a cell, $f(x_1, x_2 \ldots, x_n)$ is computed by a formula in another cell (say A1), the constant *b* is in another cell (say B1), and we enter **A1 <= B1** via the Ribbon or Task Pane. A constraint is *satisfied* when the relation it specifies is true within a small tolerance.

When your model includes uncertainty, we must examine how each constraint depends on the uncertainties and the decision variables:

- If a constraint depends only on *certain* parameters and *normal* decision variables, it is 'deterministic' and is handled in the usual way by the Solver. We call this a ***normal* constraint**.
- If a constraint depends on *uncertain variable*s and *normal* decision variables, we must specify what it *means* for the constraint to be satisfied. There are many possible *realizations* for the uncertain variables, but only single values for the decision variables. The Solver must find values for the decision variables that cause the constraint to be satisfied for *all*, or perhaps *most* but not all, realizations of the uncertainties. We call this a ***chance* constraint**. For example, we might specify that the constraint must be satisfied 95% or 99% of the time; it can be violated 5% or 1% of the time. For 95%, we denote such a constraint as **VaR $_{0.95}$ A1 <= B1**. But this form may not be your best choice – alternatives called CVaR and USet are discussed in the section "More on Chance Constraints."
- If a constraint depends on *uncertain variable*s and *recourse* decision variables, then the Solver will find an *array* of values for each of the recourse variables, corresponding to the *realizations* of the uncertain variables. Recourse decisions give the Solver flexibility to satisfy constraints that involve uncertainty; but in effect, each such constraint has many *realizations* – one for each realization of the uncertainties. We call this a ***recourse* constraint**.
- A constraint may also depend on *recourse* decision variables, and possibly normal decision variables, but not depend on any uncertain variables. This is also a ***recourse* constraint**, with many *realizations*. The Solver must find

values for the recourse variables that satisfy all the constraints where they appear – some with uncertainties, and some without.

Implicit and Explicit Forms for Constraints

When you select VaR from the dropdown list in the Constraint dialog and enter a Chance of 0.95, Analytic Solver treats the constraint cell as implicitly containing **VaR** $_{0.95}$ [*constraint*], or using sample realizations of the uncertainty PsiPercentile(*constraint*, 0.95) where *constraint* is the left hand side. To make this *explicit* on the worksheet, you can direct Analytic Solver to automatically create a **PsiCon()** function call with a "VaR" argument – using either the "Use Psi Functions to Define Model" option, or the Save Model button. You can also manually enter a **PsiPercentile()** function in the constraint left hand side cell. For more information on the PsiObj() and PsiCon() functions, see the chapter "Psi Function Reference" within Frontline Solvers Reference Guide.

Multiple Uncertainties May Offset Each Other

What happens when a constraint depends on *several* different uncertainties? Is such a constraint harder or easier to satisfy than a constraint that depends on just one uncertainty?

In the simplest case, suppose we have a *linear* constraint, with coefficients a_i and decision variables x_i:

$a_1x_1 + a_2x_2 + ... + a_nx_n \leq b$

Suppose that each coefficient a_i is uncertain (and independent of all the others), with sample values drawn randomly from PsiUniform ($a_i - 0.5$, $a_i + 0.5$).

The average or *nominal* value of each coefficient is a_i. The 'worst' that can happen is that a sample is drawn where *every* coefficient is $a_i + 0.5$ – this makes the left hand side (LHS) as large as possible, so it is very likely to violate the condition LHS $\leq b$. *But this case is very unlikely to occur*.

In *most* realizations of the uncertainties, some coefficients (randomly drawn from the range $a_i - 0.5$ to $a_i + 0.5$) will be less than a_i, and some will be greater than a_i. The more uncertainties are involved, the greater the chance that some of them will draw samples less than a_i.

If we use a *chance constraint* to specify that the relation must be satisfied (say) 95% or 99% of the time, we actually have a *better* chance of satisfying this constraint when it depends on *many* uncertainties than when it depends on just one – as long as the uncertainties are independent, or at least not highly correlated with each other.

Solutions: Feasible, Optimal, Well-Hedged

A solution (set of values for the normal and recourse variables) for which all of the constraints in the Solver model are satisfied is called a *feasible solution.* For constraints that depend on uncertainties, this means that chance and recourse constraints meet their criteria for satisfaction over all the *realizations* of the uncertainties considered in the optimization.

An *optimal solution* is a feasible solution where the objective function reaches its maximum (or minimum) value – for example, the most profit or the least cost. When the objective function depends on uncertainties, this normally means that the *expected value* of the objective reaches a maximum (minimum) – but you can also use max *t* or min *t* with a chance constraint A1 >= *t* or A1 <= *t*, as described earlier.

The optimal solution to a problem with uncertainty (the 'stochastic solution') will never have an objective value that is better than one could obtain 'with 20/20 hindsight,' by solving a conventional optimization problem where the uncertainties are known. The difference between the objective value obtained 'in hindsight' and the optimal value obtained 'in foresight' is called the *expected value of perfect information* (EVPI).

The stochastic solution will often be (quite) different from the optimal solution to a problem where all uncertain variables are replaced with their nominal or average values. The latter optimization will exploit the 'point values' of the parameters, with no consideration for their variability; this will often yield a better objective value for the nominal problem, but the solution may not be feasible, let alone optimal, for many different realizations of the uncertain variables. Compared to the 'nominal' solution, the stochastic solution is more robust or 'well-hedged' against possible variations in the uncertain variables.

Solving for Recourse Variables

If we are dealing with uncertainty that *will* be resolved in the future, then at that future date, each uncertain variable will be replaced by a single value, the *realization* of the uncertainty that actually occurs. In Analytic Solver, you can enter these single values for uncertain variables in the Lock value field in the Uncertain Variable dialog, then choose to *solve for* single values of the *recourse* variables, given known single values for both the normal variables (determined by an earlier optimization) and for the uncertainties.

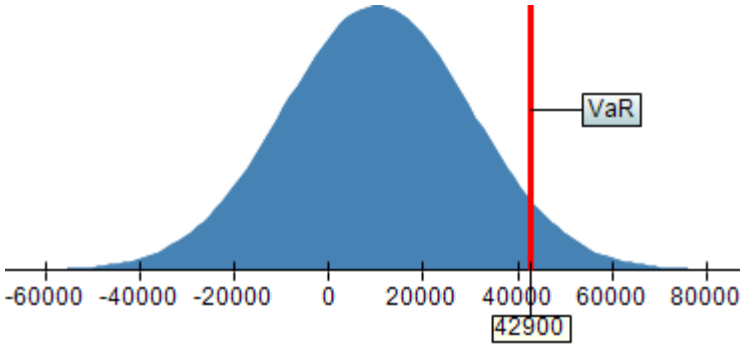
When Analytic Solver solves a problem by transforming the model, using the Deterministic Equivalent or the Robust Counterpart transformation, it computes an *array* of values for the recourse variables, one for each *realization* of the uncertainties considered during the optimization. Using the left and right Trial # arrows on the Ribbon, you can display on the worksheet the different sample values of the uncertain variable cells, and the corresponding values of the recourse variable cells – the 'wait and see' decisions in many possible scenarios. Now, the *actual* values of the uncertainties, once they become known, might be different from any one of these scenarios – so it is still useful to solve for single values of the recourse variables as described above.

More on Chance Constraints

As explained above, if a constraint depends on *uncertain variable*s and *normal* decision variables, we can seek solution values for the variables that cause the constraints to be satisfied for *all*, or perhaps *most* but not all, realizations of the uncertainties. If we insist that the constraints are satisfied for *all* realizations, we may not be able to *find* values for the decision variables that meet this requirement – and if we do, we will very likely 'pay for this' via worse values for the objective function.

Instead, we can seek solution values for the variables that cause the constraints to be satisfied for *most*, but not necessarily all, realizations of the uncertainties. We might specify that the constraint must be satisfied (it must not exceed a given limit) 95% or 99% of the time; it can be violated 5% or 1% of the time.

This is depicted in the chart below, where 95% of the area under the curve is to the left of the bar (i.e. the constraint right hand side value), and 5% is to its right.



This is one form of a *chance constraint*; the criterion that it must be satisfied for all realizations of the uncertainties up to a given percentile (say 95%) makes it a *VaR* (Value at Risk) constraint. We write this constraint as **VaR $_{0.95}$ A1 <= B1**. Analytic Solver supports two other criteria besides *VaR* that may be better choices for many models.

A chance constraint includes:

- A *left hand side* that depends on decision variables and uncertainties.
- A *relation* that must be either <= or >=. (A *chance* constraint can't be an equality. Note however that a *recourse* constraint *can* be an equality.)
- A *right hand side* that should be constant in the problem (if the RHS depends on decision variables or uncertainties, Analytic Solver converts LHS <= RHS into the form LHS – RHS <= 0).
- A *criterion* that may be VaR (Value at Risk), CVaR (Conditional Value at Risk), or USet (Uncertainty Set). These criteria are discussed below.
- A *measure* that may be a percentile 0.01 – 0.99 for VaR or CVaR, or a 'budget of uncertainty' (any positive value) for USet.

Value at Risk Measure

Chance constraints defined by a percentile or VaR (Value at Risk) measure have been used since the early 1960s. Such constraints offer a good deal of modeling flexibility, and they are easy to understand in terms of the probability that the constraint will be satisfied. Value at Risk is used in the banking and securities industries, and its use is mandated by the international Basel II accords. But chance constraints in this form have several drawbacks:

- A VaR constraint with probability 95% requires only that the constraint be satisfied – not violated – 95% of the time; it **says nothing about the magnitude of the violation** that may occur the other 5% of the time. For example, a portfolio of securities that is VaR-constrained to lose no more than $100,000 95% of the time could still lose $1 million+ at other times.
- As a measure of risk, the VaR criterion is **not subadditive**, a property expected of any 'coherent risk measure.' For example, if two portfolios A and B are VaR-constrained to not lose money 95% of the time, it is reasonable to expect that a combined portfolio A+B should have a *95% or better* chance of not losing money – but this is *not* guaranteed by the two portfolio VaR constraints.
- A VaR constraint is **not necessarily convex**; hence, using such a constraint in an otherwise convex model (for example, any linear programming or convex quadratic model) will radically affect its 'solvability' – it means that

a globally optimal solution cannot be guaranteed, and solution time may rise exponentially with model size.

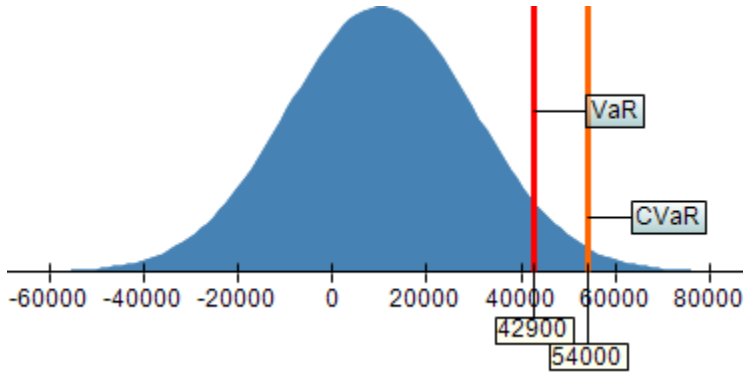
Further, when Analytic Solver uses robust optimization methods to automatically transform a model with VaR constraints into a larger but deterministic 'robust counterpart' model, it first approximates the non-convex VaR constraint with a convex CVaR constraint, and then transforms the CVaR constraint. Since CVaR is always **more conservative** than VaR as a risk measure, the robust counterpart solution will 'pay a price' in conservativeness, with a worse objective value. Users are often better off using CVaR directly.

Note: **VaR** $_{0.95}$ **A1 <= B1** specifies that the 95th percentile of the realizations of A1 must be less than or equal to B1. Since VaR only describes the left side of the graph, not the right or "tail", **VaR** $_{0.95}$ **A1 >= B1** specifies that the *5th* percentile of the realizations of A1 must be less than or equal to B1.

Conditional Value at Risk Measure

To deal with the problems of Value at Risk cited above, an alternative risk measure called *Conditional Value at Risk* or CVaR (also called *Expected Tail Loss* or ETL) was developed in the late 1990s. **VaR** $_{0.95}$ **A1 <= B1** specifies that the 95th percentile of the realizations of A1 must be less than or equal to B1; realizations beyond the 95th percentile may be greater than B1 by any amount. In contrast, **CVaR** $_{0.95}$ **A1 <= B1** specifies that the *expected value* of ***all*** the realizations of A1 up to the 95th percentile must be less than or equal to B1.

Below is a chart that compares VaR and CVaR. VaR is the value (42,900) that lies at the 95th percentile of the realizations of the constraint left hand side; 5% of the realizations are greater than 42,900 and lie in the graph to the right of this point. CVaR (54,000) is the *expected* value (i.e. the mean or average value) of ***all*** the realizations that lie in the 'tail' to the right of the VaR (Note that, if **CVaR** $_{0.05}$ **A1 <= B1** is satisfied for some B1, then **VaR** $_{0.05}$ **A1 <= B1** is also (more than) satisfied.



As a risk measure, Conditional Value at Risk has several advantages over VaR:

- Unlike VaR, a CVaR constraint at 95% places a **bound on the average magnitude of the violations** that may occur 95% of the time.
- CVaR is a 'coherent risk measure.' It is **subadditive**, so if two portfolios A and B are CVaR-constrained to not lose money 95% of the time, then a combined portfolio A+B has the *same or better* chance of not losing money.
- A CVaR constraint is **always convex**. Models consisting of all convex functions can be solved to global optimality, and solved to very large size using modern interior point optimization methods.

Uncertainty Set Measure

Analytic Solver supports a third criterion for uncertainty in a chance constraint, which reflects the approach taken in most of the literature on *robust optimization* methods. This criterion, called *USet* (for uncertainty set), is applicable only to *linear* constraints, with coefficients a_i and variables x_i:

$a_1x_1 + a_2x_2 + ... + a_nx_n \leq b$

where some or all of the coefficients a_i may depend on the uncertainties. It is useful to think of the vector $[a_1\ a_2\ ...\ a_n]$ as having a *nominal* or expected value, and a *variation* from this value for each realization of the uncertainties.

A constraint of the form **USet$_\Omega$ A1 <= B1**, where $a_1x_1 + a_2x_2 + ... + a_nx_n$ is in A1, and *b* is in B1, specifies that A1 <= B1 must be satisfied for ***all*** *variations* from the *nominal* value of $[a_1\ a_2\ ...\ a_n]$ that do not exceed a bound Ω, measured by a norm. The bound Ω is often called the *budget of uncertainty* for the constraint. A very large Ω says that the constraint must be satisfied for practically all variations of the coefficients from nominal; a Ω of 0 effectively ignores uncertainty, requiring only that A1 <= B1 for the nominal value of $[a_1\ a_2\ ...\ a_n]$, and saying nothing about departures from this value.

Analytic Solver allows you to choose among four different norms to measure variation from the nominal value: The L1, L2, L-Infinity and D norms – as described in "Uncertainty Sets and Norms" later in this chapter.

Diagnosing Your Model's Use of Uncertainty

When you create a large model, or modify a large conventional optimization model to include many uncertainties and many constraints, you may or may not realize exactly how the model depends on the uncertainties. Just as you might accidentally use a formula that creates a nonlinear dependence on a decision variable, when you intended to create a linear programming model, you might introduce a dependence on uncertainty in a constraint that you intended to be deterministic. Analytic Solver can *diagnose* the use of uncertainty in your model, comparing it to an 'intended' use of uncertainty that you specify in the Task Pane Platform tab Diagnosis group **Intended Use of Uncertainty** option. After clicking the Analyze button, you can select **Reports – Optimization – Uncertainty** for a report of *exceptions* to your intended use of uncertainty.

Problems and Solution Methods

Previous sections of this chapter have described how you can **create models that involve uncertainty** in Analytic Solver, using certain and uncertain parameters, normal and recourse decision variables, normal and chance constraints, and your objective function. You create your models in the same way, regardless of the model transformation or solution method that will be used to solve the problem.

As outlined in the Introduction chapter, Analytic Solver is designed to find *good* solutions – given enough time – to models involving uncertainty in their **most general form**. But Analytic Solver is also designed to *automatically* recognize common special cases such as stochastic linear programming models, and find proven *optimal* solutions at much *faster* speeds. As with conventional LPs, the modeling assumptions of stochastic LPs are somewhat restrictive, but in a wide range of real-world applications, these assumptions can be satisfied. The great

advantage of a stochastic LP is its potential *scalability* to tens of thousands of variables and constraints or more.

Before we can discuss classes of problems and how they are solved using Analytic Solver, we must explain how two key *concepts* – decision-dependent uncertainties and recourse decisions – affect the use of two key *solution methods* – stochastic programming and simulation optimization.

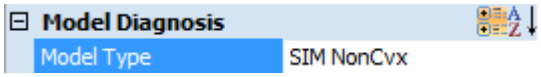
Decision-Dependent Uncertainties

As described in the Introduction section, in many real-world problems, the uncertain variables being modeled are *independent* of the decision variables. In other real-world problems, the uncertainties are *dependent* on the decision variables – they change when the decision variables change.

The methods of ***stochastic programming*** (SP) were created, more than fifty years ago, to deal with problems where the uncertainties are *independent* of the decisions. Much more recently, methods of *robust optimization* (RO) were created, also to deal with problems where uncertainties are *independent* of the decisions. Most methods in the SP and RO literature **cannot be applied** to problems where the uncertainties are dependent on decision variables. But where they can be applied, these methods are scalable to large models, and they generally yield optimal solutions.

The methods of ***simulation optimization*** were created, also more than fifty years ago, to deal with problems where the uncertainties may be *dependent* on the decisions. *This dependence makes the problem much harder to solve*. Where SP and RO methods often are based on linear programming and conic optimization, simulation optimization is usually based on methods such as genetic and evolutionary algorithms, and tabu and scatter search. These methods are more flexible and general – but they require far more solution time, are generally not scalable to large models, and yield only 'improved' solutions, not optimal solutions.

In Microsoft Excel, you can create models where the uncertainties are either independent of, or dependent on the (normal or 'first stage') decision variables. Analytic Solver can detect decision-dependent uncertainties and report this when you choose **Optimize – Analyze Original Problem** or click the Analyze button in the Task Pane:



To solve *SIM NonCvx* (non-convex) problems using simulation optimization, you can use the built-in Evolutionary Solver (based on genetic algorithms) or the plug-in OptQuest Solver (which uses tabu and scatter search). You can also use built-in or plug-in nonlinear Solver Engines, in conjunction with Analytic Solver's *multistart* methods, to solve many such problems.

Resolving Uncertainty and Recourse Decisions

The methods of ***simulation optimization*** were developed to solve problems where the uncertainty will not be resolved over the horizon of interest. Hence, these solution methods find optimal values only for normal or 'here and now' decision variables; virtually all simulation optimization methods in the literature **have no concept of recourse decisions**.

Unfortunately, simulation optimization has often been misapplied to problems where the uncertainty *will* be resolved over the horizon of interest. Users may believe that their simulation optimization model will find the best possible decision in the presence of uncertainty. But this is very unlikely to be true, if it's possible to make certain decisions on a 'wait and see' basis. Recourse decisions create *flexibility* for the optimizer, making it easier to satisfy the constraints and attain a better objective.

The methods of ***stochastic programming*** were developed to solve problems where the uncertainty will be resolved over the horizon of interest. Recourse decisions – the ability to make certain decisions on a 'wait and see' basis – have been extensively studied in the SP literature, and many high-performance solution methods for two-stage SP problems with recourse have been developed.

Classes of Problems Involving Uncertainty

An optimization problem that includes uncertain variables is usually called a *stochastic optimization* or *stochastic programming* problem.

Below, we'll classify such problems based on the following factors:

- How the objective and constraints depend on the decision variables
- Whether the uncertain variables depend on the decision variables
- Whether the problem includes recourse decisions (i.e. whether it is one-stage with only normal variables, or two-stage with recourse variables)
- Whether the problem includes chance constraints

We'll also briefly describe how the three solution methods currently supported by Analytic Solver – robust optimization, stochastic programming, and simulation optimization – can be applied to these problems.

One-Stage Problems

One-Stage Linear Programming Problems

The simplest case is a one-stage stochastic linear programming problem:

- The objective and constraints **depend linearly** on the decision variables.
- The uncertain variables are **independent** of the decision variables.
- The problem includes **no recourse decisions**.
- The problem includes **chance constraints** to deal with the uncertainty.

This kind of problem arises if you start with a conventional, deterministic linear programming model (where all coefficients are certain), you add uncertain variables using functions such as **=PsiUniform(0,1)** or **=PsiNormal(2,1.5)** in cells, and you add formulas to compute the objective or certain constraints based on these cells, so that the LP coefficients are now uncertain.

Since no recourse decisions are available, the Solver must find values for the (normal or first-stage) decision variables that satisfy the constraints (normal and chance constraints) and maximize or minimize the objective.

We could solve this problem with **simulation optimization** methods. But since it is linear, this problem is especially well suited for **robust optimization** methods. With RO methods we can solve *much larger* models, hundreds of

times faster than with simulation optimization. In the Task Pane Platform tab, we set the Optimization Model group option **Solve Uncertain Models** to Stochastic Transformation, and we set the Transformation group option **Stochastic Transformation** to Robust Counterpart. When we click Optimize, the transformed model is created and solved.

One-Stage Quadratic Programming Problems

A slightly more complex case is a one-stage stochastic problem with a quadratic objective and all linear constraints:

- The objective is a **deterministic, convex quadratic** function of the decision variables – it doesn't depend on the uncertainties.
- The uncertain variables are **independent** of the decision variables.
- The problem includes **no recourse decisions**.
- The problem includes **chance constraints** to deal with the uncertainty.

The situation here is basically the same as for one-stage stochastic linear programming problems. We can apply **simulation optimization** methods, but we can also apply more scalable **robust optimization** methods, as long as the objective doesn't depend on the uncertainties.

One-Stage Nonlinear Optimization Problems

The situation changes if we have a one-stage stochastic *nonlinear* problem:

- The objective or the constraints are **general nonlinear**, convex or non-convex functions of the decision variables.
- The uncertain variables may be **dependent** on the decision variables.
- The problem includes **no recourse decisions**.
- The problem includes **chance constraints** to deal with the uncertainty.

We cannot use Analytic Solver's robust optimization methods or stochastic programming methods on problems with general nonlinear, possibly non-convex functions. Our only option is to use **simulation optimization**; this is feasible since the problem does not include any recourse decisions. Given that we are using simulation optimization, we can allow the uncertainties to be dependent on the decisions, although some speed gains are possible if they are not.

Two-Stage Problems

Two-Stage Linear Programming Problems

A very common case is a two-stage stochastic linear programming problem:

- The objective and constraints **depend linearly** on the decision variables.
- The uncertain variables are **independent** of the decision variables.
- The problem includes both normal decisions and **recourse decisions**.
- The problem may or may not include **chance constraints**.

The presence of recourse decisions in the problem implies that at least some (and usually all) of the uncertainty *will* be resolved over the horizon of interest. Hence the problem is called 'two-stage,' where the normal decisions are made at the first stage – before the uncertainties are resolved – and the recourse

decisions are made at the second stage – after they are resolved. The Solver must find single values for the normal variables, and multiple values for the recourse variables (for each realization of the uncertainties) that satisfy the constraints and optimize the objective.

We cannot solve this problem with conventional **simulation optimization** methods, because these methods have no concept of recourse decisions. But since the problem is linear, we can use either **stochastic programming** or **robust optimization** methods – and with these methods we can solve *much larger* models, hundreds of times faster than with simulation optimization. In the Task Pane Platform tab, we set the Optimization Model group option **Solve Uncertain Models** to Stochastic Transformation, and we set the Transformation group option **Stochastic Transformation** to either Deterministic Equivalent or Robust Counterpart. When we click Optimize, the transformed model is created and solved.

If we choose the 'Determ Equivalent,' we can place integer constraints on the normal and recourse variables (though this may make the model more difficult to solve). But the model cannot include chance constraints, and the transformed model may become quite large (its size depends on the *product* of the number of recourse variables and constraints, and the number of simulation trials).

If we choose the 'Robust Counterpart', the model can include chance constraints, and the transformed model will be significantly smaller and solve faster than if we choose 'Determ Equivalent.' But we cannot place integer constraints on the recourse variables, and the solution may be more conservative than with 'Determ Equivalent.'

Two-Stage Quadratic Programming Problems

A slightly more complex case than the one above is a two-stage stochastic problem with a quadratic objective and all linear constraints:

- The objective is a **deterministic, convex quadratic** function of the decision variables – it doesn't depend on the uncertainties or the recourse variables.
- The uncertain variables are **independent** of the decision variables.
- The problem includes both normal decisions and **recourse decisions**.
- The problem includes **no chance constraints**.

Again the presence of recourse decisions in the problem implies that at least some (and usually all) of the uncertainty *will* be resolved over the horizon of interest. We cannot solve this problem with conventional **simulation optimization** methods, because these methods have no concept of recourse decisions. But we can use **stochastic programming** methods – and these methods are far more scalable than simulation optimization methods would be. In the Task Pane Platform tab, we set the Optimization Model group option **Solve Uncertain Models** to Stochastic Transformation, and we set the Transformation group option **Stochastic Transformation** to either Deterministic Equivalent. When we click Optimize, the transformed model is created and solved.

Two-Stage Nonlinear Optimization Problems

If we have a two-stage stochastic nonlinear problem:

- The objective or the constraints are **general nonlinear**, convex or non-convex functions of the decision variables.

- The uncertain variables may be **dependent** on the decision variables.
- The problem includes **recourse decisions**.
- The problem may or may not include **chance constraints**.

We cannot use Analytic Solver's **robust optimization** methods or **stochastic programming** methods on problems with general nonlinear functions, and we cannot use conventional **simulation optimization** methods either, because these methods have no concept of recourse decisions. But future Frontline Systems products may be able to solve such problems; contact us for more information.

Advanced Topics

Bounds, Discretization, and Correlation

An uncertainty specified via a probability distribution such as PsiUniform(0,1) has finite bounds of 0 and 1, but it has a practically infinite set of possible values between 0 and 1; we can only consider a *sample* of the possible values during an optimization. An uncertainty specified via PsiNormal(0,1) has infinite bounds, as well as an infinite set of possible values. In practice, however, most of the probability mass of the Normal distribution lies within three standard deviations on either side of the mean, and a reasonable *sample* of values from the Uniform and Normal distributions can be used for computations.

Analytic Solver uses Monte Carlo simulation to generate samples of uncertainties, based on the probability distributions specified by the user. It uses the minimum and maximum values for each distribution obtained during the simulation as 'effective' lower and upper bounds, which are used in constructing the robust counterpart to an uncertain model.

When Analytic Solver solves a stochastic LP (as explained above) by forming the 'deterministic equivalent' problem, the Monte Carlo trials are used as 'scenarios' in constructing this problem; hence they serve as a discretization of any continuous probability distributions specified by the user.

The impacts of uncertainties on each coefficient of the objective and the constraints may be *correlated* – either because multiple coefficients depend on the same primitive uncertainty, or because correlation was deliberately induced among several uncertain variables. When Analytic Solver solves a stochastic LP by forming the 'deterministic equivalent' problem, the correlations are reflected in the Monte Carlo trials used to construct the problem. When it solves a stochastic LP using robust optimization methods, the robust transformation takes into account the observed correlations in the sample.

Uncertainty Sets and Norms

As described in the earlier section "More on Chance Constraints," if a chance constraint is linear in the decision variables, you can use the *USet* (uncertainty set) criterion, in lieu of the VaR or CVaR criterion. The advantage of using this criterion is that the robust counterpart model more accurately reflects the degree to which you want the chance constraint to be satisfied, which can lead to less conservative solutions, with better objective values. Consider a constraint:

$a_1x_1 + a_2x_2 + \ldots + a_nx_n \leq b$

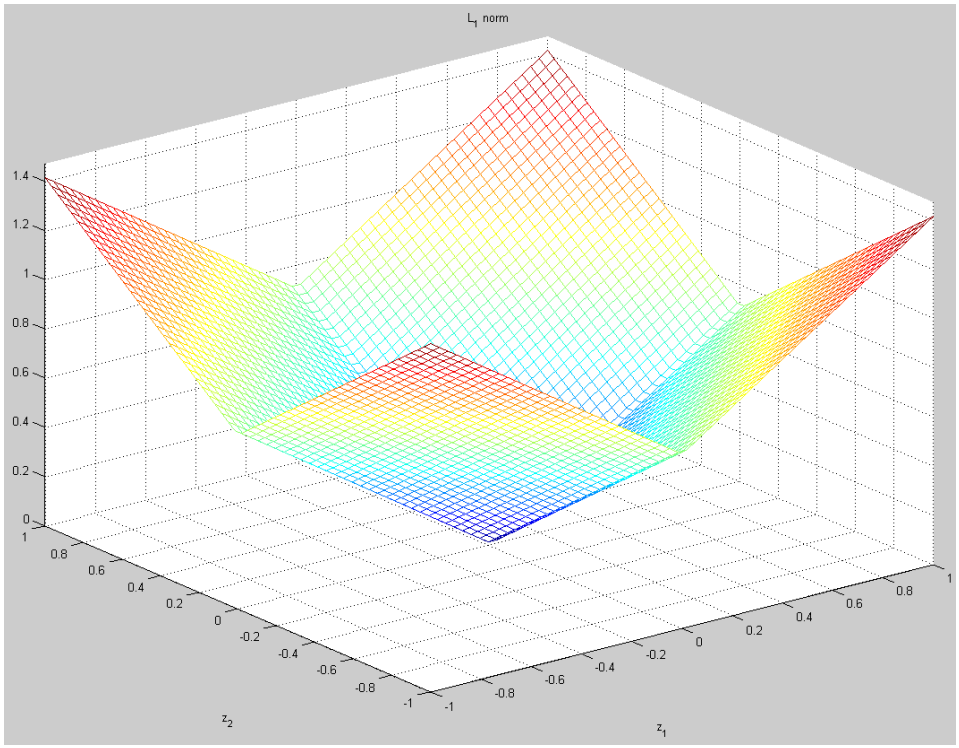
where $=a_1x_1 + a_2x_2 + ... + a_nx_n$ is in A1, b is in B, and some or all of the coefficients a_i may depend on uncertain variables z_1, z_2, ... It is useful to think of the vector $[a_1\ a_2\ ...\ a_n]$ as having a *nominal* or expected value, and a *variation* from this value for each realization of the uncertain variables.

A constraint of the form **USet$_\Omega$ A1 <= B1** specifies that A1 <= B1 must be satisfied for ***all*** *variations* from the *nominal* value of $[a_1\ a_2\ ...\ a_n]$ that do not exceed a bound Ω, measured by a norm. The *uncertainty set* includes all the points formed by adding a vector of allowed variations to the vector of nominal values; the bound Ω is often called the *budget of uncertainty* for the constraint.

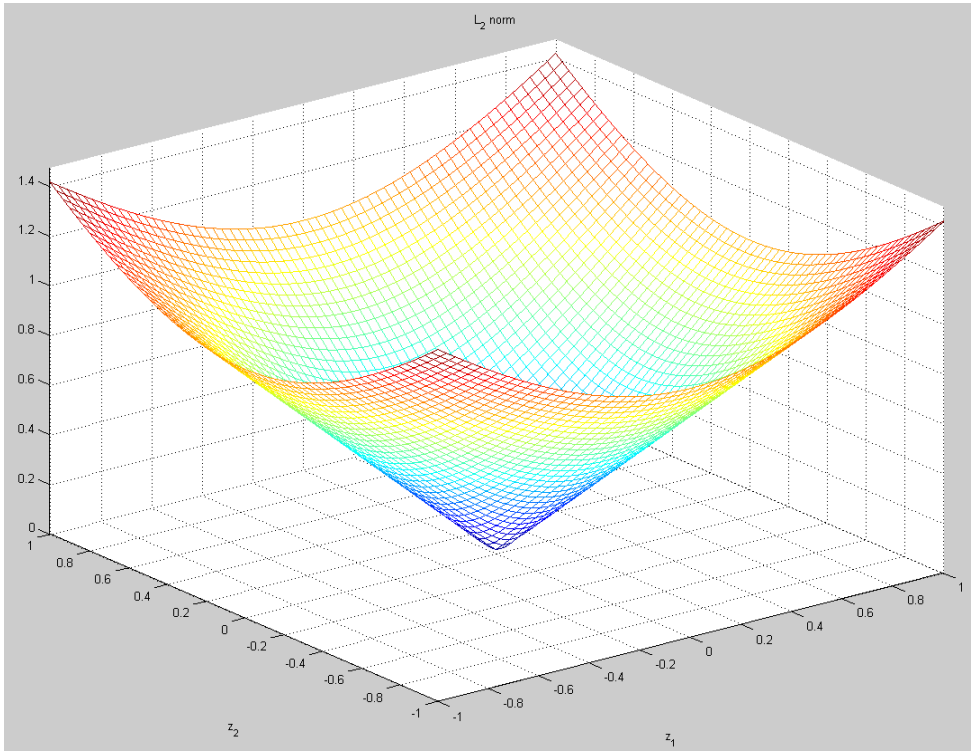
Analytic Solver allows you to choose among four different norms to measure variation from the nominal value: The L1, L2, L Inf (Infinity) and D norms. (One choice of norm applies to all chance constraints.) The graphs shown on the following pages may help you visualize the shape of the uncertainty set (based on two uncertain variables z_1, z_2) for each of the norms.

The D norm represents the intersection of the L1 norm and the L-Inf norm; thus it can define a 'tighter' uncertainty set than either of these norms alone. For the D norm, Ω can be interpreted as a bound on the *number* of coefficients $[a_1\ a_2\ ...\ a_n]$ that depart from nominal values. When the D norm is used, the robust counterpart of a stochastic LP problem is a (larger, conventional) LP problem; when the L2 norm is used, the robust counterpart is an SOCP problem.

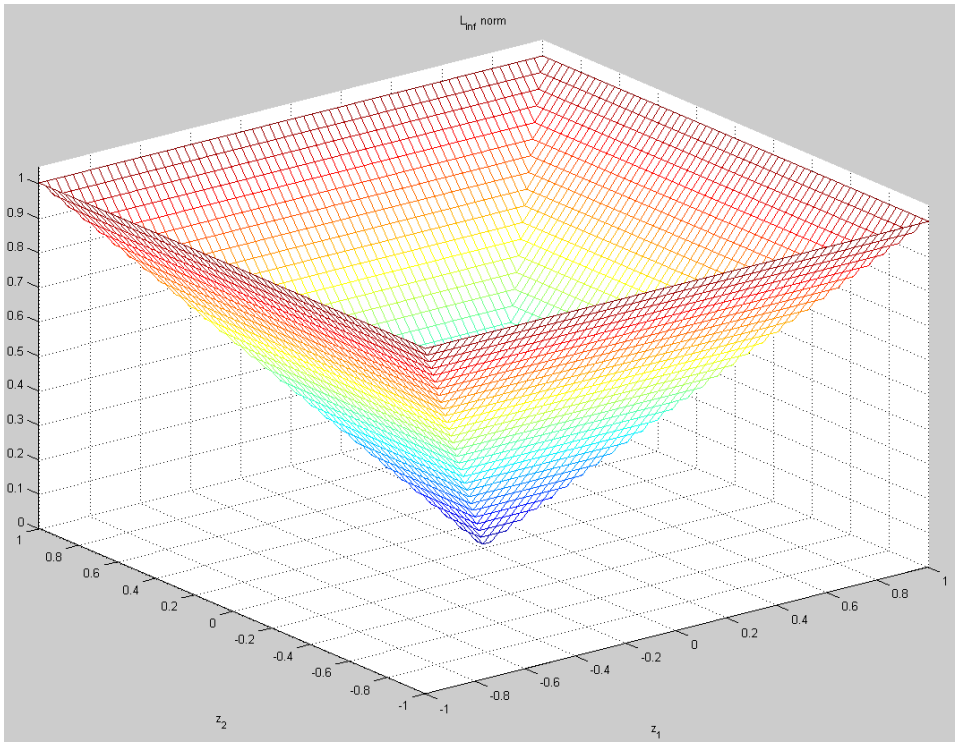
L1 Norm



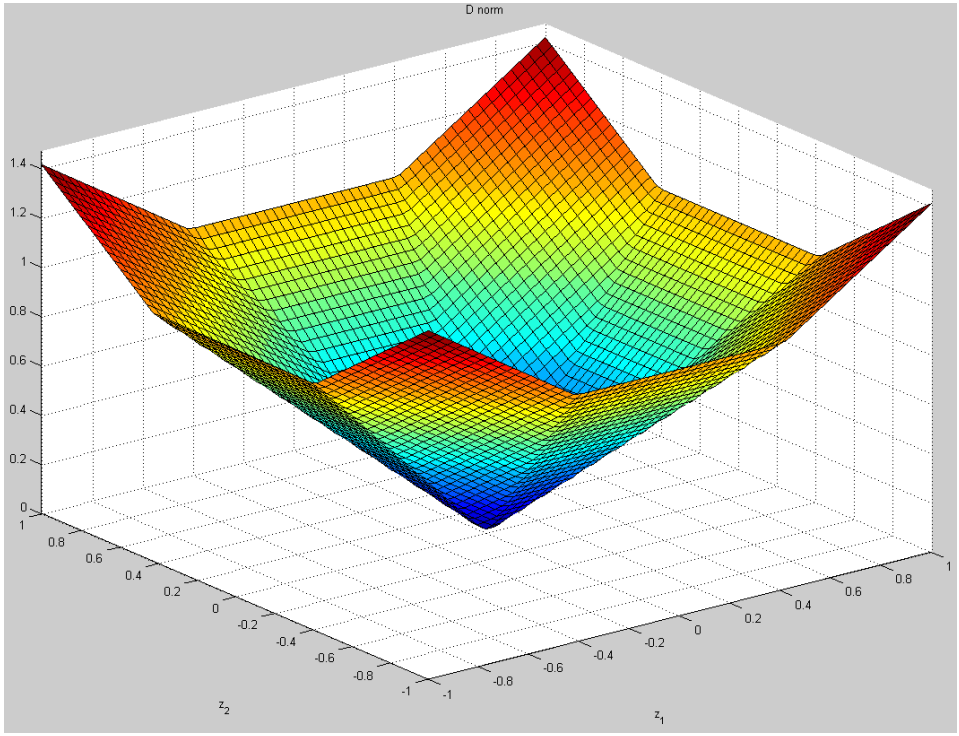
L2 Norm



L Inf Norm



D Norm


D norm
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
z_2
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
z_1

Best Practices for Building Large-Scale Models

Introduction

It's a maxim that a successful Solver model will grow in size over time. When the initial results from an optimization model demonstrate ways to achieve significant cost savings, improved schedules, higher quality or increased profits, management is naturally interested in applying these methods to bigger problems. This might involve extending the model to include more plants, warehouses, assembly lines, or personnel; to bring in other divisions or geographic regions; or to cover more time periods, more detailed process steps, or more specific parts or products. The result is an increase in the number of decision variables, constraints, and cells in your model.

When your model grows in size, it becomes more challenging to design and maintain, and also more challenging to solve. Good modeling practices – touched upon in the chapter "Examples: Conventional Optimization" – become *far* more important, so your model remains comprehensible to other Excel users, auditable for errors, and easy to modify. Issues such as your model type (LP, QP, QCP, SOCP, NLP or NSP), sparsity, and scaling also become *far* more important, since they strongly influence the time it takes to solve your model, and the reliability of the solutions you obtain.

This chapter can only briefly survey good modeling practices – entire books have been devoted to this subject (we will recommend some). It focuses on steps you can take to obtain faster and more reliable solutions for large models using the Analytic Solver including:

- Steps towards better performance that are easy to apply in most situations
- Steps you can take – with more design and modeling effort – to improve the *formulation* of your model, by replacing non-smooth or nonlinear constraints with linear (or integer linear) constraints
- Steps you can take to enable Analytic Solver to analyze your model more efficiently

Designing Large Solver Models

A large Solver model in Microsoft Excel is both a large spreadsheet workbook and a large optimization model. If you plan to build such a model, you'll be well advised to learn about good spreadsheet modeling practices, and about good optimization modeling techniques.

We highly recommend the textbook *Management Science: The Art of Modeling with Spreadsheets* by Stephen G. Powell and Kenneth R. Baker, published by John Wiley & Sons, listed in the following chapter "References and Further Reading." Unlike other management science textbooks, this book teaches you "best practices" in modeling and spreadsheet engineering, as well as techniques of linear and nonlinear optimization using Excel.

Other books on good spreadsheet design are hard to find, but through resources like the Amazon.com Marketplace, you may be able to locate a copy of John Nevison's book *Microsoft Excel Spreadsheet Design* (Prentice-Hall, 1990), or his earlier works *1-2-3 Spreadsheet Design* (1989) or *The Elements of Spreadsheet Style* (1987), both of which are still useful in designing modern spreadsheets. A relatively new (2003) book, *Excel Best Practices for Business* by Loren Abdulezer, includes chapters on spreadsheet construction techniques, "makeovers" of spreadsheets developed by others, and spreadsheet auditing.

Training courses in Microsoft Excel often cover at least some elements of good spreadsheet design. They are offered in many venues, from universities and community colleges to public seminars, in-house corporate training, and classes sponsored by computer dealers. Check the course outline or syllabus to see if it features spreadsheet design and good modeling practices, and other topics most relevant to you.

A readily available book on optimization modeling techniques is H. Paul William's *Model Building in Mathematical Programming, 4th Edition* (John Wiley, 1999), listed at the end of the chapter "Introduction." Focusing on modeling for linear and integer programming problems, it includes a treatment of large-scale model structure and decomposition methods that is hard to find elsewhere.

Spreadsheet Modeling Hints

Below is a brief set of suggestions for planning, designing and constructing large Solver models:

Start with a Plan. Plunging in and entering numbers and formulas immediately will quickly lead to problems when constructing a large spreadsheet. Write down your objectives and sketch out a design before you begin working on the real spreadsheet.

Build a Prototype. Plan in advance to build a prototype, *throw it away*, and then build the real spreadsheet model. What you learn from building and solving the prototype will probably save you time in the long run.

Create a Table of Contents. In the upper left corner of your first worksheet, include comments that point readers to the major areas or sections of the spreadsheet.

Separate Data and Formulas. Avoid using constants in formulas, unless they are intrinsic to the mathematical definition of the function you are using. Instead, place constants in cells, and refer to those cells in formulas. Create separate areas on the spreadsheet for input data and for calculations, and identify these with distinct colors, borders or shading.

Document Assumptions, Parameters and Methods. As John Nevison suggested, seek to "surface and label every assumption" in your model. Use labels or cell comments to document key formulas and complex calculations.

Use defined names. Use Excel's Insert Name Define and Insert Name Create commands to assign meaningful names to individual cells and cell ranges. This will help make your formulas clearer and more flexible.

Use and Separate Two-Dimensional Tables. Many elements of your model will lend themselves to a row-column table representation. Create separate table areas, with distinct colors, borders and shading. Collect non-table data (such as individual parameters) into a separate area.

Use Excel Tools to View and Audit Your Spreadsheet. Use the slider to zoom in Excel 2010/2013/2016 to get a high-level view of your spreadsheet's structure. Select 'Show Formulas' on the Formulas tab in Excel 2010/2013/2016 to display formulas instead of values, and scan them for consistency. Learn to use Excel's auditing functions to trace precedents and dependents of your formulas.

Use a Spreadsheet Auditing Tool. Several auditing tools are available, including *SpACE* from the UK Customs and Excise Audit unit, *OAK* from Operis Ltd. in the UK, and the *Spreadsheet Detective* from Southern Cross Software in Australia.

Optimization Modeling Hints

Identify Your Model's Index Sets. Your decision variables, constraints, and many intermediate calculations will fall into groups that are *indexed* by elements such as products (A, B, …), regions (North, South, …), time periods (January, February, …) and similar factors. Identify and write down these index sets and their members. Then organize the columns and rows of your table areas using these index sets. Use the top row and left column of each table area for index set member names as labels.

Identify Your Decision Variables. Once you've identified the quantities that will be decision variables, and how they are indexed (for example, units made by product A, B,… or shipments by region North, South,…), it's usually easier to determine the constraints and their indexing.

Determine the Data You'll Need. In building large optimization models, you will frequently spend a good part of your time figuring out what data you need, how you will get it (and keep it up to date), and how you'll have to summarize or transform it for the purposes of the model. This may involve getting help from your IT department or from other groups that create or maintain the data.

Define Balance Constraints. It is easy to overlook "balance" or "continuity" constraints that arise from the physical or logical structure of your model. For example, in a multi-period inventory model, the ending inventory at time *t* must equal the beginning inventory at time *t+1*. At each node of a network model (such as a warehouse), the beginning item quantity plus incoming deliveries minus outgoing shipments must equal the ending item quantity ("what goes in must come out").

Learn to Use Binary Integer Variables. Many relationships that you might find difficult to model at all, and many where you might otherwise use IF, CHOOSE or other non-smooth or discontinuous functions, can be effectively modeled with binary integer variables. The section below "Improving the Formulation of Your Model" describes many situations where you can use such variables to organize your model.

Using Multiple Worksheets and Data Sources

Large Solver models and their data are often organized into multiple worksheets of a single workbook. Some large models reference data found in other workbooks. Given the large number of data elements, the sources from which you are getting the data, and the procedures you use to keep the data up to date, multiple worksheets are often necessary or at least useful for organizing your data.

Analytic Solver Pro, Risk/Premium Solver Pro and Premium Solver Pro require that cells containing decision variables and constraint left hand sides are on the active worksheet. But Analytic Solver allows you to define decision variables and constraint left hand sides on any worksheet of a workbook. For this and many other reasons, you are well advised to upgrade to one of these products if your model grows in size. With either product, the formulas in your objective and constraint cells can refer to cells on other worksheets, and those cells on other worksheets can contain formulas that depend, directly or indirectly, on decision variable cells. For more information, see the Frontline Solvers Reference Guide.

Several commentators on good spreadsheet modeling practice feel that models defined on a single worksheet are easier to understand and maintain. In Excel 2010 and beyond, a single worksheet can have up to 16,384 columns and 1,048,576 rows. So you may want to keep the core of your Solver model – the formulas (i) that are used to compute your objective and constraints and (ii) that depend on the decision variables – on a *single worksheet*. If you find that you can better structure your model by placing decision variables and constraints on different worksheets, it's highly recommended that you adopt a consistent scheme for choosing blocks of variable and constraint (and other formula) cells, and referencing these cells across worksheets.

Some of the data you need may be available in relational databases, OLAP databases or data warehouses. Microsoft Excel provides rich facilities, such as external data ranges and PivotTables, to bring such data into an Excel worksheet. The raw data, even if partially summarized from database records or transactional data, often needs to be further transformed and summarized on your worksheet(s). This is usually easy to do with Excel formulas. But for clarity in your model, we recommend that you use separate worksheet areas, with distinct colors, borders or shading, for formulas that simply massage the data and do not participate in the solution process (i.e. do not depend on the variables). The Solver can determine which formulas depend on the variables, but *you* or your colleagues may find it difficult to do so if the formulas are intermixed.

Quick Steps Towards Better Performance

The rest of this chapter focuses on steps you can take to obtain *faster and more reliable solutions* for large models from Analytic Solver. This section describes steps that are easy to apply in most situations.

For users of Analytic Solver Basic and Analytic Solver Upgrade, the best recommendation we can make to improve performance is to *upgrade to Analytic Solver Comprehensive, Analytic Solver Optimization or Analytic Solver Simulation.* This is more than just a "sales pitch" – every step you take costs something, either in terms of money or your effort. For most professionals, the cost of upgrading will be repaid if it saves just a few hours of time. And you can find out *at no cost* whether the upgrade will be worthwhile.

For users of Analytic Solver Comprehensive or Analytic Solver Optimization, we highly recommend that you *try solving your model with our field-installable Solver Engines* – especially the Large-Scale SQP Solver, Knitro Solver, MOSEK Solver Engine, and XPRESS Solver Engine. While the difference in cost may be greater, the same rationale applies: If you can solve your model more quickly or more reliably by upgrading the software, this is almost always cheaper (and yields results sooner) than spending many hours or days of valuable professional time.

Ensure that You Have Enough Memory

If the Solver seems unusually slow and you are using Analytic Solver Desktop, check whether the hard disk activity LED (present on most PCs) is flickering during the solution process. If it is, memory demands may be causing Windows to swap data between main memory and disk, which greatly slows down the Solver. If you're investing money and, especially, hours of your time to develop an optimization model, consider that RAM is very cheap, and relatively easy to install. We recommend *at least* 1 GB RAM if you are working with large Solver models – 2 GB or more is certainly desirable. However, the best solution is simply to run your simulation model using Analytic Solver Cloud. Since the Cloud app runs on Microsoft's Azure App Service, memory is not an issue in the cloud!

Analyze Your Model for Scaling Problems

Poorly scaled calculations are a frequent cause of long solution times and unreliable solution results, for both linear and nonlinear problems. For a further discussion, see "Problems with Poorly Scaled Models" in the chapter "Getting Results: Conventional Optimization."

Add Constraints to Your Model

Frequently, you can improve solution time by adding constraints to your model which may not be *essential* in defining the problem, but which do *further constrain* the search space that the Solver must explore. It's true that the Solver must do more work to handle the additional constraints, but this extra work usually has an excellent payoff if the constraints are "binding" (i.e. satisfied with equality) at some point during the solution process.

The greatest payoff often comes from additional constraints that are simple bounds on the decision variables. This is because (i) it's usually easier for you to determine realistic lower and upper bounds on the variables than to formulate new general constraints, (ii) it's easy to enter bounds on the variables via the Ribbon Constraints choice, and (iii) each of the Solver engines is able to handle bounds on the variables more efficiently than general constraints.

Users often omit upper bounds on their decision variables, and sometimes omit lower bounds as well. A first step towards improving performance is to enter the tightest bounds on the variables that you can, without eliminating possible good solutions.

Since bounds on the variables are especially important for the performance of the Evolutionary Solver and for multistart methods for global optimization used with the nonlinear Solver engines, the Engine tab options for these Solver engines include an option **Require Bounds on Variables**, which is *True* by default. When this box is checked, the Solver will stop with an error message if some variables do not have lower or upper bounds at the time you click Solve. If you are using the Interval Global Solver or the OptQuest Solver, bounds on all variables are *required* – the Solver will always stop with an error message if bounds on the variables are missing.

Improving the Formulation of Your Model

The type of problem you are trying to solve, and the solution method or Solver engine that must be used, has a major impact on solution time:

- Linear programming problems can be solved most quickly.

- Quadratic programming problems take somewhat more time.
- Nonlinear optimization problems take considerably more time.
- Non-smooth problems take by far the greatest amount of time.

This section discusses techniques you can use to replace nonlinear functions, and even non-smooth functions, with equivalent (or nearly equivalent) linear or quadratic functions, or with linear functions and binary integer variables. As explained in the chapter "Mastering Conventional Optimization Concepts," a problem with integer variables can take much longer to solve than a problem without such variables. However, an integer linear problem formulated using the techniques described in this section may still take significantly *less* time to solve than the equivalent nonlinear or non-smooth problem. Moreover, if your problem is integer linear, you can find a *guaranteed* optimal solution, or a solution that is guaranteed to be within at least x% of optimal, whereas with a nonlinear or non-smooth problem you will have no such guarantees. As a rough guide, non-smooth models with more than 1,000 variables may be difficult or impossible to solve in a reasonable amount of time – but equivalent models formulated with linear functions and binary integer variables can often be solved efficiently with the LP/Quadratic Solver. And with the Large-Scale LP/QP Solver, MOSEK Solver or XPRESS Solver, you can often solve linear integer problems of 10,000, 100,000 or more variables in a reasonable amount of time.

A caveat: If you currently have a model with many nonlinear or non-smooth functions, and you decide to implement some of these techniques to speed up solution of your model, bear in mind that you can use the LP/Quadratic Solver, Large-Scale LP/QP Solver, or XPRESS Solver only for models where *all of the problem functions* are linear (except for the objective function, which may be quadratic). If you create a model with a *mix* of nonlinear or non-smooth functions and linear functions using binary integer variables, it may still take a long time to solve.

Techniques Using Linear and Quadratic Functions

Below are three common situations where you might at first expect that a nonlinear function is required to express the desired relationship – but with a simple transformation or approximation, you can use a linear or quadratic function instead.

Ratio Constraints

You may want to express a relationship that seems to require dividing one or more variables by other variables. Suppose that you have a portfolio of 1-month, 3-month and 6-month CDs, with the amounts of each CD in cells C1, D1 and E1, and you wish to limit the average maturity to 3 months. You might write a constraint such as:

(1*C1 + 3*D1 + 6*E1) / (C1 + D1 + E1) <= 3

This constraint left hand side is a nonlinear function of the variables, so you would have to use the GRG Solver to find a solution. However, the same constraint can be rewritten (multiplying both sides by the denominator, then collecting terms) as:

(1*C1 + 3*D1 + 6*E1) <= 3*(C1 + D1 + E1), i.e. -2*C1 + 3*E1 <= 0

This constraint is a linear function of the variables, so you would be able to use the much faster LP/Quadratic Solver to find a solution. (This transformation above relies on the fact that C1 + D1 + E1 >= 0.)

Mini-Max and Maxi-Min

You may want to minimize the maximum of a group of cells such as C1:C5 (or maximize the minimum of a group of cells). It is tempting to use an objective function such as MAX(C1:C5)– but as explained in the chapter "Mastering Conventional Optimization Concepts," MAX (and MIN) are non-smooth functions, so you'd need to use at least the GRG Solver, and perhaps the Evolutionary Solver to find a solution. Instead, you can introduce another variable D1, make D1 the objective to be minimized, and add the constraint:

C1:C5 <= D1

The effect of this constraint is to make D1 equal to the maximum of C1:C5 at the optimal solution. And if the rest of your model is linear, you can use the much faster LP/Quadratic Solver to find a solution.

Quadratic Approximations

If you cannot represent the entire problem using linear functions of the variables, try to formulate it as a quadratic (QP) or quadratically constrained (QCP) problem, with a quadratic objective and/or constraints. You may be able to use a local, quadratic approximation to a smooth nonlinear function *f* near a point *a*:

$$f(x) \cong f(a) + f'(a)(x - a) + \tfrac{1}{2} f''(a)(x - a)^2$$

where $f'(a)$ denotes the first derivative, and $f''(a)$ denotes the second derivative of the function *f* at the point *a*. Several Solver engines offer excellent performance on QP problems, and the SOCP Barrier Solver and the MOSEK Solver offer good to excellent performance on QCP problems.

Even if you cannot eliminate nonlinear functions from your problem altogether, you can improve solution time by making an effort to ensure that as many variables as possible occur linearly in the objective and all of the constraints. If you're using the GRG Solver, you can set its Engine tab option **Recognize Linear Variables** to True, to save time during the solution process. And the Large-Scale GRG Solver and Large-Scale SQP Solver engines also recognize both *linearly occurring variables* and *linear constraints* automatically, for still faster solutions. The Large-Scale SQP Solver is particularly effective when used with Analytic Solver Comprehensive or Analytic Solver Optimization because it uses the Interpreter's Structure analysis to *break down each function into linear and nonlinear terms*, which it handles as efficiently as possible.

You can use the Ribbon choice **Optimize – Analyze Original Problem** or the Task Pane Analyze button to easily determine the number of linear variables, functions, and occurrences of variables in functions, as illustrated in the chapter "Examples: Conventional Optimization."

Techniques Using Linear Functions and Binary Integer Variables

Below are three common situations where you might at first expect that a non-smooth function such as IF is required to express the desired relationship – but you can instead use a binary integer variable and one or two linear functions to define an equivalent relationship. The techniques described here are similar to

those used when Analytic Solver *automatically transforms* your model, but you can apply these techniques yourself to handle situations where the automatic transformation is not available.

Fixed-Charge Constraints

You may have a quantity *x* in your model that must "jump" from zero to some (fixed or variable) non-zero value, under certain conditions. For example, a machine on a production line may have a fixed setup time or cost if it is used at all, plus a time or cost per unit produced. You can avoid creating a non-smooth function for *x* by introducing a binary integer variable *y* (which is 1 if x is used and 0 if it isn't), and adding a constraint *x* <= *My*, where *M* is a constant that is larger than any possible value for *x*.

For example, suppose you have a machine that has a setup time of 10 minutes, but once set up will process a widget every 30 seconds. Let cell C1 hold the number of widgets you are producing on this machine, and use cell E1 for a binary integer variable *y* that is 1 if you produce *any* widgets on this machine. Then the total production time can be computed as =0.5*C1+10*E1. Assuming that C1 can be at most 10,000, let M1 = 10000 and add a constraint:

C1 <= M1*E1 (or C1 – M1*E1 <= 0)

If variable C1 is nonnegative (C1 >= 0) and variable E1 is binary integer (E1 = binary), then C1 is forced to be 0 whenever E1 is 0, or equivalently E1 is forced to be 1 whenever C1 is greater than 0. Since the production time calculation and the constraint are both linear functions, you can solve the problem with the LP/Quadratic Solver and the Branch & Bound method. This is called a *fixed-charge* constraint.

You can sometimes use a **semi-continuous** variable to model this kind of situation, instead of a binary variable, continuous variable, and "Big M" constraint. At the optimal solution, a semi-continuous variable must either be zero, or must lie within a specified continuous range. This is usually even more efficient than using a fixed-charge constraint as outlined above.

Either-Or Constraints

Constraints in an optimization problem are implicitly connected by the logical operator AND – all of them must be satisfied. Sometimes, however, your model may call for either one constraint (say *f(x)* <= *F*) or another constraint (say *g(x)* <= *G*) to be satisfied. You might consider using the OR function in Excel, but as noted in the chapter "Mastering Conventional Optimization Concepts," this function is non-smooth. Instead, you can introduce a binary integer variable *y* and a constant *M*, where *M* is greater than any possible value for *f(x)* or *g(x)*, and add the constraints *f(x)* – *F* <= *My* and *g(x)* – *G* <= *M*(1-*y*). Now, when *y*=0, *g(x)* is unrestricted and *f(x)* <= *F*; when *y*=1, *f(x)* is unrestricted and *g(x)* <= *G*.

For example, imagine you want to allocate your purchases among several suppliers in different geographic regions, each of whom has imposed certain conditions on their price bids. Suppose that one supplier's bid requires that you either purchase at least 400 units from their Chicago warehouse or else purchase at least 600 units from their Phoenix warehouse, in order to obtain their most favorable pricing. Let cell C1 hold the number of units you would purchase from Chicago, and cell D1 hold the number of units you would purchase from Phoenix. Assume that cell M1 contains 10,000 which is more than the maximum number of units you intend to purchase. You can model the supplier's either-or requirement with a binary integer variable in cell E1 and the following constraints:

400 – C1 <= M1*E1
600 – D1 <= M1*(1-E1)

Notice that we have reversed the sense of the constraint left hand sides to reflect the "at least" (>=) requirement. If E1=0, then C1 (units purchased from Chicago) must be at least 400, and the second constraint has no effect. If E1=1, then D1 (units purchased from Phoenix) must be at least 600, and the first constraint has no effect.

IF Functions

In the chapter "Mastering Conventional Optimization Concepts," we used =IF(C1>10,D1,2*D1), where C1 depends on the decision variables, as an example of a non-smooth function: Its value "jumps" from D1 to 2*D1 at C1=10. If you use this IF function directly in your model, you'll either have to try the Task Pane Platform tab **Nonsmooth Model Transformation** option, or solve the model with the Evolutionary Solver. Instead, you can avoid the IF function and solve the problem with the nonlinear GRG Solver – or even the LP/Quadratic Solver – by introducing a binary integer variable (say E1) that is 1 if the conditional argument of the IF is TRUE, and 0 otherwise. Add the constraints:

C1 – 10 <= M1*E1
10 – C1 <= M1*(1–E1)

When E1 is 0, the first constraint forces C1 <= 10, and the second constraint has no effect. When E1 is 1, the first constraint has no effect, and the second constraint forces C1 >= 10. (If C1=10 exactly, this formulation allows either E1=0 or E1=1, whichever one yields the better objective.) The value of the IF function can then be calculated as D1*E1 + 2*D1*(1-E1), which simplifies to D1*(2-E1) in this example. If D1 is constant in the problem, this is a linear function; if D1 depends linearly on the variables, it is a quadratic; otherwise, it is smooth nonlinear. In all cases, the non-smooth behavior has been eliminated.

Depending on how you use the result of the IF function in the rest of your model, you may be able to take this strategy further. Suppose, for example, that if $f(x) >= F$ then you want to impose the constraint $g(x) <= G$; if $f(x) < F$ then you don't need this constraint. You can then use a binary variable y (cell E1 in the example above), and impose constraints like the pair above plus an additional constraint on $g(x)$:

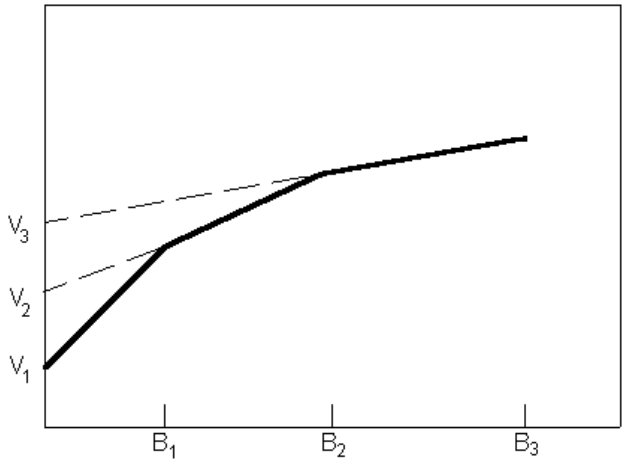
$f(x) – F <= My$
$F – f(x) <= M(1-y)$
$g(x) – G <= M(1-y)$

If y is 0, $f(x) <= F$ is enforced, and the second and third constraints have no effect. If y is 1, $f(x) >= F$ and $g(x) <= G$ are enforced, and the first constraint has no effect. If $f(x)$ and $g(x)$ are linear functions of the variables, the constraints involving y remain linear, and the problem can be solved with Branch & Bound and the LP/Quadratic Solver.

Using Piecewise-Linear Functions

Many problems involve "stepped" price schedules or quantity discounts, where you might at first expect that a non-smooth function such as CHOOSE or LOOKUP is required to express the relationship. You might be surprised to learn that you can instead use linear functions and binary integer variables to express the relationship.

For example, you might be purchasing parts from a vendor who offers discounts at various quantity levels. The graph on the next page represents such a discount schedule, with three prices and three "breakpoints." You have a decision variable *x* representing the quantity to order.



The three prices (slopes of the line segments) are c_1, c_2 and c_3. V_1 represents a fixed initial cost; V_2 and V_3 are also constant in the problem and can be computed from:

$V_2 = V_1 + c_1*B_1 - c_2*B_1$
$V_3 = V_2 + c_2*B_2 - c_3*B_2$

In the model, the variable *x* is replaced by three variables x_1, x_2 and x_3, representing the quantity ordered or shipped at each possible price. Also included are three 0-1 or binary integer variables y_1, y_2 and y_3. Since you want to minimize costs, the objective and constraints are:

Minimize $V_1*y_1 + V_2*y_2 + V_3*y_3 + c_1*x_1 + c_2*x_2 + c_3*x_3$
Subject to $x_1 \le B_1*y_1$, $x_2 \le B_2*y_2$, $x_3 \le B_3*y_3$

If the cost curve is concave as shown above, this is sufficient; but if the function is non-concave (it may vary up and down), additional "fill constraints" are needed:

$y_1 + y_2 + y_3 \le 1$
$x_1 \le B_1*y_2$
$x_2 \le B_2*y_3$

This approach is called a "piecewise-linear" function. It can be used in place of a CHOOSE or LOOKUP function, and it results in a linear integer model instead of a difficult-to-solve non-smooth model. Piecewise-linear functions can also be used to approximate a smooth nonlinear function, by using line segments with slopes matching the gradient of the nonlinear function at various intermediate points.

Organizing Your Model for Fast Solution

This section describes ways you can organize your model so that Analytic Solver can analyze it more efficiently. Most of this section is devoted to an in-depth discussion of "fast problem setup" for *linear* and *quadratic* models (possibly with integer variables); it is not applicable to *nonlinear* and *non-smooth* models. Because the Polymorphic Spreadsheet Interpreter in Analytic Solver has largely superseded this form of fast problem setup, this section is

relevant primarily for very large LP models (100,000 variables or more), where memory required for the Interpreter may be greater than available RAM and cause swapping to disk.

Fast Problem Setup

If your model is linear or quadratic, you may find that the Solver spends most of its time with "Setting Up Problem..." on the Excel status bar, then speeds through the "Trial Solutions" very quickly. The setup time is required to extract the LP coefficients of the problem functions by recalculating the worksheet. (The LP coefficients are the first partial derivatives of the problem functions with respect to the variables, and they are obtained by the method of *finite differencing*, which requires *n + 1* recalculations if there are *n* decision variables.)

Although the time taken to extract the LP coefficients was drastically decreased in V2017-R2, even more of this setup time can be avoided if you write the formulas for the objective function and *all* of the constraint left hand sides using the functions recognized for *fast problem setup*: SUM, SUMPRODUCT, DOTPRODUCT, QUADPRODUCT and MMULT. This may require some work on your part to revise a model you have already constructed, but you'll be rewarded with a *5- to 100-fold speed improvement* in setup time, compared to the time taken by the Excel Solver or the Excel Interpreter.

You can always express a linear or quadratic programming problem using these functions for the objective and all of the constraints, although you may need to introduce new sets of cells to hold the calculated coefficients so that these cells can be referenced by one of the fast problem setup functions.

The PSI Interpreter in Analytic Solver uses the techniques of *automatic differentiation* to obtain the LP coefficients faster and more accurately than they can be obtained via finite differencing. Because the Interpreter handles almost every kind of Excel formula and built-in function, you don't have to do the work of designing your model – or revising an existing model – to use only the small set of functions recognized for fast problem setup.

Fast problem setup is still available in Analytic Solver as a specialized method of extracting the constant Jacobian matrix (the LP coefficients) of a linear or quadratic problem, and the constant Hessian matrix (the QP coefficients) of a quadratic objective function – but it is used only if you set the Task Pane Platform tab Optimization group Interpreter option to **Excel Interpreter**. If your LP or QP model is very large, defining it in fast problem setup format may still save time compared to use of the PSI Interpreter – but the advantage is not nearly as great as the 5- to 100-fold speed improvement mentioned above.

The following subsections describe the functions supported for fast problem setup, and the form of the function arguments that you must use to ensure that they are recognized for fast setup purposes.

The SUM Function

The simplest case of a function recognized for fast problem setup is a formula such as =SUM(C1:C10) where C1 through C10 are decision variables. An example of the use of SUM to define constraints can be found in the "Shipping Routes" sheet in the SOLVSAMP.XLS workbook included with Microsoft Excel. Note that a SUM of decision variables is a linear function where all of the coefficients are 1. To be recognized in fast problem setup, your formula must consist *only* of =SUM(*cells*) (with no constants) where every cell

referenced is a decision variable. You may use absolute or relative references or defined names in the arguments to SUM.

The SUMPRODUCT Function

The SUMPRODUCT function is documented in Microsoft Excel online Help. It returns the sum of the products of corresponding elements in its two arguments, which is exactly the form of a linear function:

$a_1x_1 + a_2x_2 + ... + a_nx_n$

SUMPRODUCT requires that its two arguments refer to the same *number* of cells in the same *orientation* (either a row, a column or a rectangular area of cells). Only single selections, not multiple selections, are permitted in the arguments. If SUMPRODUCT is used in an array formula (see below), it will return the same value in every resulting array element, which is usually not the result you want. (The DOTPRODUCT function, described below, has more flexible arguments and is far more useful in array formulas.) To be recognized in fast problem setup, your formula must consist *only* of =SUMPRODUCT(*cell range, cell range*) where one of the cell ranges consists *entirely* of decision variables, and the other cell range consists *entirely* of cells that are constant in the Solver problem. You may list the arguments in either order, using absolute or relative references or defined names.

Other Functions for Fast Problem Setup

Use of the MMULT function is illustrated below under "Using Array Formulas." To be recognized in fast problem setup, your formula must follow the same rules as for SUMPRODUCT: It must consist *only* of =MMULT(*cell range, cell range*) where one cell range specifies the decision variables, and the other cell range specifies the corresponding coefficients.

The DOTPRODUCT and QUADPRODUCT functions are described in their own sections below. To be recognized in fast problem setup, your usage of these two functions must follow the same rules as for SUMPRODUCT.

To qualify as a quadratic programming (QP) problem – which can be solved efficiently by the LP/Quadratic Solver engine – only the *objective function* (not any of the constraints) may use QUADPRODUCT, or any other quadratic form.

Using Array Formulas

Optimization models in algebraic form can often be expressed more compactly using indexing and summation notation. For example, the five constraints in EXAMPLE1 could be written as:

$$\sum_{j=1}^{3} a_{ij} x_j,\ i=1,...,5$$

The SUMPRODUCT function corresponds to the summation expression above for one constraint. The *entire set* of five constraint formulas could be defined with the array form of the DOTPRODUCT function (described in detail later in this section). In EXAMPLE1, you would select cells C11 to C15 and "array-enter" the following formula:

{=DOTPRODUCT(D9:F9,D11:F15)}

The braces above are not typed, but they appear when you "array-enter" the formula by pressing CTRL-SHIFT-ENTER instead of just ENTER. If you

aren't familiar with array formulas in Microsoft Excel, you can read about them in Excel's online Help. They are one of the most useful features of Microsoft Excel.

If your LP model is "dense" and regular in form rather than "sparse," you may wish to consider use of Microsoft Excel's matrix built-in functions, such as MMULT which (when array-entered into a group of cells) yields the matrix product of its two operands. For example, the five constraints in EXAMPLE1 (normally installed into C:\Program Files\Frontline Systems\Analytic Solver Platform\Examples\StandardExamples.xls could be written in vector-matrix form as:

Ax <= **b**

where **A** is the matrix of coefficients, **x** is the vector of decision variables and **b** is the vector of constraint right hand sides. In the Microsoft Excel formula language, the left hand side of this expression could be written as:

{=MMULT(_A,TRANSPOSE(_X))}

(The TRANSPOSE function is needed only to "match up" the orientation of the matrix _A with the row vector _X.) In worksheet EXAMPLE1, if you insert defined names _A for the coefficients D11:F15 and _X for the variables D9:F9, then select cells C11:C15 and array-enter the above formula, it will compute the values of all five constraints.

The PSI Interpreter in Analytic Solver recognizes most kinds of array formulas supported by Microsoft Excel. But (for rather technical reasons) the use of array formulas actually involves a speed *disadvantage* in the PSI Interpreter when the coefficients are extracted via automatic differentiation.

If you're using Analytic Solver, we recommend that you use array formulas where they make sense, and focus on making your model simple and easy to maintain. In a large model, you'll probably find that you want or need to use multiple tabular areas for the formulas that define your constraints, and it may be inconvenient or impractical to define entire constraint left hand sides with functions like MMULT and TRANSPOSE.

Using the Add-in Functions

Analytic Solver products define two special Excel functions: DOTPRODUCT and QUADPRODUCT. These functions behave just like Excel built-in functions: You can use them in formulas in any spreadsheet (not only in Solver models). When you use the Insert Function… menu option, these functions will appear in the "Select a Function" or "Paste Function" list (classified as Math & Trig functions), and you'll be prompted with named edit fields for their arguments.

In addition, DOTPRODUCT and QUADPRODUCT are recognized for purposes of fast problem setup as described earlier in this chapter. They are also recognized by the PSI Interpreter.

Using DOTPRODUCT

DOTPRODUCT is a generalized version of the Excel function SUMPRODUCT, and it is very useful for defining the objective function and constraints of linear programming problems. DOTPRODUCT is also recognized for fast problem setup as described above, provided that you follow the rules outlined earlier: Your formula must consist *only* of =DOTPRODUCT(*cell reference, cell reference*) where all of the cells in one of the cell references are decision

variables, and all of the cells in the other cell reference are constant in the Solver problem. Each *cell reference* must be either an *individual selection* or a *defined name*, but the cell ranges specified by the two arguments need not have the same "shape" (row, column, or rectangular area).

For use in Excel and for purposes of fast problem setup, DOTPRODUCT will accept defined names that specify *multiple selections* for either of its arguments. For example, if you had designed a model where the decision variables consisted of *several* rectangular cell selections, you could still calculate the objective function for your model with *one* call to DOTPRODUCT.

DOTPRODUCT always processes its arguments in *column, row, area* order – in an individual selection it reads cells across columns, wrapping around to subsequent rows, and in a multiple selection it reads the individual cell selections in the order in which they are listed. For example, the formula:

=DOTPRODUCT(A1:C2,D1:D6)

will calculate as =A1*D1+B1*D2+C1*D3+A2*D4+B2*D5+C2*D6.

The Array Form of DOTPRODUCT

If SUMPRODUCT is used in an array formula, it returns a scalar (single number) result, which is returned in every cell of the array. However, if DOTPRODUCT is used (with the proper arguments) in an array formula, it returns an *array result*. You can use this capability to calculate the left hand sides of several constraints with a single array formula. In a sparse model where you'd like to use the built-in function MMULT to compute the constraint values, but the variables and constraints aren't laid out in a single matrix, you can use the array form of DOTPRODUCT instead.

Further, when you use the array form of DOTPRODUCT, Analytic Solver will recognize this form and use it to process many constraints at once in problem setup. (The array form is recognized for fast problem setup, and it's also recognized by the PSI Interpreter.) If you can't use the array form, even the simple form of DOTPRODUCT will save time in problem setup.

DOTPRODUCT will return an array value when the number of cells in one of its arguments is an *even multiple* of the number of cells in its other argument. As an example, consider the calculation of parts used in the LP model EXAMPLE1. The decision variables are in cells D9 to F9 (3 cells), and the coefficients of the constraint left hand sides – the number of parts used for each product – are in cells D11 to F15 (15= 3*5 cells). We want to calculate the left hand sides of the constraints in cells C11 to C15. To do this, we would first select the group of five cells C11:C15 with the mouse. Then we would type:

=DOTPRODUCT(D9:F9,D11:F15)

completing the entry with CTRL+SHIFT+ENTER instead of just ENTER. The formula will display as {=DOTPRODUCT(D9:F9,D11:F15)} – the braces are added by Microsoft Excel when the formula is array-entered. With the cell values shown in EXAMPLE1 prior to solution (e.g. 100 for each of the decision variables), this array formula will calculate 200 in C11, 100 in C12, 500 in C13, 200 in C14 and 400 in C15. Hence, it will compute the same set of values as the array expression shown earlier: {=MMULT(_A, TRANSPOSE(_X))}.

Whether it is used in the simple form or the array form, DOTPRODUCT always processes its arguments in *column, row, area* order. In the array form, when the cells in the "shorter" argument have all been processed and cells remain to be processed in the "longer" argument, DOTPRODUCT "wraps around" to the beginning of the "shorter" argument. In the example above, cell C11 calculates

the value =D9*D11+E9*E11+F9*F11; cell C12 computes =D9*D12+E9*E12+F9*F12; and so on. Keep this rule in mind when you use the array form of DOTPRODUCT, and keep your spreadsheet layouts as simple as possible!

Using QUADPRODUCT

The QUADPRODUCT function can be used to define the objective for quadratic programming problems in a single function call, as required for fast problem setup.

As explained in "Quadratic Functions" in the chapter "Mastering Conventional Optimization Concepts," a quadratic function is a sum of terms, where each term is a (positive or negative) constant (called a *coefficient*) multiplied by a *single variable* or the *product of two variables*. This means that in order to represent the most general quadratic function, we might have a coefficient for each instance of a single variable, and a coefficient for each possible *pair* of two variables. The QUADPRODUCT function is designed to supply coefficients for each single variable and each pair of variables, in a manner similar to SUMPRODUCT and DOTPRODUCT.

You supply the arguments of QUADPRODUCT as shown below:

=QUADPRODUCT(*variable cells, single coefficients, pair coefficients*)

The first argument must consist entirely of decision variable cells. The second and third arguments must consist entirely of cells whose values are *constant* in the optimization problem; if these cells contain formulas, those formulas must not refer to any of the decision variables. The second argument supplies the coefficients to be multiplied by each single variable in the first argument, using an element-by-element correspondence. The third argument supplies the coefficients to be multiplied by each *pair* of variables drawn from the first argument. Hence, if there are n cells in the first argument, there must be n^2 cells in the third argument. If the variables are represented by $x_1,x_2,...,x_n$, the single coefficients by $a_1,a_2,...,a_n$, and the pair coefficients by $c_1,c_2,...,c_N$ where $N = n^2$, QUADPRODUCT computes the function:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} c_{n(i-1)+j}\, x_i\, x_j + \sum_{j=1}^{n} a_j\, x_j$$

The pairs are enumerated starting with the first cell paired with itself, then the first cell paired with the second cell, and so on. For example, if the first argument consisted of the cells A1:A3, there should be nine cells in the third argument, and the values in those cells will be multiplied by the following pairs in order: A1*A1, A1*A2, A1*A3, A2*A1, A2*A2, A2*A3, A3*A1, A3*A2, and A3*A3. The value returned by QUADPRODUCT is the sum of all of the coefficients multiplied by their corresponding single variables or pairs of variables.

Multiple selections can be used for each argument of QUADPRODUCT, subject to the same considerations outlined above for DOTPRODUCT: You can use the general syntax for multiple selections in Microsoft Excel, but defined names are needed for purposes of fast problem setup, and multiple selections are not accepted by the PSI Interpreter.

A common application of quadratic programming is to find an "efficient portfolio" of securities – often called *portfolio optimization*. Worksheet EXAMPLE4 in the **StandardExamples.xls** workbook, used in the chapter "Examples: Conventional Optimization," illustrates portfolio optimization using

the Markowitz method. This model uses the QUADPRODUCT function to compute the variance of a portfolio of five securities, and uses this quantity as the objective to be minimized, subject to a constraint that gives a lower limit on the portfolio return. Because the *objective* is a quadratic function, and the *constraints* (including the bound on return) are all linear functions, this Solver model is a quadratic programming (QP) problem which can be handled by the LP/Quadratic Solver in Analytic Solver Comprehensive and Analytic Solver Optimization.

References and Further Reading

Introduction

Although this Guide provides many valuable hints for making effective use of Analytic Solver, it does not attempt to teach you everything about optimization, Monte Carlo simulation, and stochastic optimization. We strongly recommend that you consult one of the books cited below, or discuss your problem with a **knowledgeable consultant** at Frontline Systems, at a nearby university, or at a firm specializing in optimization and simulation methods. There's a vast literature on problems of various types and for various industries and business situations that have been solved successfully with the methods available in the Solver. Don't reinvent the wheel – find out how others have solved problems similar to yours!

You may also want to attend a **training seminar** on risk analysis and simulation, optimization, and other advanced techniques in Excel, presented by Frontline Systems instructors or consultants who work closely with us. For current information on training seminars, visit www.solver.com or contact us at info@solver.com.

Textbooks Using Analytic Solver

***Management Science: The Art of Modeling with Spreadsheets*, 4th** Edition by Stephen G. Powell and Kenneth R. Baker, published by John Wiley & Sons, ISBN 978-1118582695.

Management Science, written by faculty members at Dartmouth's Tuck School of Business, helps business professionals gain the essential skills needed to develop real expertise in business modeling. The 4th Edition uses Analytic Solver Platform throughout the text, and describes how to use most of its features. Overall, this book teaches you "best practices" in modeling and spreadsheet engineering, methods for data visualization, analysis and data mining, and techniques of linear and nonlinear optimization, Monte Carlo simulation, and stochastic optimization using Excel. Additional open-ended case studies that are less structured are included, along with new exercises.

Spreadsheet Modeling and Decision Analysis: A Practical Introduction to Management Science, 7th Edition by Cliff T. Ragsdale, published by Cengage Publishing, ISBN 978-1285418681.

Cliff Ragsdale's book was first to base all of its optimization examples on the Microsoft Excel Solver, and it has become the best-selling MBA textbook for management science. You'll find a discussion of linear, nonlinear and integer programming; an explanation of sensitivity analysis and how to use the Solver's reports; topics like goal programming and multiobjective optimization; and additional coverage of regression, time series analysis, queuing, project management, decision analysis, and other topics. The 7th Edition uses Analytic Solver Platform for its examples.

Essentials of Business Analytics, 1st Edition by Jeffrey D. Camm, James J. Cochran, Michael J. Fry, Jeffrey W. Ohlmann and David R. Anderson, published by Cengage Publishing, ISBN 978-1285187273.

This book provides coverage over the full range of descriptive analytics (classical statistics), predictive analytics (data mining), and prescriptive analytics (optimization and simulation), integrating several important analytics topics not covered by any other single book. It includes step-by-step instructions to help students learn how to use Excel and Analytic Solver Platform. Practical, relevant problems at a variety of difficulty levels help students learn the material. Applications are drawn from all functional business areas: finance, marketing, operations, etc. Data sets are available for most exercises and cases.

Business Analytics, 1st Edition by James Evans, published by Pearson Publishing, ISBN 978-0132950619.

This book provides readers with the fundamental concepts and tools needed to understand the emerging role of business analytics in organizations, how to apply basic business analytics tools in Excel, and how to communicate with analytics professionals to effectively use and interpret analytic models and results for making better business decisions. The 1st Edition (which appeared before Analytic Solver Platform was released) teaches both forecasting and data mining methods using XLMiner, and optimization, simulation and other topics using Risk Solver Platform.

Textbooks Using Solver or Premium Solver

VBA for Modelers - Developing Decision Support Systems Using Microsoft Excel, 4th Edition by S. Christian Albright, published by Cengage Publishing.

This unique book will prove invaluable to anyone seeking to use VBA (Visual Basic Application Edition) to programmatically control Microsoft Excel and build custom applications. It includes a basic introduction to VBA and the Excel object model, and 16 example applications developed in depth with VBA source code, many of them calling the Solver's VBA functions. The applications include blending, product mix, production scheduling and similar models, plus capital budgeting, stock trading, option pricing and portfolio optimization.

Other Textbooks

Model Building in Mathematical Programming, 5th Edition by H.P. Williams, published by John Wiley, ISBN 978-1118443330. Though it doesn't cover spreadsheet optimization, this book is still valuable for its explanation of model-building approaches, especially if you are building large-scale optimization models. It provides an in-depth treatment of modeling for linear and integer programming problems. It mentions nonlinear models only briefly, but it offers a unique treatment of large-scale model structure and decomposition methods. It also includes a complete discussion of 24 models drawn from various industries.

Academic References

The following academic journal articles, written by the developers of the Excel Solver, Premium Solver Pro, Analytic Solver Pro, Premium Solver Platform,

Risk Solver Platform and Analytic Solver Platform, describe many of the algorithms and technical methods used in these products. The first article describes the design of the original Excel Solver. You can download PDF versions of the first three articles at **http://www.solver.com/academic.htm**:

D. Fylstra, L. Lasdon, J. Watson and A. Waren. Design and Use of the Microsoft Excel Solver. *INFORMS Interfaces* 28:5 (Sept-Oct 1998), pp. 29-55.

I. Nenov and D. Fylstra. Interval Methods for Accelerated Global Search in the Microsoft Excel Solver. *Reliable Computing* 9 (2003): pp. 143–159.

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