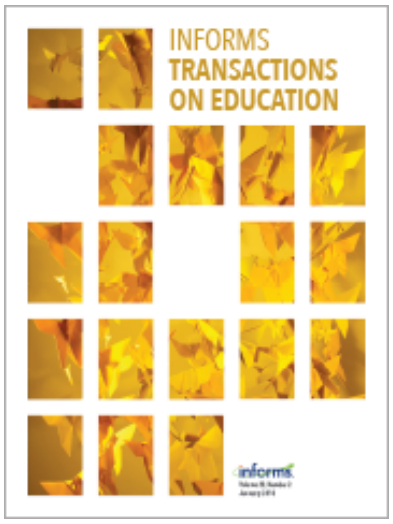

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Teaching Note

Analytic Visualization of Solver Output

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Data visualization is an essential component of modern analytics, supporting communication and understanding. While data visualization has been explored extensively in the context of descriptive analytics and big data, its use in prescriptive analytics, specifically for explaining and interpreting optimization results, has largely been ignored. In this teaching note we describe how data visualization can be applied effectively to facilitate the communication and understanding of standard Excel Solver output reports in a simple, nontechnical fashion.

Keywords: visualization; teaching optimization; developing communication skills
History: Received: March 2014; accepted: January 2015.

Introduction

Business analytics, or simply analytics, is the use of data, information technology, statistical analysis, quantitative methods, and mathematical or computer-based models to help managers gain improved insight about their business operations and make better, fact-based decisions (Evans 2013). Another definition is that it is "a process of transforming data into actions through analysis and insights in the context of organizational decision making and problem solving." (Liberatore and Luo 2010, p. 314). Business analytics begins with the collection, organization, and manipulation of data and is supported by three major components: descriptive analytics, predictive analytics, and prescriptive analytics (Lustig et al. 2010).

Perhaps the most useful component of business analytics, which makes it truly unique and has spurred its popularity, is data visualization (Tufte 2001). As Levine notes, "Analytic ideas and findings are often surprising, subtle and technically complex. These qualities can make them challenging to communicate, regardless of the audience. On the other hand, analysts have a great deal of freedom over the manner in which they communicate ideas and findings—some overarching, general principles can help analysts make decisions in this regard." (Levine 2013, p. 65). Visualizing data and results of analyses provide a way of easily communicating data at all levels of a business, and can reveal surprising patterns and relationships. Visualization is by no means new; many articles have used charts or other visual representations to explain results (Markham and Palocsay 2006) or improve pedagogy (Baloukas et al. 2009, Lazaridis et al. 2007). Visualization has also been explored extensively in the context of descriptive analytics and big data (Few 2004). Jones (1996) published an early treatise on visualization in optimization, featuring applications to the modeling life cycle and examples such as network routing and facility location. However, we are unaware of any attempts to exploit visualization to facilitate the communication and understanding of standard Excel Solver output reports.

Solver is a well-known add-in packaged with Excel that was developed by Frontline Systems, Inc. (http://www.solver.com), and can be used to solve many different types of optimization problems. However, interpreting the output from Solver requires some technical knowledge of linear optimization concepts and terminology, such as reduced costs and shadow prices. Visualization can help analysts present optimization results in forms that are more understandable, and can be easily explained to managers and clients in a report or presentation. In this teaching note, we describe how data visualization can be applied effectively to communicate the results of Solver output reports for linear optimization. The author has incorporated these concepts in one module of an undergraduate course on spreadsheet analytics in the Business Analytics minor in

the Lindner College of Business at the University of Cincinnati, and also in the second edition of his textbook (Evans 2015).

An Investment Example

We will use a simple textbook problem drawn from Evans (2013):

A recent MBA graduate, Dara, has gained control over custodial accounts that her parents had established. Currently, her money is invested in four funds, but she has identified several other funds as options for investment. She has $100,000 to invest with the following restrictions:

1. Keep at least $5,000 in savings.
2. Invest at least 14% in the money market fund.
3. Invest at least 16% in international funds.
4. Keep 35% of funds in current holdings.
5. Do not allocate more than 20% of funds to any one investment except for the money market and savings account.
6. Allocate at least 30% into new investments.

Table 1 shows the anticipated investment returns and expenses. The objective is to maximize the net return on investment.

Table 1 Investment Returns and Expenses

Fund	Average return (%)	Expenses (%)
1. Large cap blend (current holding)	17.2	0.93
2. Small cap growth (current holding)	20.4	0.56
3. Green fund (current holding)	26.3	0.70
4. Growth and income (current holding)	15.6	0.92
5. Multi-cap growth	19.8	0.92
6. Mid-cap index	22.1	0.22
7. Multi-cap core	27.9	0.98
8. Small cap international	35.0	0.54
9. Emerging international	36.1	1.17
10. Money market fund	4.75	0
11. Savings account	1.0	0

Figure 1 shows a spreadsheet model with the optimal solution. The model and all subsequent charts can be found in the supplemental spreadsheet file "Dara's Investments Model and Visualizations.xlsx" (available as supplemental material at http://dx.doi.org/10.1287/ited.2015.0136). The standard Solver Answer and Sensitivity Reports are shown in Figures 2 and 3,

Figure 1 Spreadsheet Model and Optimal Solution

	A	B	C	D	E	F
1	Dara's investments					
2			Average Return	Expenses	Net Return	
3		1 Large cap blend	17.20%	0.93%	16.27%	current holding
4		2 Small cap growth	20.40%	0.56%	19.84%	current holding
5		3 Green fund	26.30%	0.70%	25.60%	current holding
6		4 Growth & income	15.60%	0.92%	14.68%	current holding
7		5 Multi-cap growth	19.80%	0.92%	18.88%	
8		6 Mid-cap index	22.10%	0.22%	21.88%	
9		7 Multi-cap core	27.90%	0.98%	26.92%	
10		8 Small cap international	35.00%	0.54%	34.46%	
11		9 Emerging international	36.10%	1.17%	34.93%	
12		10 Money market fund	4.75%	0.00%	4.75%	
13		11 Savings account	1.00%	0.00%	1.00%	
14		Amount available	$ 100,000.00			
15						
16			Amount Invested	Minimum	Maximum	
17		1 Large cap blend	$ -		$ 20,000.00	
18		2 Small cap growth	$ 15,000.00		$ 20,000.00	
19		3 Green fund	$ 20,000.00		$ 20,000.00	
20		4 Growth & income	$ -		$ 20,000.00	
21		5 Multi-cap growth	$ -		$ 20,000.00	
22		6 Mid-cap index	$ -		$ 20,000.00	
23		7 Multi-cap core	$ 6,000.00		$ 20,000.00	
24		8 Small cap international	$ 20,000.00		$ 20,000.00	
25		9 Emerging international	$ 20,000.00		$ 20,000.00	
26		10 Money market fund	$ 14,000.00	$ 14,000.00		
27		11 Savings account	$ 5,000.00	$ 5,000.00		
28		Total	$ 100,000.00			
29						
30		Total International	$ 40,000.00	$ 16,000.00		
31		Current Holdings	$ 35,000.00	$ 35,000.00	(=)	
32		New Investments	$ 65,000.00	$ 30,000.00		
33			Return			
34		Total Net	$ 24,304.20			

Figure 2 Solver Answer Report

Objective Cell (Max)

Cell	Name	Original Value	Final Value
$C$34	Total Net Return	0	24304.2

Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
$C$17	1 Large cap blend Amount Invested	$ -	$ -	Normal
$C$18	2 Small cap growth Amount Invested	$ -	$ 15,000.00	Normal
$C$19	3 Green fund Amount Invested	$ -	$ 20,000.00	Normal
$C$20	4 Growth & income Amount Invested	$ -	$ -	Normal
$C$21	5 Multi-cap growth Amount Invested	$ -	$ -	Normal
$C$22	6 Mid-cap index Amount Invested	$ -	$ -	Normal
$C$23	7 Multi-cap core Amount Invested	$ -	$ 6,000.00	Normal
$C$24	8 Small cap international Amount Invested	$ -	$ 20,000.00	Normal
$C$25	9 Emerging international Amount Invested	$ -	$ 20,000.00	Normal
$C$26	10 Money market fund Amount Invested	$ -	$ 14,000.00	Normal
$C$27	11 Savings account Amount Invested	$ -	$ 5,000.00	Normal

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$C$28	Total Amount Invested	$ 100,000.00	$C$28=$C$14	Binding	0
$C$30	Total International Amount Invested	$ 40,000.00	$C$30>=$D$30	Not Binding	24000
$C$31	Current Holdings Amount Invested	$ 35,000.00	$C$31=$D$31	Binding	0
$C$32	New Investments Amount Invested	$ 65,000.00	$C$32>=$D$32	Not Binding	35000
$C$17	1 Large cap blend Amount Invested	$ -	$C$17<=$E$17	Not Binding	20000
$C$18	2 Small cap growth Amount Invested	$ 15,000.00	$C$18<=$E$18	Not Binding	5000
$C$19	3 Green fund Amount Invested	$ 20,000.00	$C$19<=$E$19	Binding	0
$C$20	4 Growth & income Amount Invested	$ -	$C$20<=$E$20	Not Binding	20000
$C$21	5 Multi-cap growth Amount Invested	$ -	$C$21<=$E$21	Not Binding	20000
$C$22	6 Mid-cap index Amount Invested	$ -	$C$22<=$E$22	Not Binding	20000
$C$23	7 Multi-cap core Amount Invested	$ 6,000.00	$C$23<=$E$23	Not Binding	14000
$C$24	8 Small cap international Amount Invested	$ 20,000.00	$C$24<=$E$24	Binding	0
$C$25	9 Emerging international Amount Invested	$ 20,000.00	$C$25<=$E$25	Binding	0
$C$26	10 Money market fund Amount Invested	$ 14,000.00	$C$26>=$D$26	Binding	0
$C$27	11 Savings account Amount Invested	$ 5,000.00	$C$27>=$D$27	Binding	0

Figure 3 Solver Sensitivity Report

Objective Cell (Max)

Cell	Name	Final Value
$C$34	Total Net Return	24304.2

Decision Variable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$C$17	1 Large cap blend Amount Invested	$ -	$ (0.04)	0.1627	0.0357	1E+30
$C$18	2 Small cap growth Amount Invested	$ 15,000.00	$ -	0.1984	0.0576001	0.0357001
$C$19	3 Green fund Amount Invested	$ 20,000.00	$ 0.06	0.256	1E+30	0.0576
$C$20	4 Growth & income Amount Invested	$ -	$ (0.05)	0.1468	0.0516	1E+30
$C$21	5 Multi-cap growth Amount Invested	$ -	$ (0.08)	0.1888	0.0804	1E+30
$C$22	6 Mid-cap index Amount Invested	$ -	$ (0.05)	0.2188	0.0504	1E+30
$C$23	7 Multi-cap core Amount Invested	$ 6,000.00	$ -	0.2692	0.0754001	0.0504001
$C$24	8 Small cap international Amount Invested	$ 20,000.00	$ 0.08	0.3446	1E+30	0.0754
$C$25	9 Emerging international Amount Invested	$ 20,000.00	$ 0.08	0.3493	1E+30	0.0801
$C$26	10 Money market fund Amount Invested	$ 14,000.00	$ (0.22)	0.0475	0.2217	1E+30
$C$27	11 Savings account Amount Invested	$ 5,000.00	$ (0.26)	0.01	0.2592	1E+30

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$C$28	Total Amount Invested	$ 100,000.00	$ 0.27	100000	14000	6000
$C$30	Total International Amount Invested	$ 40,000.00	$ -	16000	24000	1E+30
$C$31	Current Holdings Amount Invested	$ 35,000.00	$ (0.07)	35000	5000	14000
$C$32	New Investments Amount Invested	$ 65,000.00	$ -	30000	35000	1E+30

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respectively. Although these reports may be easily understood by users with a good knowledge of linear optimization, they are replete with jargon and concepts that will not be clearly understood by nontechnical users. Presenting such information visually is important to explain such results to managers and users, and students should develop the skills to be able to translate technical output and incorporate it into useful business presentations.

Visualizing the Solver Solution

The first thing that one might do is to visualize the values of the optimal decision variables and constraint functions, drawing upon the model solution or the information contained in the Answer Report. Typically, the default chart created in Excel ignores essential information such as data values. One of the challenges facing users is to select the most useful type of chart and style to convey useful information (Alexander and Walkenbach 2010). Excel provides a variety of chart options in the Chart Styles group under the Chart Tools Design tab, and also under the Quick Layout button in the Chart Layouts group. We suggest that users explore the styles and layout options to choose a more appropriate visualization. Many of the charts in this paper have been customized from these options. Figure 4, for example, is a simple bar chart that shows the values of the optimal investments. In this figure (selected from the Chart Styles options and modified to remove the background shading), labels on the bars enhance the chart to clearly show the accurate values of the variables.

For investment portfolios, one would typically be interested in the mixture of investments. Figure 5, for example, shows a pie for visualizing the (nonzero) percentages invested in each fund. Analytics professionals do not recommend pie charts (Few 2004) because they can be more difficult to compare pie slices visually; a preferred representation is shown using a column chart in Figure 6. Note, however, that

Figure 4 An Excel Bar Chart for the Optimal Solution

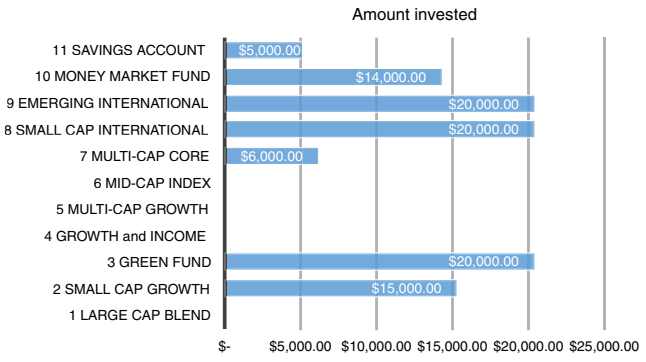


Figure 5 Pie Chart for (Nonzero) Percentages Invested

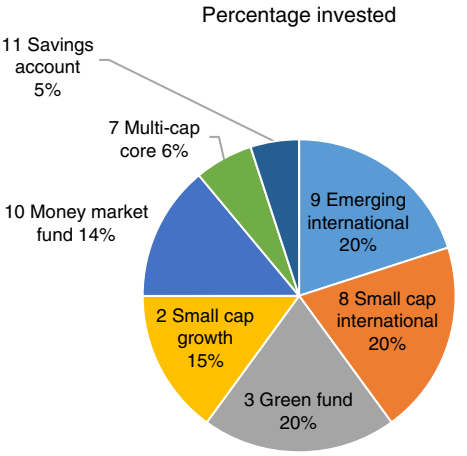
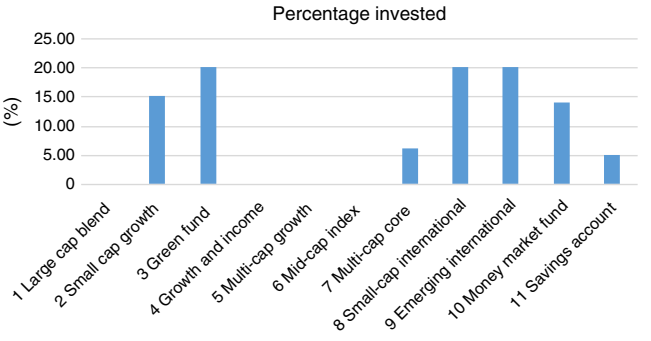


Figure 6 Alternative Column Chart for Percentages Invested



a bar chart (such as the one in Figure 4) may be somewhat easier to read as the lengthy titles can be read more naturally horizontally.

More insight can be gained by the combination chart shown in Figure 7. This chart illustrates the net return (see the range E3:E13 in Figure 1), sorted from high to low, as a line chart, superimposed over a column chart for the amount invested. While we see that investments with the highest returns are at the maximum level of $20,000, we also see some anomalies that might cause one to question the results. For example, we see that the money market fund, with a low rate of return, is funded at a high level; similarly, the multi-cap core fund (the third column) has the third highest rate of return, yet is only funded by a small amount. This can be explained by the fact that the money market fund has a minimum funding requirement of $14,000 and meets this requirement; the low rate of return precludes any further funding of this. The multi-cap core result can be explained by the constraints. The problem requires at least $35,000 in current holdings, $16,000 in international, along with $19,000 in the money market fund and savings account, a total of $70,000. Since the international funds have the highest returns, they should be funded to the maximum level, adding another $24,000

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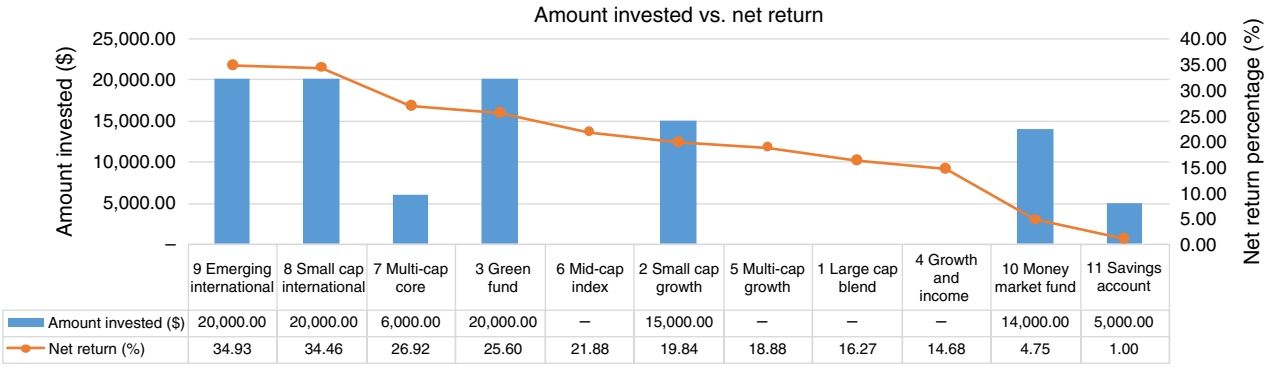
Figure 7 Combination Chart for Amount Invested vs. Net Return



	9 Emerging international	8 Small cap international	7 Multi-cap core	3 Green fund	6 Mid-cap index	2 Small cap growth	5 Multi-cap growth	1 Large cap blend	4 Growth and income	10 Money market fund	11 Savings account
Amount invested ($)	20,000.00	20,000.00	6,000.00	20,000.00	–	15,000.00	–	–	–	14,000.00	5,000.00
Net return (%)	34.93	34.46	26.92	25.60	21.88	19.84	18.88	16.27	14.68	4.75	1.00

Figure 8 Visualization of Solution and Slack Values on Upper Bound Constraints

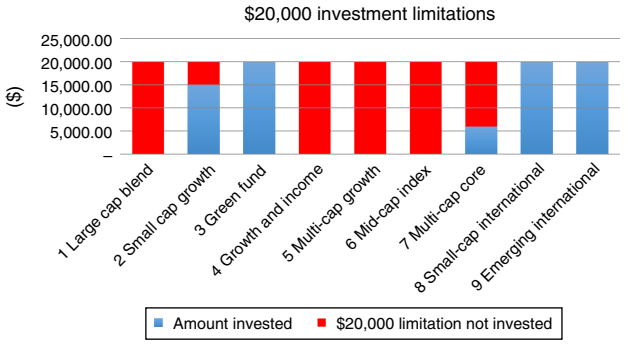
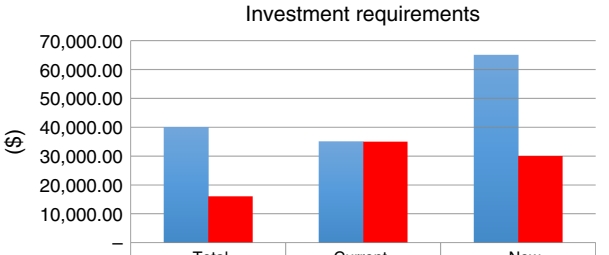


Figure 9 Visualization of Slack Values for Structural Constraints



	Total international	Current holdings	New investments
Amount invested ($)	40,000.00	35,000.00	65,000.00
Requirement ($)	16,000.00	35,000.00	30,000.00

to the total. The remaining $6,000 should be allocated to the fund with the next highest return; that is, the multi-cap core fund. Although this is certainly easy to argue, the fact is that the visualization can easily identify potential issues that require further explanation.

Slack values corresponding to each investment (from the upper or lower bound constraints) in the Solver Answer report represent either the amounts that can be invested before exceeding the 20% ($20,000) limitation on the first nine funds, or any amounts exceeding the minimum requirement on the money market or savings account funds. Figure 8 is a simple visualization of the dollar amounts invested and amounts not invested with respect to the $20,000 limitation. The stacked bar chart allows an easy comparison among the different funds.

For the structural constraints (international, current holdings, and new investments—constraints 2, 3, and 4 in the problem statement), Figure 9 shows the amounts invested in comparison with the requirement.

Visualizing Sensitivity Information

The Sensitivity Report is more challenging to visualize effectively. The reduced costs describe how much the net return coefficient on an investment must be changed to force the value of a variable that is currently zero in the solution to become positive. Because Solver handles simple bounds implicitly, the reduced costs for variables at their upper or lower bounds are equivalent to shadow prices, and are interpreted as the amount that the objective coefficient must change before the value will decrease from its upper bound or increase from its lower bound. For example, the net return on the large cap blend fund must be reduced by a negative $0.04 (i.e., increased by $0.04) to make it attractive to invest in that fund. Similarly, the net return on the small cap international fund must be reduced by $0.08 before it will fall from its $20,000 limit, and the net return on the money market fund must increase by $0.22 before the amount invested will increase from its minimum requirement.

Figure 10 shows a visualization of this reduced cost information as a stacked column chart. The chart displays the net return coefficients for each investment, and the change required before the value of that variable will change. To construct this chart, the reduced costs from the Solver Sensitivity report need to be multiplied by −1 to visualize correctly.

We may also visualize the ranges over which the unit cost coefficients may change without changing the optimal values of the decision variables (the Allowable Increase and Allowable Decrease values in the Solver Sensitivity report) by using an Excel

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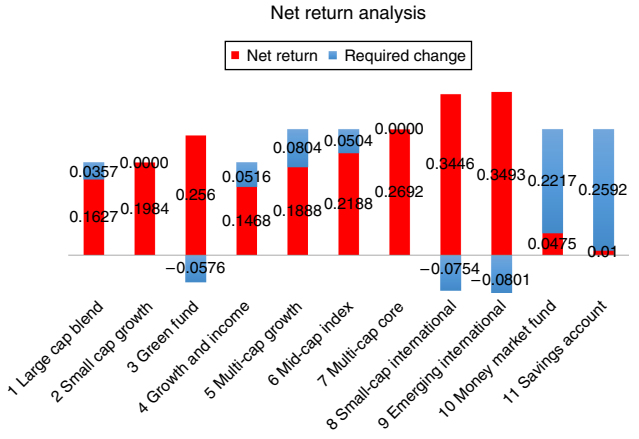
Figure 10 Visualization of Reduced Costs



"high-low-close" stock chart. To do this, follow these steps:

1. Create a table in the worksheet by adding the Allowable Increase values and subtracting the Allowable Decrease values from the cost coefficients as shown in Figure 11. Replace 1E+30 by #N/A in the worksheet so that infinite values are not displayed.

2. Highlight the range of this table and insert an Excel High-Low-Close Stock Chart and name the series as Maximum, Minimum, and Current.

3. Click the chart, and in the Format tab of *Chart Tools*, go to the *Current Selection* group to the left of the ribbon and click on the drop down box (it usually says "Chart Area"). Find the series you wish to format and then click *Format Selection*.

4. In the *Format Data Series* pane that appears in the worksheet, click the paint icon and then Marker, making sure to expand the Marker Options menu.

5. Choose the type of marker you wish and increase the width of the markers to make them more visible. We chose an × for the current value, a triangle for the minimum value, and a dash for the maximum value. This results in the chart shown in Figure 12.

Figure 11 Table for Constructing Stock Chart

Fund	Maximum	Minimum	Current
1 Large cap blend	0.1984	#N/A	0.1627
2 Small cap growth	0.2560001	0.1626999	0.1984
3 Green fund	#N/A	0.1984	0.256
4 Growth and income	0.1984	#N/A	0.1468
5 Multi-cap growth	0.2692	#N/A	0.1888
6 Mid-cap index	0.2692	#N/A	0.2188
7 Multi-cap core	0.3446001	0.2187999	0.2692
8 Small cap international	#N/A	0.2692	0.3446
9 Emerging international	#N/A	0.2692	0.3493
10 Money market fund	0.2692	#N/A	0.0475
11 Savings account	0.2692	#N/A	0.01

Figure 12 Visualization of Allowable Cost Coefficient Ranges

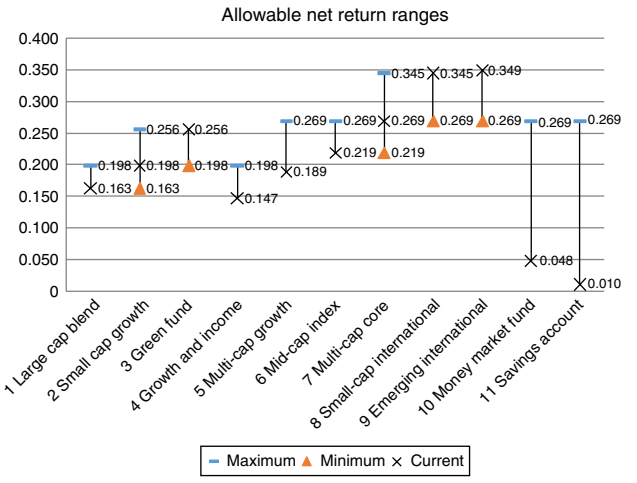
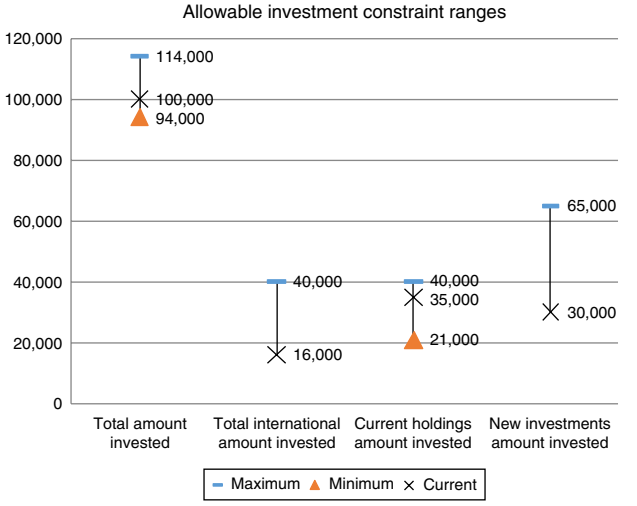


Figure 13 Visualization of Allowable Shadow Price Ranges



We can interpret the chart as follows. For those lines that have no maximum limit (no dash), the net return coefficients can increase to infinity; for those that have no lower limit (no triangle), the net return coefficient can decrease indefinitely. Otherwise, the range is clearly shown.

Shadow prices show the impact of changing the right-hand side of a binding constraint. Figure 13 shows the ranges based on the Allowable Increase and Allowable Decrease values over which these prices are valid, using a similar approach as described earlier for the cost coefficient ranges.

Parametric Analysis Visualizations

Frontline Systems' Analytic Solver Platform provides the capability of performing one- and two-way parametric analyses for optimization models (as an alternative, Chris Albright provides a free Solver Table add-in; see http://kelley.iu.edu/albrightbooks/). For

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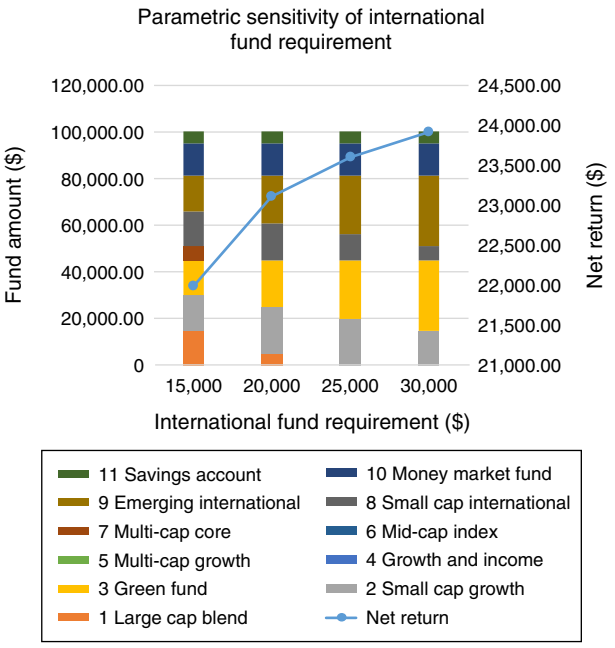
Figure 14 One-Way Parametric Sensitivity Analysis Table

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	International Fund Requirement	Net Return	1 Large cap blend	2 Small cap growth	3 Green fund	4 Growth & income	5 Multi-cap growth	6 Mid-cap index	7 Multi-cap core	8 Small cap international	9 Emerging international	10 Money market fund	11 Savings account
2	$15,000	$21,995.20	$15,000.00	$15,000.00	$15,000.00	$0.00	$0.00	$0.00	$6,000.00	$15,000.00	$15,000.00	$14,000.00	$5,000.00
3	$20,000	$23,116.10	$5,000.00	$20,000.00	$20,000.00	$0.00	$0.00	$0.00	$0.00	$16,000.00	$20,000.00	$14,000.00	$5,000.00
4	$25,000	$23,606.10	$0.00	$20,000.00	$25,000.00	$0.00	$0.00	$0.00	$0.00	$11,000.00	$25,000.00	$14,000.00	$5,000.00
5	$30,000	$23,917.60	$0.00	$15,000.00	$30,000.00	$0.00	$0.00	$0.00	$0.00	$6,000.00	$30,000.00	$14,000.00	$5,000.00

Figure 15 Visualization of One-Way Parametric Sensitivity Table



this example, we will illustrate both a one-way and two-way parametric sensitivity analysis table and visualizations. Figure 14 shows the results of varying the International Fund requirement between $15,000 and $30,000 on the net return and amounts allocated to each fund. These results are visualized in the combination chart in Figure 15. The stacked bar portion of the chart shows the fund allocations as the requirement is varied; the line chart using the secondary axis shows the increase in the net return as the International Fund requirement is increased.

Figure 16 shows the results of a two-way parametric analysis, varying both the International Fund requirement as well as the Current Holdings requirement (#N/A error code signifies infeasibility). In a two-way table, only one output value can be computed; in this case, the net return. Because Analytic Solver Platform creates a standard Excel PivotTable, we could easily create a Pivot Chart to illustrate the results as shown in Figure 17. By filtering any of the variables, we can also display alternate views of the data, as shown in Figure 18.

Figure 17 Pivot Chart Visualization of Two-Way Sensitivity Table

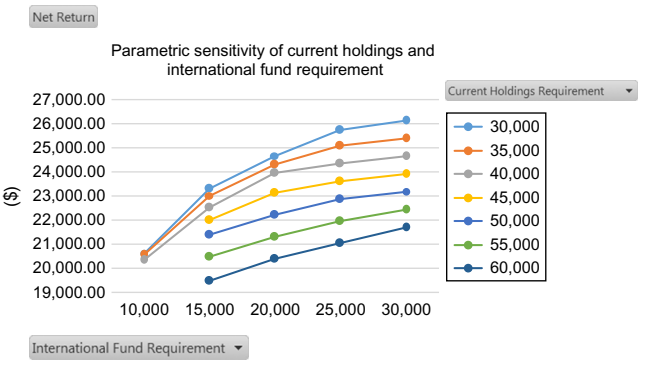
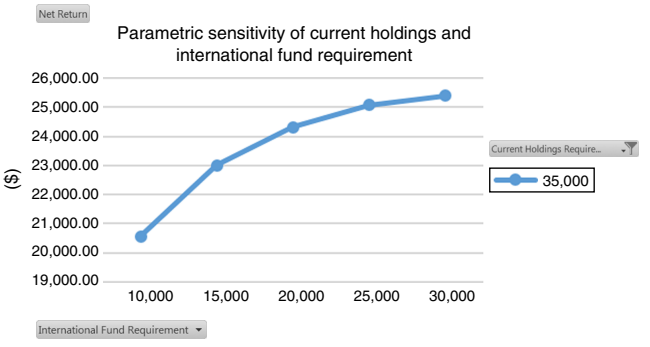


Figure 18 Filtered Pivot Chart



Conclusions

Interpreting and communicating the results of optimization solutions using Excel Solver can be challenging because of the terminology used and technical

Figure 16 Two-Way Parametric Sensitivity Table

	A	B	C	D	E	F	G	H
1	Net Return	Current Holdings Requirement						
2	International Fund Requirement	$30,000.00	$35,000.00	$40,000.00	$45,000.00	$50,000.00	$55,000.00	$60,000.00
3	$10,000	$20,640.50	$20,571.80	$20,361.80	#N/A	#N/A	#N/A	#N/A
4	$15,000	$23,290.30	$23,009.80	$22,527.70	$21,995.20	$21,383.20	$20,469.60	$19,480.60
5	$20,000	$24,658.20	$24,304.20	$23,950.20	$23,116.10	$22,206.60	$21,297.10	$20,387.60
6	$25,000	$25,723.70	$25,068.10	$24,337.10	$23,606.10	$22,875.10	$21,965.60	$21,037.30
7	$30,000	$26,110.60	$25,379.60	$24,648.60	$23,917.60	$23,186.80	$22,436.80	$21,682.30

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understanding of optimization required. Simple Excel charts can enhance the communication of Solver optimization results through data visualization and improve the ability to explain optimization concepts to managers and clients without appropriate technical background. These ideas can also supplement traditional classroom instruction and enhance students' analytics communication skills.

Supplemental Material

Supplemental material to this paper is available at http://dx.doi.org/10.1287/ited.2015.0136.

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