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Teaching Note

Some Practical Issues with Excel Solver: Lessons for Students and Instructors

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Spreadsheets have become the principal software application for teaching decision models in most business schools. In particular, Excel Solver is used extensively for solving and analyzing optimization models. However, there are a number of important issues in using Solver of which many users are unaware. These include the impact of spreadsheet design and cell formatting on Solver reports, handling of lower and upper bound constraints, and dealing with the implications of implicit assumptions in spreadsheet models when interpreting Solver sensitivity reports. Students and instructors, as well as most popular textbooks, rarely pay sufficient attention to these issues. This article summarizes these important issues, provides guidelines for avoiding problems, and offers examples that can be incorporated into the classroom.

Key words: excel solver; spreadsheet implementation; model assumptions; sensitivity analysis

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Introduction

Excel Solver is used today in nearly all mainstream management sciences textbooks and courses in business schools throughout the world for teaching optimization modeling. In using such software, many mainstream textbooks and instructors ignore some very important issues that transcend the “point-and-click” process of implementing and solving spreadsheet optimization models. Some of these have been addressed in prior literature. For example, Conway and Ragsdale (1997), addressed some of the early issues associated with logical design of spreadsheet models. The paper by Fylstra et al. (1998), which comprehensively describes how Solver was designed and developed, addresses other practical issues associated with using the software. These include the impact of spreadsheet design and naming conventions, cell formatting on Solver reports, and handling of lower and upper bound constraints. However, being roughly a decade old, many current instructors have probably not seen this paper. It also does not provide detailed examples suitable for classroom illustration and instruction. This article summarizes these and other important practical issues associated with using Solver that are not addressed in sufficient detail in current texts, such as dealing with the implications of implicit assumptions in spreadsheet models when interpreting Solver sensitivity reports. This article also

provides guidelines for avoiding potential problems and offers simple examples that can easily be incorporated into the classroom.

Spreadsheet Design and Solver Report Readability

How one designs a spreadsheet model will affect how Solver creates the names used in the output reports. Poor spreadsheet design can make it difficult or confusing to interpret the answer and sensitivity reports. Thus, it is important to understand how to do this properly. Some textbooks provide useful and practical guidelines for modeling optimization problems on spreadsheets; see, for instance, Albright et al. (2003), Powell and Baker (2004), and Ragsdale (2001). However, these texts do not clearly address the relationship of spreadsheet design on report readability.

Consider a simple product mix model:

$$\text{Max } 48A + 70B$$

$$6A + 6B \leq 3,000$$

$$3A + 5B \leq 1,750$$

$$A, B \text{ nonnegative.}$$

An innocuous-looking spreadsheet implementation of this model is shown in Figure 1. Figure 2 shows the Solver-generated Answer Report. Note that the names

Figure 1 Spreadsheet Implementation of Product Mix Model

	A	B	C	D
1	Product Mix Problem			
2				
3	<i>Data</i>			
4				
5		Product A	Product B	
6	Unit profit	\$ 48.00	\$ 70.00	Amount Available
7	Resource 1 Requirement/Unit	6	6	3000
8	Resource 2 Requirement/Unit	3	5	1750
9				
10	<i>Decision Variables</i>			
11		Product A	Product B	
12	Units Produced	375	125	
13				
14	<i>Objective</i>			
15				
16	Profit	\$26,750.00		
17				
18	<i>Constraints</i>			
19				
20	Resource 1 Used	3,000		
21	Resource 2 Used	1,750		

for the objective, “Profit Product A,” and constraints, “Resource 1 Used Product A,” and “Resource 2 Used Product A” are quite misleading as they should not refer to Product A.

Solver assigns names to target cells, changing cells, and constraint function cells by concatenating the text in the first cell containing text to the left of the cell with the first cell containing text above it (see Fylstra et al. 1998, p. 50). Thus, in the simple product mix model in Figure 1, the name assigned to the objective function cell, B16, is the concatenation of the text in cells A16 and B11. The constraint function names are likewise created by concatenating cells A20 and A21 with cell B11. Poor selection of text names and locations in the spreadsheet can easily produce output reports that are unintelligible or at the very least, difficult to interpret, particularly in more complex models. A better spreadsheet design that anticipates the Solver assigned names to the objective and constraint function cells is shown in Figure 3. As is evident in the Solver Answer Report in Figure 4, the names correctly identify the cells to which they correspond.

Figure 2 Solver Answer Report

A	B	C	D	E	F	G
1	Microsoft Excel 11.0 Answer Report					
2	Worksheet: [Lego example.xls]Sheet1					
3	Report Created: 6/1/2007 9:20:24 AM					
4						
5						
6	Target Cell (Max)					
7	Cell	Name	Original Value	Final Value		
8	\$B\$16	Profit Product A	\$ -	\$ 26,750.00		
9						
10	Adjustable Cells					
11	Cell	Name	Original Value	Final Value		
12	\$B\$12	Product A	0	375		
13	\$C\$12	Product B	0	125		
14						
15						
16	Constraints					
17	Cell	Name	Cell Value	Formula	Status	Slack
18	\$B\$20	Resource 1 Used Product A	3,000	\$B\$20<=\$D\$7	Binding	0
19	\$B\$21	Resource 2 Used Product A	1,750	\$B\$21<=\$D\$8	Binding	0

Figure 3 Improved Spreadsheet Design for the Product Mix Model

	A	B	C	D
1	Product Mix Problem			
2				
3	<i>Data</i>			
4				
5		Product A	Product B	
6	Unit profit	\$ 48.00	\$ 70.00	Amount Available
7	Resource 1 Requirement/Unit	6	6	3000
8	Resource 2 Requirement/Unit	3	5	1750
9				
10	<i>Decision Variables</i>			
11		Product A	Product B	
12	Units Produced	375	125	
13				
14	<i>Objective</i>			
15				
16	Profit	\$ 26,750.00		
17				
18	<i>Constraints</i>			
19				
20	Resource 1	Amount Used 3,000		
21	Resource 2	1,750		

Solver Reports and Cell Formatting

Depending on how cells in your spreadsheet model are formatted, the Sensitivity Report produced by Solver may not reflect the accurate values of reduced costs or shadow prices because an insufficient number of decimal places are displayed. Fylstra et al. (1998) notes that this pitfall was a result of a Microsoft specification, whereby the report worksheets inherit the formatting from the cells in the user’s model. I have encountered numerous instances of such errors that have resulted in the misinterpretation of results in homework assignments.

To see this, consider the simple transportation model shown in Figure 5. Figure 6 shows the Solver Sensitivity Report. Note that the default values of the reduced costs and shadow prices are expressed as integers. Figure 7 shows the correct values after reformatting column E to have two decimals. The problem appears to stem from the fact that the changing cell range, B13:E14, and constraint function ranges (B15:E15 and F13:F14) were input, and consequently

Figure 4 Answer Report for Improved Spreadsheet Model

A	B	C	D	E	F	G
1	Microsoft Excel 11.0 Answer Report					
2	Worksheet: [Lego example.xls]Sheet1					
3	Report Created: 6/1/2007 9:37:31 AM					
4						
5						
6	Target Cell (Max)					
7	Cell	Name	Original Value	Final Value		
8	\$B\$16	Profit	\$ 26,750.00	\$ 26,750.00		
9						
10	Adjustable Cells					
11	Cell	Name	Original Value	Final Value		
12	\$B\$12	Units Produced Product A	375	375		
13	\$C\$12	Units Produced Product B	125	125		
14						
15						
16	Constraints					
17	Cell	Name	Cell Value	Formula	Status	Slack
18	\$B\$20	Resource 1 Amount Used	3,000	\$B\$20<=\$D\$7	Binding	0
19	\$B\$21	Resource 2 Amount Used	1,750	\$B\$21<=\$D\$8	Binding	0

Figure 5 Transportation Model Spreadsheet

	A	B	C	D	E	F
1	Transportation Model					
2						
3	Data					
4	Distribution Center					
5	Plant	Cleveland	Baltimore	Chicago	Phoenix	Capacity
6	Marietta	\$ 12.60	\$ 14.35	\$ 11.52	\$ 17.58	1200
7	Minneapolis	\$ 9.75	\$ 12.63	\$ 8.11	\$ 15.88	800
8	Demand	150	350	500	1000	
9						
10	Model					
11	Distribution Center					
12	Plant	Cleveland	Baltimore	Chicago	Phoenix	Total shipped
13	Marietta	0	200	0	1000	1200
14	Minneapolis	150	150	500	0	800
15	Demand met	150	350	500	1000	
16						
17	Total cost					
18	\$	27,862.00				

Figure 6 Default Solver Sensitivity Report

A	B	C	D	E	F	G	H
1	Microsoft Excel 11.0 Sensitivity Report						
2	Worksheet: [Transportation Model.xls]Sheet1						
3	Report Created: 7/10/2007 4:43:44 PM						
4							
5							
6	Adjustable Cells						
7			Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
8	Cell	Name					
9	\$B\$13	Marietta Cleveland	0	1	12.6	1E+30	1.13
10	\$C\$13	Marietta Baltimore	200	0	14.35	1.13	0.02
11	\$D\$13	Marietta Chicago	0	2	11.52	1E+30	1.69
12	\$E\$13	Marietta Phoenix	1000	0	17.58	0.02	1E+30
13	\$B\$14	Minneapolis Cleveland	150	0	9.75	1.13	1E+30
14	\$C\$14	Minneapolis Baltimore	150	0	12.63	0.02	1.13
15	\$D\$14	Minneapolis Chicago	500	0	8.11	1.69	1E+30
16	\$E\$14	Minneapolis Phoenix	0	0	15.88	1E+30	0.02
17							
18	Constraints						
19			Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
20	Cell	Name					
21	\$B\$15	Demand met Cleveland	150	11	150	0	150
22	\$C\$15	Demand met Baltimore	350	14	350	0	200
23	\$D\$15	Demand met Chicago	500	10	500	0	200
24	\$E\$15	Demand met Phoenix	1000	18	1000	0	1000
25	\$F\$13	Marietta Total shipped	1200	0	1200	1E+30	0
26	\$F\$14	Minneapolis Total shipped	800	-2	800	200	0

Figure 7 Reformatted Sensitivity Report

A	B	C	D	E	F	G	H
1	Microsoft Excel 11.0 Sensitivity Report						
2	Worksheet: [Transportation Model.xls]Sheet1						
3	Report Created: 7/10/2007 4:43:44 PM						
4							
5							
6	Adjustable Cells						
7			Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
8	Cell	Name					
9	\$B\$13	Marietta Cleveland	0	1.13	12.6	1E+30	1.13
10	\$C\$13	Marietta Baltimore	200	0.00	14.35	1.13	0.02
11	\$D\$13	Marietta Chicago	0	1.69	11.52	1E+30	1.69
12	\$E\$13	Marietta Phoenix	1000	0.00	17.58	0.02	1E+30
13	\$B\$14	Minneapolis Cleveland	150	0.00	9.75	1.13	1E+30
14	\$C\$14	Minneapolis Baltimore	150	0.00	12.63	0.02	1.13
15	\$D\$14	Minneapolis Chicago	500	0.00	8.11	1.69	1E+30
16	\$E\$14	Minneapolis Phoenix	0	0.02	15.88	1E+30	0.02
17							
18	Constraints						
19			Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
20	Cell	Name					
21	\$B\$15	Demand met Cleveland	150	11.47	150	0	150
22	\$C\$15	Demand met Baltimore	350	14.35	350	0	200
23	\$D\$15	Demand met Chicago	500	9.83	500	0	200
24	\$E\$15	Demand met Phoenix	1000	17.58	1000	0	1000
25	\$F\$13	Marietta Total shipped	1200	0.00	1200	1E+30	0
26	\$F\$14	Minneapolis Total shipped	800	-1.72	800	200	0

formatted, without any decimals. If one changes the formatting of the changing cell range only, then the reduced costs are correctly formatted in the sensitivity report, but the shadow prices are not because they are associated with the constraint functions. However, if one also formats the constraint function ranges, all output will be correctly formatted. The simplest way to address this issue is to select the reduced cost and shadow price ranges in the Sensitivity Report and format them to have at least two or three decimal places. This eliminates the need to add useless decimals to decision variable and constraint function cells in the spreadsheet which will, of course, always have integer solutions.

Lower and Upper Bound Constraints

Solver handles simple lower bounds (e.g., $x \geq 10$) and upper bounds (e.g., $x \leq 150$) quite differently from ordinary constraints in the Sensitivity Report (Fylstra et al. 1998, p. 50). In Solver, lower and upper bounds are treated in a manner similar to nonnegativity constraints, which also do not appear explicitly as constraints in the model. Solver does this to increase the efficiency of the solution procedure used; for large models this can represent significant savings in computer processing time. While the technical reasons for this are well known, and provide computational efficiency (see, for instance, Bazarrá et al. 1990, p. 206), this can be quite confusing to undergraduate and MBA-level students because it makes it more difficult to interpret the sensitivity information.

To illustrate this, consider a modified version of the product mix problem to which we have added a lower bound constraint on the number of units of Product A that must be produced ($A \geq 400$). The model (with the new solution) is shown in Figure 8. We included the minimum requirement in cell B8 and then added a constraint to Solver to reflect this requirement ($B12 \geq B8$). The Sensitivity Report is shown in Figure 9. (Note also that the reduced cost and shadow price column were reformatted as per the discussion in the previous section. Without doing this, the default shadow price for Resource 1 was displayed as 12!)

Notice that in the Sensitivity Report of Figure 9, the lower bound constraint does not appear in the Constraints section. The reduced cost tells how much the objective coefficient needs to change in order for a variable to become positive in an optimal solution. We see that the reduced cost for Product A is $-\$22$. In the optimal solution we are only producing the minimum number of units of Product A required by the model. This is because, from a managerial perspective, it is simply not profitable to produce more with a unit profit of only \$48. The interpretation of this

Figure 8 Solver Model with Lower Bound Requirement

	A	B	C	D
1	Product Mix Problem			
2				
3	<i>Data</i>			
4				
5		Product A	Product B	
6	Unit profit	\$ 48.00	\$ 70.00	Amount Available
7	Resource 1 Requirement/Unit	6	6	3000
8	Resource 2 Requirement/Unit	3	5	1750
9	Minimum requirement	400		
10				
11	<i>Decision Variables</i>			
12		Product A	Product B	
13	Units Produced	400	100	
14				
15	<i>Objective</i>			
16		Profit		
17		\$ 26,200.00		
18				
19	<i>Constraints</i>			
20		Amount Used		
21	Resource 1	3,000		
22	Resource 2	1,700		

reduced cost means that the current objective coefficient is \$22 lower than what it would need to be in order to force the solution to produce more than the 400 units. If we increased the objective coefficient to more than $\$48 + \$22 = \$70$, then the solution would change and it would now be profitable to produce more units of Product A.

An alternate way to interpret the reduced cost is as a shadow price of the lower bound constraint. If we increase the right-hand side of the lower bound constraint by one, we are essentially forcing the solution to produce more than the minimum requirement. How much would the objective function change if we do this? It would decrease by \$22 because we would lose money by producing an extra unit of a non-profitable product. In fact, notice that by adding the constraint, we forced an additional 25 units of Product A to be made from the base case. With a shadow price of $-\$22$, the total profit decreased by $25(\$22)$ or \$550. Therefore, the reduced cost associated with Product A is the same as the shadow price of the lower bound constraint. In general, any variable that is at its lower or upper bound in the final solution will appear in the Adjustable Cells section and have a nonzero reduced

Figure 9 Solver Sensitivity Report with Lower Bound Requirement

A	B	C	D	E	F	G	H
1	Microsoft Excel 11.0 Sensitivity Report						
2	Worksheet: [product mix design example.xls]Sheet1						
3	Report Created: 6/1/2007 9:52:58 AM						
4							
5							
6	Adjustable Cells						
7			Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
8	Cell	Name					
9	\$B\$13	Units Produced Product A	400	-22.00	48	22	1E+30
10	\$C\$13	Units Produced Product B	100	0.00	70	1E+30	22
11							
12	Constraints						
13			Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
14	Cell	Name					
15	\$B\$21	Resource 1 Amount Used	3,000	11.67	3000	60	600
16	\$B\$22	Resource 2 Amount Used	1,700	0.00	1750	1E+30	50

Figure 10 Modified Product Mix Model with Auxiliary Variable

	A	B	C	D
1	Product Mix Problem			
2				
3	<i>Data</i>			
4				
5		Product A	Product B	
6	Unit profit	\$ 48.00	\$ 70.00	Amount Available
7	Resource 1 Requirement/Unit	6	6	3000
8	Resource 2 Requirement/Unit	3	5	1750
9	Minimum requirement	400		
10				
11	<i>Decision Variables</i>			
12		Product A	Product B	
13	Units Produced	400	100	
14	Auxiliary Variable	400		
15				
16	<i>Objective</i>			
17		Profit		
18		\$ 26,200.00		
19				
20	<i>Constraints</i>			
21		Amount Used		
22	Resource 1	3,000		
23	Resource 2	1,700		

cost, and the value of the reduced cost may be interpreted as the shadow price of the bound constraint.

Using reduced costs as shadow prices can be a bit confusing. Fortunately, there are a couple of ways of handling this to eliminate the difficulty of correctly interpreting the reduced cost as a shadow price. Fylstra et al. (1998) suggest modifying the right-hand side of bounded constraints to be a formula rather than a constant; for example, “0 + 5” rather than the constant “5.” Another approach, which one of my students inadvertently stumbled upon, is to define a new set of cells for any decision variables that have upper or lower bound constraints by referencing (not copying) the original changing cells in the spreadsheet model. This is shown in Figure 10 in cell B14, labeled “Auxiliary Variable.” The cell formula for B14 is =B13; we have simply referenced the changing cell for Product A. In the Solver model, use this auxiliary variable cell to define the bound constraint; that is, $B14 \geq B9$. Looking at the Sensitivity Report for this model in Figure 11, we now see that the Constraints section has a new row corresponding to this constraint and that the shadow price is the same as the reduced cost in the previous Sensitivity Report. Another advantage of using this approach is that we also know the allowable increase and decrease for the shadow price, which was not available in the previous Sensitivity Report.

Understanding Assumptions in Using Sensitivity Analysis¹

The final issue that we address concerns, not Solver design issues, but a more thorough understanding

¹ This issue was brought to my attention by one of my students, Mr. Marcus Glasgow. I gratefully acknowledge his contribution to the analysis of this example.

Figure 11 Sensitivity Report for Modified Model

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
\$B\$13	Units Produced Product A	400	0.00	48	22	1E+30
\$C\$13	Units Produced Product B	100	0.00	70	1E+30	22

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
\$B\$14	Auxiliary Variable Product A	400	-22.00	400	100	25
\$B\$22	Resource 1 Amount Used	3,000	11.67	3000	60	600
\$B\$23	Resource 2 Amount Used	1,700	0.00	1750	1E+30	50

of the assumptions underlying Solver results. Most analytical procedures have built-in assumptions that govern the correctness (or lack thereof) of the technique. Examples include analysis of variance, linear regression, and many other statistical procedures. While such assumptions are often explained in lectures, it is rare that textbook examples and homework problems require students to carefully consider them. A case in point is sensitivity analysis in linear optimization. One crucial assumption in interpreting sensitivity analysis information for changes in model parameters is that all other model parameters are held constant. Thus, it is easy to fall into a trap of ignoring them and blindly crunching through the numbers without due consideration of these assumptions. This is particularly true when using spreadsheet models.

Model complexity can confound the situation, as can the manner in which the analysis is taught in the classroom and textbooks. While popular current textbooks note this requirement, the impact of modeling on this assumption is often not clearly addressed. By simply providing examples where the assumptions hold, students can easily ignore them. We provide one example that illustrates this issue along with some suggestions for dealing with it in lectures and assignments.

The following is a modified example drawn from an old operations research text (Eck 1976, pp. 129–130):

A small winery, Walker Wines, buys grapes from local growers and blends the pressings to make two types of wine: shiraz and merlot. It costs \$1.60 to purchase the grapes needed to make a bottle of shiraz, and \$1.40 to purchase the grapes needed to make a bottle of merlot. The contract requires that they provide at least 40% but not more than 70% shiraz. Based on some market research it is estimated that the base demand for shiraz is 1,000 bottles, but increases by 5 bottles for each \$1 spent on advertising while the base demand for merlot is 2,000 bottles and increases by 8 bottles for each \$1 spent on advertising. Production should not exceed demand. Shiraz sells for \$6.25 per bottle while merlot is sold for \$5.25 per bottle. Walker Wines

has \$50,000 available to purchase grapes and advertise its products, with an objective of maximizing profit contribution.

To formulate this model, let

S = number of bottles of shiraz produced,
 M = number of bottles of merlot produced,
 A_s = dollar amount spent on advertising shiraz, and
 A_m = dollar amount spent on advertising merlot.

The objective is to maximize profit
 (revenue minus costs)

$$= (\$6.25S + \$5.25M) - (\$1.60S + \$1.40M + A_s + A_m)$$

$$= 4.65S + 4.85M - A_s - A_m.$$

Constraints are defined as follows.

- Budget cannot be exceeded:
 $\$1.60S + \$1.40M + A_s + A_m \leq \$50,000.$
- Contractual requirements must be met:
 $0.4 \leq S/(S + M) \leq 0.7$
 or, expressed in linear form:
 $0.6S - 0.4M \geq 0$ and $0.3S - 0.7M \leq 0.$
- Production must not exceed demand:
 $S \leq 1,000 + 5A_s$
 $M \leq 2,000 + 8A_m.$
- Nonnegativity.

Figure 12 shows a spreadsheet implementation of this model along with the Solver solution. Figure 13 shows the Solver Sensitivity Report.

A variety of practical questions can be posed around the Sensitivity Report. For example, suppose that the accountant noticed a small error in computing the profit contribution for shiraz. The cost of shiraz

Figure 12 Spreadsheet Implementation of Walker Wines

A	B	C	D	E	F
1	Walker Wines Product Mix				
2					
3	Data				
4		Shiraz	Merlot		
5	Cost/bottle	\$ 1.60	\$ 1.40		
6	Price/bottle	\$ 6.25	\$ 5.25		
7					
8	Base demand	1,000.00	2,000.00		
9	Increase/\$1 Adv.	5	8		
10	Min. percent requirement	40%			
11	Max. percent limitation	70%			
12					
13	Total Budget	\$ 50,000.00			
14					
15	Model				
16					
17	Total profit				
18	\$	124,775.64			
19		Shiraz	Merlot	Total	
20	Unit profit	\$ 4.65	\$ 3.85		
21	Advertising dollars	\$ 3,912.37	\$ 851.53	\$ 4,763.90	
22	Demand	20,561.86	8,812.23	29,374.09	
23	Quantity produced	20,561.86	8,812.23	29,374.09	
24					
25	Min. percent requirement	8812.227074	>=	0	
26	Max. percent limitation	0	<=	0	
27					
28				Used	Unused
29	Budget	\$ 36,811.35	\$ 13,188.65	\$ 50,000.00	\$ -

Figure 13 Walker Wines Solver Sensitivity Report

	A	B	C	D	E	F	G	H
1	Microsoft Excel 11.0 Sensitivity Report							
2	Worksheet: [Walker Wines Revised.xls]Solver Results							
3	Report Created: 5/30/2007 10:24:32 AM							
4								
5								
6	Adjustable Cells							
7								
8		Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
9		\$C\$21	Advertising dollars Shiraz	\$ 3,912.37	\$ -	-1	3.771790808	0.266393443
10		\$D\$21	Advertising dollars Merlot	\$ 851.53	\$ -	-1	0.361111111	112.8666667
11		\$C\$23	Quantity produced Shiraz	20,561.86	0.00	4.65	1E+30	0.053278689
12		\$D\$23	Quantity produced Merlot	8,812.23	0.00	3.85	0.045138889	14.10833333
13								
14	Constraints							
15								
16		Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
17		\$C\$23	Quantity produced Shiraz	20,561.86	0.69	0	21297.93978	195000
18		\$D\$23	Quantity produced Merlot	8,812.23	0.43	0	6964.285714	383971.4286
19		\$C\$25	Min. percent requirement Shiraz	8812.227074	0	0	8812.227074	1E+30
20		\$C\$26	Max. percent limitation Shiraz	0	0.047307132	0	6500	9256.880734
21		\$E\$29	Budget Used	\$ 50,000.00	\$ 2.46	50000	1E+30	39000

grapes should have been \$1.65 instead of \$1.60. How will this affect the solution?

Students will immediately recognize that the unit profit of shiraz drops from \$4.65 to \$4.60. As classical sensitivity analysis is taught, one would examine the allowable decrease associated with the objective coefficient and note that since the change in the profit coefficient is within the allowable decrease of 0.05328, one would conclude that no change in the optimal solution will result. However, this is not the correct interpretation. If the model is resolved using the new cost parameter, the solution changes dramatically as shown in Figure 14. Because the unit cost is also reflected in the binding budget constraint, the fundamental reason for this result is clearly that any increase in the cost of grapes causes the budget constraint to become infeasible, and thus the solution must be adjusted to maintain feasibility. This can also be illustrated clearly by providing a table showing the actual changes over the range of the parameter changes as shown in Figure 15.

Alternatively, it should be noted that the sensitivity range is correct if the change is applied to the selling price of the wine instead of the cost, for example, decreasing the selling price from \$6.25 to \$6.20. In this case, the solution remains the same, although the total profit decreases by $(\$0.05 * 20,561.86)$. The difference between the two scenarios is simple. If the selling price changes, then all other model parameters remain constant—the fundamental assumption underlying sensitivity analysis. If the cost changes, then the coefficients in the constraints also change—a violation of the assumption. Unless this is clearly understood, most students (and indeed, many instructors), will not recognize the difference.

What can be done to mitigate this issue? The simple answer is to just change the value of the parameter in

the spreadsheet and resolve. While this will obviously provide the correct solution, it defeats the purpose of sensitivity analysis. The real issue stems from confusing the spreadsheet model with the underlying linear program. One should fully understand the mathematical model first and could easily check whether the cost parameter is included in any of the constraints. However, students often create correct spreadsheet models without correctly formulating the mathematical model. In dealing with the spreadsheet model, one could use Excel’s formula auditing capability (see Figure 16). If one selects the cost of Shiraz (cell C5) and applies the “Trace Dependent” command from the formula auditing menu, we see that the unit cost influences both the unit profit (cell C20) and the bud-

Figure 14 Solver Solution with New Cost Parameter

	A	B	C	D	E	F
1	Walker Wines Product Mix					
2						
3	Data					
4			Shiraz	Merlot		
5		Cost/bottle	\$ 1.65	\$ 1.40		
6		Price/bottle	\$ 6.25	\$ 5.25		
7						
8		Base demand	1,000.00	2,000.00		
9		Increase/\$1 Adv.	5	8		
10		Min. percent requirement	40%			
11		Max. percent limitation	70%			
12						
13		Total Budget	\$ 50,000.00			
14						
15	Model					
16						
17		Total profit				
18		\$	122,231.12			
19			Shiraz	Merlot	Total	
20		Unit profit	\$ 4.60	\$ 3.85		
21		Advertising dollars	\$ 2,238.67	\$ 2,036.25	\$ 4,274.92	
22		Demand	12,193.35	18,290.03	30,483.38	
23		Quantity produced	12,193.35	18,290.03	30,483.38	
24						
25		Min. percent requirement	0	>=	0	
26		Max. percent limitation	-9145.015106	<=	0	
27						
28					Used	Unused
29		Budget	\$ 22,357.70	\$ 27,642.30	\$ 50,000.00	\$ -

Figure 15 Solver Solution Table for Parametric Changes in Unit Cost

Cost	Profit	Quantity Shiraz	Quantity Merlot	Advertising Shiraz	Advertising Merlot
\$ 1.61	\$ 124,066.40	20,478.40	8,776.46	\$ 3,895.68	847.0571
\$ 1.62	\$ 123,489.04	12,282.41	18,423.62	\$ 2,256.48	2052.9519
\$ 1.63	\$ 123,067.70	12,252.58	18,378.87	\$ 2,250.52	2047.3588
\$ 1.64	\$ 122,648.39	12,222.90	18,334.34	\$ 2,244.58	2041.7929
\$ 1.65	\$ 122,231.12	12,193.35	18,290.03	\$ 2,238.67	2036.2538

get constraint function (cell C29). Thus, one suggestion to ensure that sensitivity analysis information is interpreted properly in spreadsheet models is to ensure that any parameter changes have no formula auditing dependency on constraint functions in the spreadsheet model.

This example also brings up some important general considerations in modeling and spreadsheet implementation. The original spreadsheet implementation defined the objective function using the model:

$$\text{Maximize } (\$6.25S + \$5.25M) - (\$1.60S + \$1.40M + A_s + A_m)$$

where each of the data parameters are identified in individual cells. In this fashion, a change in either the unit selling price or the unit cost of grapes is accurately reflected in the model and solution.

However, suppose that the simplified version of the objective function is used:

$$\text{Maximize } 4.65S + 4.85M - A_s - A_m.$$

In this case, the selling prices and grape costs are aggregated. If one makes a change in the unit profit

coefficients, the solution *de facto* assumes that the change is the result of the selling price, since the cost of grapes is no longer linked to the constraint through the model data input. If the change is a result of the cost of grapes, the interpretation of the Sensitivity Report and resulting Solver solution will clearly be wrong.

Conclusions and Recommendations

This paper identifies several “hidden” issues associated with modeling linear optimization problems using spreadsheets and Excel Solver. These issues are not clearly addressed in mainstream textbooks, and can easily cause confusion, anxiety, and erroneous interpretation of Solver results among students and instructors alike. We recommend that instructors incorporate discussions and examples of these issues into lectures and assignments to help students become more cognizant of the importance in understanding the limitations of modeling and software in their problem solving and analysis activities.

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Figure 16 Excel Formula Auditing—Trace Dependents

	A	B	C	D	E	F
1	Walker Wines Product Mix					
2						
3	Data					
4			Shiraz	Merlot		
5	Cost/bottle	\$	1.60	\$	1.40	
6	Price/bottle	\$	6.25	\$	5.25	
7						
8	Base demand		1,000.00		2,000.00	
9	Increase/\$1 Adv.		5		8	
10	Min. percent requirement		40%			
11	Max. percent limitation		70%			
12						
13	Total Budget	\$	50,000.00			
14						
15	Model					
16						
17	Total profit					
18	\$		124,775.84			
19			Shiraz	Merlot	Total	
20	Unit profit	\$	4.65	\$	3.85	
21	Advertising dollars	\$	3,912.37	\$	851.53	\$ 4,763.90
22	Demand		20,561.86		8,812.23	29,374.09
23	Quantity produced		20,561.86		8,812.23	29,374.09
24						
25	Min. percent requirement		8312.227074	>=	0	
26	Max. percent limitation		0	<=	0	
27						
28					Used	Unused
29	Budget	\$	36,811.35	\$	13,188.65	\$ 50,000.00
					\$	-