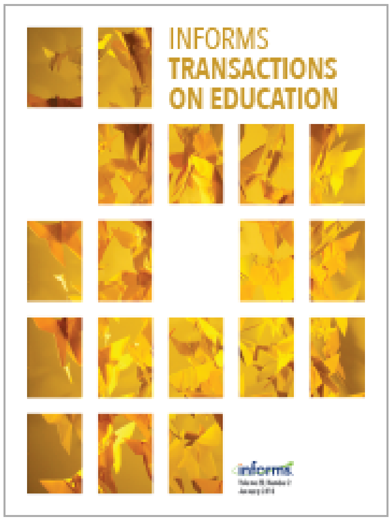

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Introducing Troubleshooting for Model Formulation, Spreadsheet Development, and Memo Communication with Feedforward

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Abstract. Novices need to learn how to recognize and correct formulation, spreadsheet, and writing mistakes. Yet quantitative business courses historically focus on examples of model formulation and more recently spreadsheet solution. This paper presents a feedforward example for formal instruction of troubleshooting issues for three domains, i.e., model formulation, spreadsheet development, and professional memo writing. The example is provided in a format for an active learning exercise.

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Keywords: active learning • developing communication skills • developing critical thinking skills • spreadsheet modeling • teaching management science

1. Introduction

The feedforward technique establishes the expectations of future work or behavior and allows the recipient to make adjustments accordingly, whereas feedback focuses on what the recipient did wrong in the past (Goldsmith 2003). Feedforward interviews are used in some professional settings in addition to performance appraisal interviews to foster communication between managers and employees about employees' best practices for future successes (Budworth et al. 2015). While feedforward is most commonly associated with managers and changes in the workplace, it can also be useful in academic environments (Kluger and Van Dijk 2010).

In an academic environment, the feedforward technique enables the instructor to convey information to students about the direction and the expected quality of their work before assessment (Hendry et al. 2016, Baker and Zuvela 2013). Feedforward also helps students identify their own performance shortcomings (Laryea 2013, Duncan 2007, Carless 2006). Hendry et al. (2016) report that when using feedforward in their exemplar-based assessment, 74% of students reported benefitting most from the instructor's explanation of expected quality of work. Using the feedforward technique, students in class receive timely information about their upcoming assignment and can use the feedforward to improve future work. Feedforward can be applied to various academic disciplines.

In management science, novice model builders commonly experience difficulties building a model (Williams et al. 2016a, Yoder and Kurz 2015, Williams et al. 2014, Riddle 2010, Brown and Dell 2007, Dombrovskaia and Guzman 2006, Stevens and Palocsay 2004, Murphy and Panchanadam 1999), developing a spreadsheet solution (Grossman et al. 2016; Powell et al. 2009, 2008; Grossman 2006; Kruck 2006; Kreie et al. 2000; Panko 1998; Panko and Sprague 1998), and describing their model and their subsequent recommendations in writing (Williams et al. 2016a, 2014; Brown and Rosenthal 2008; Grossman et al. 2008). Various researchers have promoted teaching techniques for each of these domains that may be integrated with feedforward in the management science discipline. Brown and Dell (2007) present common formulation mistakes, including constraint coefficient errors and operator errors, along with corrections in their individual component approach. Students may benefit from the exercise of identifying mistakes because it is a skill they will likely need in practice (Lyytinen and Robey 1999).

In addition, multiple researchers have promoted the management science learning outcome to strengthen spreadsheet modeling skills (Grossman et al. 2016, Palocsay and Markham 2014). Specifically, researchers have pointed out the importance of designing, planning, organizing, clearly labeling, simplifying, maintaining consistency, and testing for good spreadsheets (Powell et al. 2009, 2008; Kruck 2006; Kruck and Sheetz 2001; Kreie et al. 2000; Panko 1998; Panko and Sprague 1998).

The quality of communication about models is integral to the success of analytical work in practice (Brown and Rosenthal 2008, Grossman et al. 2008). Brown and Rosenthal (2008) indicate that model formulations are seldom well documented and frequently omit the nonmathematical problem summary. Williams et al. (2016b) and Carrithers et al. (2008) promote managerial summaries to help students develop technical communication skills. What is missing from the literature is an approach that can be used to point out common mistakes with a whole problem in three domains, i.e., formulation, spreadsheet development, and written communication.

We applied the feedforward technique to formal instruction during the class lecture to illustrate common errors and corrections in a production planning context. For business education, these analytical and communication skills are an integral part of standard 9, Curriculum Content, of the Association to Advanced Collegiate Schools of Business (AACSB) 2013 accreditation requirements (AACSB 2017).

2. Teaching Instrument

Grossman et al. (2016) and Grinde and Kammermeyer (2003) promote connecting modeling to a business context. The business context for the feedforward teaching instrument presented here is a fictitious company, i.e., Performance Machining. The teaching instrument is composed of seven business memos and a class exercise form. We selected the memo format to introduce the business scenario and follow-up communications to align with expectations students will encounter in a professional writing situation. Table 1 summarizes the structure for the feedforward teaching instrument.

Appendix A provides the most recent version of the complete teaching instrument, including the seven memos and the class exercise form. Memo 1 is written by a manager to a junior analyst. It contains some details about the business scenario, including the decisions that the manager faces, the manager's minimum production requirements, the manager's objective, and the special packaging budget. It also expresses the manager's expectations for a recommended production plan, an impact summary that details the resource requirements of the production plan, the proximity of the production plan to the minimum production requirements, and the sensitivity of the production plan to the marketing forecast. Memos 2–4 are from the marketing, procurement, and operations managers to the junior analyst to provide the information requested such as marketing forecasts, raw material costs, special packaging costs, labor costs, production times, and machining labor available. Memos 1 to 4 provide information about constraints that make the production planning problem challenging.

The junior analyst begins working on the production planning problem and responds as shown in Memo 5. Memo 5 shows multiple mistakes in each of the three domains, i.e., writing, model formulation, and Excel spreadsheet development, that a typical novice might make. The mistakes in Memo 5 are typical of what an instructor may see on a management science homework assignment that requires all three domains. A class exercise form with three labeled sections is used to help students summarize the mistakes they find in each of the three domains. Because Excel provides a message that the first modeling attempt has failed to provide a feasible solution, the students can then learn from the mistakes by troubleshooting in each of the domains.

Memo 6 is the response memo from the manager. It provides coaching advice organized according to general error types for communication, logic, data entry, and spreadsheet development. The instructor can caution students that few general managers would have the time to provide such detailed feedback. While the literature presents multiple taxonomies for errors due to problem complexity and context for use (Powell et al. 2008), our fictitious manager in Memo 6 uses only four general error labels. We note that the communication, logic, and data entry errors may have an impact on all three domains, i.e., the memo, the model formulation, and the spreadsheet. Spreadsheet development errors not only impact the spreadsheet domain but also the recommendation in the memo domain.

Next the junior analyst corrects his mistakes and responds with Memo 7. In Memo 7, the junior analyst adds a brief description of the problem including the manager's objective and the problem constraints.

Table 1. Structure of the Teaching Instrument for Each Component of the Feedforward Active Learning Exercise

Component	Description of component
Initial communication	
Memo 1	Memo from the general manager requesting a production planning recommendation with expectations for a summary of the impacts on the machine utilization and packaging expenditures, proximity to the minimum management production requirements, and the sensitivity to the moving average versus sales force composite forecasts
Memo 2	Memo from the marketing manager describing sales forecasts
Memo 3	Memo from the procurement manager stating raw materials costs and special packaging costs
Memo 4	Memo from the operations manager describing production times per product per process step and number of labor shifts available for machining
Memo 5	First memo from the junior analyst with multiple memo writing, formulation, and spreadsheet development mistakes
Class exercise form	Form that contains three labeled sections for the class to summarize the errors they find in the junior analyst's memo, formulation, and Excel spreadsheet domains
Follow-up communication	
Memo 6	Memo from the general manager describing communication, logic, data entry, and spreadsheet development mistakes in each of the three domains
Memo 7	Revised follow-up memo from junior analyst with corrected memo, corrected formulation, and corrected Excel spreadsheet

After editing Table A.1, the junior analyst edits the formulation and the spreadsheet model, and then solves the spreadsheet model. Then the junior analyst adds a recommended solution, creates Table A.2 which shows the resource utilization for the recommended production plan, and creates Table A.3 which shows how close the production plan recommendation is to the minimum production requirements. Furthermore, the junior analyst illustrates how sensitive the objective is to the total demand forecast in Figure A.1. The junior analyst compares the recommended production plans for two different marketing forecasts in Table A.4. The junior analyst concludes Memo 7 with the follow-up comment that the model could be revised for additional business scenarios. Attached to Memo 7 is a corrected model formulation with detailed descriptors and a corrected, well annotated spreadsheet solution.

3. Implementation Experience and Extensions

This active learning exercise has evolved over four semesters. The first two authors used this exercise with lecture discussions to give students experience finding mistakes on their own in an undergraduate management science course. It was used in the first third of the course following four weeks of course work in linear programming formulation and spreadsheet solutions for problems with up to four decision variables.

The active learning exercise began as a series of handouts. Initially, the students received a handout of the first five memos and a Class Exercise Form to list mistakes for each of the three domains. Students studied the five memos and recorded mistakes individually for over 15 minutes. During this time, students familiarized themselves with the manager's initial request and expectations, after which they discussed their error lists with classmates for another 15 minutes. Some students asked for clarification on the minimum management requirement, indicating that they had identified a constraint construction mistake. Class discussion then followed for about 15 minutes during which class members discussed the errors that were identified and why the elements were considered errors. During this discussion, students most quickly pointed out the formulation and spreadsheet mistakes related to incorrect objective components, including coefficients and Max (versus Min), right-hand side (RHS) unit mismatches, an incorrect operator, and an incorrect cell range. Students required coaching to discuss the junior analyst's communication errors, such as the missing problem description, missing constraint label units, and the missing page headings.

Next, students received a handout with the sixth memo which provided comments from the general manager. While the sixth memo provided managerial feedback for the fictitious junior analyst, it would be considered feedforward for the class. Students who participated in the class exercise gained valuable insights from the comments in the sixth memo as to managerial expectations for professional writing, model formulation, and Excel spreadsheet development which they could use in their subsequent homework assignments.

Finally, students received the seventh memo from the junior analyst as a color printed handout. Students were asked to compare the mistakes they identified with the corrections shown in color on the seventh memo. The lecture exercise was implemented in approximately one hour.

Our exercise may be extended by breaking it up over multiple lectures with outside work assignments. For example, students could be given Memos 1 to 4 and asked to create their own formulation, spreadsheet solution, and memo response as a homework assignment. In the following class, Memo 5 and the Class Exercise Form could be distributed. Students may be asked to identify mistakes in each domain in Memo 5, including its attachment, and record their answers on the Class Exercise Form. A second extension would be to provide only part of Memo 6 from the general manager so that the students receive managerial expectations and identify mistakes in multiple iterations. Sitkin (1992) discusses the benefits of individuals identifying their own mistakes. Furthermore, the two extensions could be combined by asking students to evaluate their own formulation, spreadsheet development, and writing mistakes in their homework response to Memos 1 to 4 after studying the general manager's feedback memos.

4. Conclusions and Pragmatic Implications

It is critical for novices to develop model formulation, spreadsheet solution methodology, and communication skills for business problems. In this activity, this goal is supported by presenting a business scenario with integrated troubleshooting issues for model formulation, spreadsheet development, and professional memo writing that can be used as an active learning exercise. Our goal was to guide students in recognizing common mistakes before the course mid-point so they could apply that knowledge in the remainder of the course.

Although we developed this feedforward in-class exercise to encourage students to be more proactive in finding and correcting various types of mistakes in an undergraduate management science class, the concept has been used in other disciplines outside management (Hendry et al. 2016, Rae and Cochrane 2008, Duncan 2007). Educators have an opportunity to use feedforward to introduce expectations for problem solving and professional writing into their quantitative courses.

Appendix A

MEMO 1: ORIGINAL PRODUCTION PLANNING MEMO REQUEST
DATE: July 14, 2016
TO: Joe Dunn, Junior Analyst
FROM: Bob Goodwin, General Manager
RE: Performance Machining Production Plan

Determine the number of units of Models 101, 102, and 103 to produce next month. Make at least 50 of each product while minimizing total costs (labor, raw materials, and special packaging). Note that the total special packaging budget is $3,000. Confer with the marketing, procurement, and operations managers. Analyze both the sales force composite and moving average forecasts for the total number of units produced. Respond by next week with your recommended production plan and its impact on the total costs, machining requirements, packaging budget, and minimum production requirements, as well as its sensitivity to marketing forecasts. Attach your solution approach.

MEMO 2: MEMO FROM MARKETING MANAGER
DATE: July 14, 2016
TO: Joe Dunn, Junior Analyst
FROM: Sue Lee, Marketing Manager
RE: Performance Machining Marketing Information

This memo is to follow-up your phone request for sales forecasts for Models 101, 102, and 103. I anticipate at least half of sales coming from Model 101. Sales force composite forecasts for the total sales of all three products are at least 400 units. However, the moving average forecast for total sales is at least 350 units. I recommend using the sales force composite forecast.

MEMO 3: MEMO FROM PROCUREMENT MANAGER
DATE: July 14, 2016
TO: Joe Dunn, Junior Analyst
FROM: Saffron Smith, Procurement Manager
RE: Performance Machining Procurement Information

This memo is to follow-up your phone request for raw material costs. The raw material costs per Models 101, 102, and 103 are $5, $3, and $6, respectively. The special packaging cost per Model 101 is $5 per unit, while it is $7 per unit for Model 102. Model 103 has no special packaging.

MEMO 4: MEMO FROM OPERATIONS MANAGER
DATE: July 14, 2016
TO: Joe Dunn, Junior Analyst
FROM: Juan Lopez, Operations Manager
RE: Performance Machining Production Plan

This memo is to follow-up your phone request for labor costs and production times. Labor costs are $18/hour for each of the processes. There are three steps in the production process with the following production times (minutes) and eight hour shifts available next month.

	Production times (minutes)			
Process step	Model 101	Model 102	Model 103	Machine time available
Cutting	30	15	30	25 eight-hour shifts
Polishing	75	30	60	50 eight-hour shifts
Fitting	45	30	30	37.5 eight-hour shifts

MEMO 5: JUNIOR ANALYST'S FIRST RESPONSE MEMO
TO: Bob Goodwin, General Manager
FROM: Joe Dunn, Junior Analyst
Re: Production Planning Problems

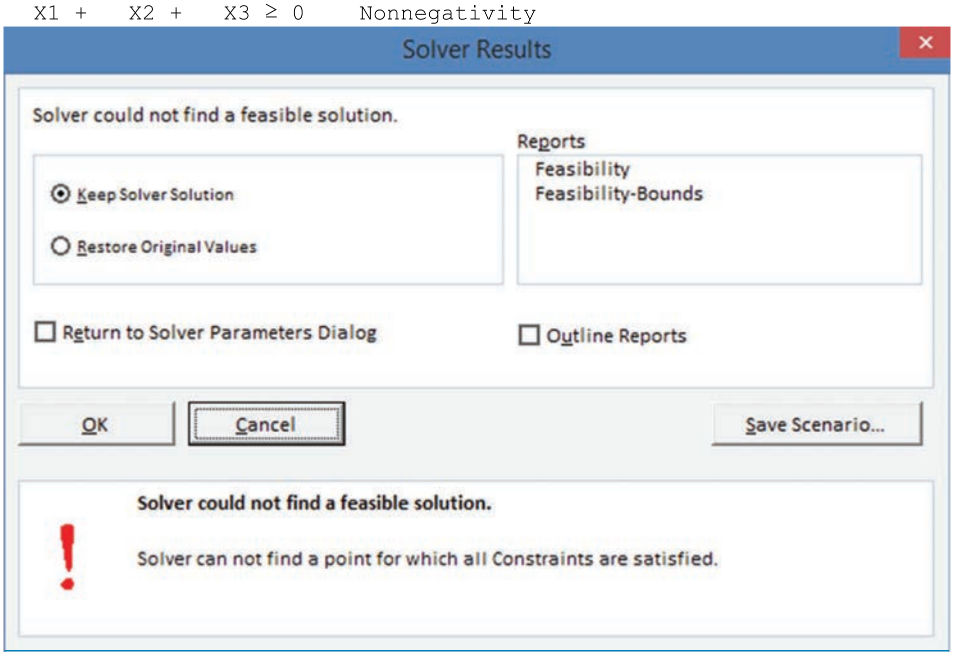
I have not been able to develop a recommendation yet. My infeasible production planning model is attached. Please advise.

MEMO 5: JUNIOR ANALYST'S FIRST RESPONSE MEMO ATTACHMENT

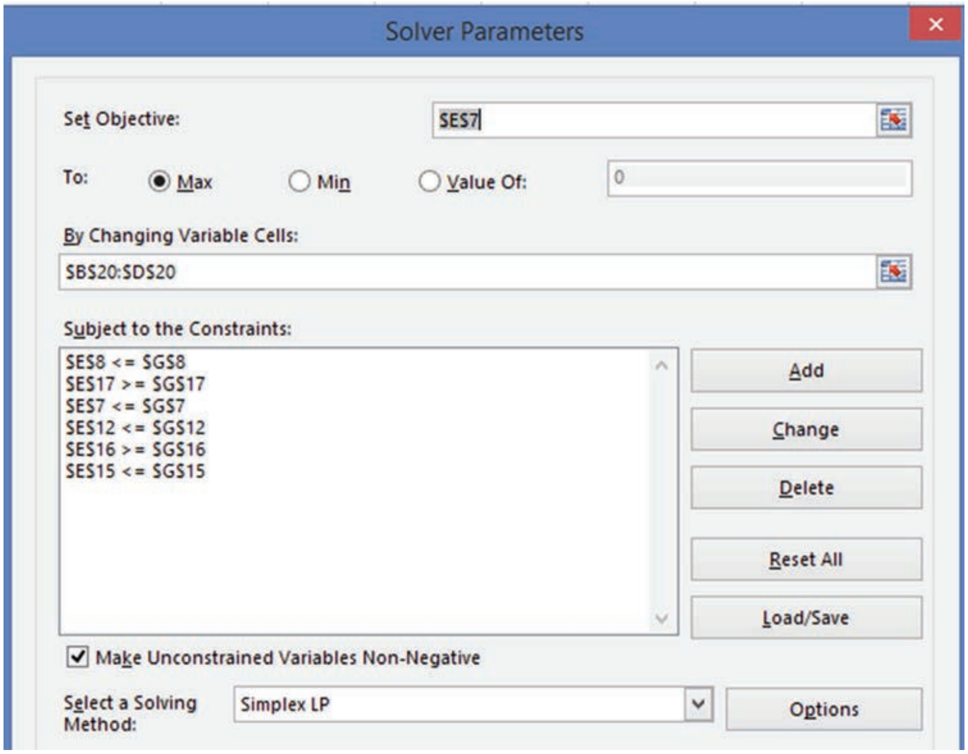
	101	102	103
Cutting	9	4.5	9
Polishing	22.50	9	9
Fitting	13.50	9	9
Raw	5	3	6
Pkg	5	7	
Total	50	32.50	33

Xi = # of units of model *i* to produce, where *i* = 1, 2, or 3

```
MIN 50X1 + 32.5X2 + 33X3
1)   30X1 + 15X2 + 30X3 ≤ 200  Cutting time
2)   75X1 + 30X2 + 60X3 ≤ 400  Polishing time
3)   45X1 + 30X2 + 30X3 ≤ 300  Fitting time
4)    5X1 +  7X2        ≤ 2000 Special packaging budget
5)     X1 +   X2 +   X3 ≤ 400  Total production requirement
6)     X1               ≥ 200  Model 101 minimum production requirement
7)            X2 +   X3 ≥ 100  Models 102 & 103 minimum production requirement
8)     X1 +   X2 +   X3 ≥ 0    Nonnegativity
```



	A	B	C	D	E	F	G
1		Production Planning for Performance Machining					
2							
3		Model 101, X1	Model 102, X2	Model 103, X3			
4	Unit Profit	50	32.5	33			
5							
6		Assembly time per unit produced			Time used		Available
7	Cutting	30	15	30	200	≤	200
8	Polishing	75	30	60	400	≤	400
9	Fitting	45	30	30	400	≤	300
10							
11		Special packaging budget			Packaging budget used		$ Available
12	Packaging dollars	5	7	0	93.33333333	≤	2000
13							
14		Production requirements			Excess		Minimum
15	Total #	1	1	1	13.3333333	≤	400
16	101	1			0	≥	200
17	102 & 103		1	1	13.3333333	≥	100
18							
19		Model 101, X1	Model 102, X2	Model 103, X3	Total Profit		
20	Units Produced	0	13.33333333	0	433.3333333		
21							
22	Cost Category	Model 101	Model 102	Model 103			
23	Cutting cost	$9.00	$4.50	$9.00		18	labor $/hr
24	Polishing cost	$22.50	$9.00	$ 9.00			
25	Fitting cost	$13.50	$9.00	$9.00			
26	Raw materials cost	$5.00	$3.00	$6.00			
27	Packaging cost	$5.00	$7.00	$0.00			
28	TOTAL cost	$50.00	$32.50	$33.00			



	A	B	C	D	E	F	G
1			**Production Planning for Performance Machining**				
2							
3		**Model 101, X1**	**Model 102, X2**	**Model 103, X3**			
4	**Unit Profit**	=B28	=C28	=D28			
5							
6		**Assembly time per unit produced**			**Time used**		Available
7	**Cutting**	30	15	30	=SUMPRODUCT(B7:D7,$B$20:$D$20)	≤	200
8	**Polishing**	75	30	60	=SUMPRODUCT(B8:D8,$B$20:$D$20)	≤	400
9	**Fitting**	45	30	30	=SUMPRODUCT(B9:D9,$B$20:$D$20)	≤	300
10							
11			**Special packaging budget**		**Packaging budget used**		$ Available
12	**Packaging dollars**	=B27	=C27	=D27	=SUMPRODUCT(B12:D12,$B$20:$D$20)	≤	2000
13							
14		**Production requirements**			**Excess**		Minimum
15	**Total #**	1	1	1	=SUMPRODUCT(B15:D15,$B$20:$D$20)	≤	400
16	**101**	1			=SUMPRODUCT(B16:D16,$B$20:$D$20)	≥	200
17	**102 & 103**		1	1	=SUMPRODUCT(B17:D17,$B$20:$D$20)	≥	100
18							
19		**Model 101, X1**	**Model 102, X2**	**Model 103, X3**	**Total Profit**		
20	**Units Produced**	0	13.3333333333333	0	=SUMPRODUCT($B$4:$D$4,$B$20:$D$20)		
21							
22	Cost Category	Model 101	Model 102	Model 103			
23	Cutting cost	=B7*$F$23/60	=C7*$F$23/60	=D7*$F$23/60		18	labor $/hr
24	Polishing cost	=B8*$F$23/60	=C8*$F$23/60	9			
25	Fitting cost	=B9*$F$23/60	=C9*$F$23/60	=D9*$F$23/60			
26	Raw materials cost	5	3	6			
27	Packaging cost	5	7	0			
28	TOTAL cost	=SUM(B23:B26)	=SUM(C23:C27)	=SUM(D23:D27)			

CLASS EXERCISE

Identify three types of mistakes in MEMO 5: JUNIOR ANALYST'S FIRST RESPONSE MEMO and the ATTACHMENT. Form small groups and fill in the tables below. Later, you will have the opportunity to share your responses with the class.

Memo mistakes	Formulation (legend, objective, constraints) mistakes

Spreadsheet mistakes

MEMO 6: TROUBLESHOOTING FEEDBACK MEMO

DATE: August 2, 2016
TO: Joe Dunn, Junior Analyst
FROM: Bob Goodwin, General Manager
Re: Production Planning Errors

There are four general categories of errors in your document that may be classified as communication, logic, data entry, and spreadsheet development errors. The communication, logic, and data entry errors impact all three domains: the memo, the model formulation, and the spreadsheet. Spreadsheet development errors also impact the recommendation in the memo domain.

Communication Errors

Memo Domain

The date and problem description including the decisions, objective, and constraints are missing, which makes it difficult to understand the context of your problem. Your cost table has no table title and no indication of units. The costs are not lined up by decimal point in the columns.

Formulation Domain

Your communication errors are predominantly omission errors. You did not define the subscripts 1, 2, and 3 in your legend. There is no objective function label to minimize costs. Constraint descriptions are missing units, which led to mismatched units for assembly time constraints.

Spreadsheet Domain

There is no descriptive title above each Excel snip. There are no top of page descriptions to indicate continued work on multiple pages. The "Unit Profit" label for the objective coefficient and the "Total Profit" label for the objective function value are incorrect. Constraint descriptions are too vague and are missing units, which led to mismatched units for the assembly time constraints.

Logic Errors

Memo Domain

If the problem had been described in the memo, some of the errors described for the formulation domain may have been replicated. There is no recommendation to report in part due to the logic mistakes.

Formulation Domain and Spreadsheet Domain (*these mistakes are manifested in both domains*)

The constraint operator is incorrect for marketing's total production requirement. Both the managerial minimum production and the non-negativity requirements are erroneously summed in single constraints. The Model 101 marketing minimum for 50% of total production is set to 200 (50% of the current minimum total 400), rather than 50% of the sum of the total production from the optimal solution.

Data Entry Errors

Memo Domain

The table contains erroneous total costs for Model 101 and Model 103.

Formulation Domain and Spreadsheet Domain (*these mistakes are manifested in both domains*)

The total cost objective function coefficients for Models 101 and 103 are incorrect. The special packaging budget in the right hand side of the special packaging budget constraint is incorrect.

Spreadsheet Development Errors

Memo Domain

There is no recommendation to report in part due to the spreadsheet development mistakes.

Spreadsheet Domain

The cell range in the Model 101 total cost is incorrect. The polishing labor cost is an incorrect number rather than the labor cost formula. There is a cell reference mistake for the objective cell and "Max" is incorrectly selected in Solver Parameters. The fitting time constraint is missing in Solver Parameters.

As you address each of these issues, if you have any additional questions, please contact me.

MEMO 7: JUNIOR ANALYST'S SECOND RESPONSE MEMO
DATE: August 16, 2016
TO: Bob Goodwin, General Manager
FROM: Joe Dunn, Junior Analyst
Re: Production Planning Recommendation

Thank you for taking the time to provide such helpful feedback. Using your feedback, I modified my solution approach. I analyzed the number of units of models 101, 102, and 103 to produce to minimize total costs subject to machine availability schedules, the special packaging budget, the minimum production requirements, and the sales force composite forecast for a total production of at least 400 units. I developed a total unit cost Table A.1 and a linear programming model as shown in the attachment.

The solution recommended by the model is to produce:
200 units of Model 101
150 units of Model 102
50 units of Model 103
400 units total.

This solution incurs total cost $17,975. Table A.1 shows the total unit costs from the labor, raw materials, and special packaging.

Table A.1. Unit Costs for Models 101, 102, and 103

Cost category	Model 101 ($)	Model 102 ($)	Model 103 ($)
Cutting labor	9.00	4.50	9.00
Polishing labor	22.50	9.00	18.00
Fitting labor	13.50	9.00	9.00
Raw materials	5.00	3.00	6.00
Special packaging	5.00	7.00	0.00
Total	55.00	32.50	42.00

The recommendation impact is summarized in two impact tables. Table A.2 shows that none of the resources were depleted with the recommended solution. Table A.3 shows that the minimum marketing and management requirements for production were either met or exceeded. Additionally, the recommended plan meets exactly the marketing requirement that at least half of the total production comes from Model 101.

Table A.2. Resource Impact for Models 101, 102, and 103

Impact category	Model 101	Model 102	Model 103	Total used	Unused
Cutting labor (minutes)	6,000	2,250	1,500	9,750	2,250
Polishing labor (minutes)	15,000	4,500	3,000	22,500	1,500
Fitting labor (minutes)	9,000	4,500	1,500	15,000	3,000
Packaging budget ($)	1,000	1,050	0	2,050	950

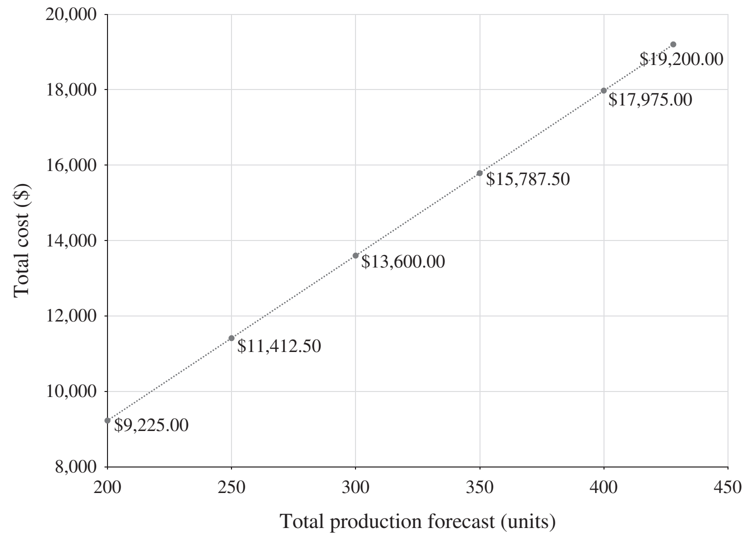
Table A.3. Minimum Requirement Impact for Models 101, 102, and 103

Impact category	Solution total	Minimum	Excess
Total marketing requirement	400	400	0
Management model 101 production requirement	200	50	150
Management model 102 production requirement	150	50	100
Management model 103 production requirement	50	50	0

In response to your request to analyze the sensitivity of the production plan to the marketing forecast, I graphed the impact of the total cost versus the total production forecast in Figure 1. The attached model shows that each additional unit forecasted adds $43.75 to the cost for the total production forecast range, 200 to 428 units. Beyond 428 units, I must resolve the model to determine the cost impact of each additional unit forecasted.

MEMO 7: (Continued)

Figure A.1. Relationship Between the Total Production Forecast and the Total Cost for the Total Production Forecast Range, 200 to 428 Units



My recommendation is based on the sales force composite forecast of 400 units. However, I also ran the attached model with the moving average forecast of 350 units. I developed Table A.4 to compare the impact of these two forecasts on the recommended production plan, total cost, resource utilization, packaging expenditures, and proximity to minimum production requirements.

Table A.4. Comparison of Production Plans for Total Sales Forecasts of 350 versus 400

	Forecast	
	Moving average: 350	Sales force composite: 400
Production plan:		
Model 101	175 units	200 units
Model 102	125 units	150 units
Model 103	50 units	50 units
Total cost:	$15,787.50	$17,975.00
Cutting labor used (left over)	8,625 minutes (3,375 minutes)	9,750 minutes (2,250 minutes)
Polishing labor used (left over)	19,875 minutes (4,125 minutes)	22,500 minutes (1,500 minutes)
Fitting labor used (left over)	13,125 minutes (4,875 minutes)	15,000 minutes (3,000 minutes)
Packaging expenditures (left over)	$1,750 ($1,250)	$2,050 ($950)
Management model 101 requirement	125 excess	150 excess
Management model 102 requirement	75 excess	100 excess
Management model 103 requirement	0 excess	0 excess

Please let me know if any additional business scenarios (e.g. different production requirements or different marketing forecasts) interest you.

MEMO 7: (Continued)

This attachment details the solution approach to develop the production plan for Models 101, 102, and 103. A linear programming model minimizes the total cost subject to the processing times available, the special packaging budget, the marketing requirements, and the management requirements. This attachment contains both the linear programming formulation and the spreadsheet solution in Excel.

Linear Programming Model Formulation

Xi = number of units of product *i* to produce, where *i* = 1 model 101, 2 model 102, 3 model 103

MIN $55X1 + 32.5X2 + 42X3$	Minimize total costs ($)
(1) $30X1 + 15X2 + 30X3 \le 12{,}000$	Cutting time (minutes) (based on 25 eight-hour shifts)
(2) $75X1 + 30X2 + 60X3 \le 24{,}000$	Polishing time (minutes) (based on 50 eight-hour shifts)
(3) $45X1 + 30X2 + 30X3 \le 18{,}000$	Fitting time (minutes) (based on 37.5 eight-hour shifts)
(4) $5X1 + 7X2 \le 3000$	Special packaging budget ($)
(5) $X1 + X2 + X3 \ge 400$	Total marketing production requirement (units)
(6) $0.5X1 - 0.5X2 - 0.5X3 \ge 0$	Model 101 minimum marketing production requirement (units)
(7) $X1 \ge 50$	Model 101 minimum management requirement (units)
(8) $X2 \ge 50$	Model 102 minimum management requirement (units)
(9) $X3 \ge 50$	Model 103 minimum management requirement (units)
(10) $X1, X2, X3 \ge 0$	Non-negativity (units)

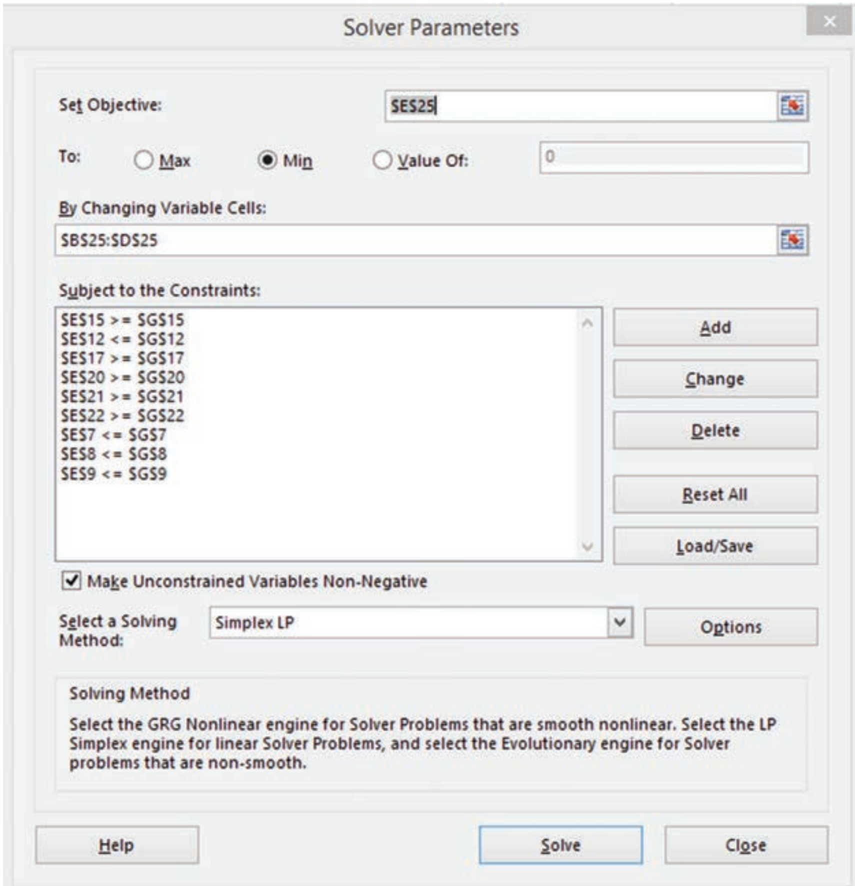
Excel Input and Output with numbers

	A	B	C	D	E	F	G
1		Production Planning for Performance Machining					
2							
3		Model 101, X1	Model 102, X2	Model 103, X3			
4	Unit Cost	55	32.5	42			
5							Minutes
6		Minutes of assembly used per unit produced			Minutes used		Available
7	Cutting	30	15	30	9750	≤	12000
8	Polishing	75	30	60	22500	≤	24000
9	Fitting	45	30	30	15000	≤	18000
10							
11		Special packaging budget			Budget used		$ Available
12	Packaging dollars	5	7	0	2050	≤	3000
13							
14		Marketing production requirements			Total production		Minimum
15	Total # marketing	1	1	1	400	≥	400
16					Excess marketing		Minimum
17	101 marketing	0.5	-0.5	-0.5	1.42109E-14	≥	0
18							
19		Management production requirements			Production		Minimum
20	101 management	1			200	≥	50
21	102 management		1		150	≥	50
22	103 management			1	50	≥	50
23							
24		Model 101, X1	Model 102, X2	Model 103, X3	Total Cost		
25	Units Produced	200	150	50	17975		
26							
27	Cost Category	Model 101	Model 102	Model 103			
28	Cutting cost	$9.00	$4.50	$9.00		18	labor $/hr
29	Polishing cost	$22.50	$9.00	$18.00			
30	Fitting cost	$13.50	$9.00	$9.00			
31	Raw materials cost	$5.00	$3.00	$6.00			
32	Packaging cost	$5.00	$7.00	$0.00			
33	TOTAL cost	$55.00	$32.50	$42.00			

MEMO 7: (Continued)

ATTACHMENT Performance Machining Production Planning Model continued

Excel Solver Parameters



Excel Sensitivity Report

Microsoft Excel 16.0 Sensitivity Report

Variable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$B$25	Units Produced Model 101, X1	200	0	55	1E+30	22.5
$C$25	Units Produced Model 102, X2	150	0	32.5	9.5	87.5
$D$25	Units Produced Model 103, X3	50	0	42	1E+30	9.5

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$E$15	Total # marketing Total production	400	43.75	400	28.57142857	200
$E$12	Packaging dollars Budget used	2050	0	3000	1E+30	950
$E$17	101 marketing Excess marketing	1.42109E-14	22.5	0	33.33333333	150
$E$20	101 management Production	200	0	50	150	1E+30
$E$21	102 management Production	150	0	50	100	1E+30
$E$22	103 management Production	50	9.5	50	50	50
$E$7	Cutting Minutes used	9750	0	12000	1E+30	2250
$E$8	Polishing Minutes used	22500	0	24000	1E+30	1500
$E$9	Fitting Minutes used	15000	0	18000	1E+30	3000

MEMO 7: (Continued)

ATTACHMENT Performance Machining Production Planning Model continued

Excel Input and Output with formulas

	A	B	C	D	E	F	G
1		Production Planning for Performance Machining					
2							
3		Model 101, X1	Model 102, X2	Model 103, X3			
4	Unit Cost	=B33	=C33	=D33			
5							Minutes
6		Minutes of assembly used per unit produced			Minutes used		Available
7	Cutting	30	15	30	=SUMPRODUCT(B7:D7,$B$25:$D$25)	≤	12000
8	Polishing	75	30	60	=SUMPRODUCT(B8:D8,$B$25:$D$25)	≤	24000
9	Fitting	45	30	30	=SUMPRODUCT(B9:D9,$B$25:$D$25)	≤	18000
10							
11		Special packaging budget			Budget used		$ Available
12	Packaging dollars	=B32	=C32	=D32	=SUMPRODUCT(B12:D12,$B$25:$D$25)	≤	3000
13							
14		Marketing production requirements			Total production		Minimum
15	Total # marketing	1	1	1	=SUMPRODUCT(B15:D15,$B$25:$D$25)	≥	400
16					Excess marketing		Minimum
17	101 marketing	0.5	-0.5	-0.5	=SUMPRODUCT(B17:D17,$B$25:$D$25)	≥	0
18							
19		Management production requirements			Production		Minimum
20	101 management	1			=SUMPRODUCT(B20:D20,$B$25:$D$25)	≥	50
21	102 management		1		=SUMPRODUCT(B21:D21,$B$25:$D$25)	≥	50
22	103 management			1	=SUMPRODUCT(B22:D22,$B$25:$D$25)	≥	50
23							
24		Model 101, X1	Model 102, X2	Model 103, X3	Total Cost		
25	Units Produced	200	150	50	=SUMPRODUCT($B$4:$D$4,$B$25:$D$25)		
26							
27	Cost Category	Model 101	Model 102	Model 103			
28	Cutting cost	=B7*$F$28/60	=C7*$F$28/60	=D7*$F$28/60		18	labor $/hr
29	Polishing cost	=B8*$F$28/60	=C8*$F$28/60	=D8*$F$28/60			
30	Fitting cost	=B9*$F$28/60	=C9*$F$28/60	=D9*$F$28/60			
31	Raw materials cost	5	3	6			
32	Packaging cost	5	7	0			
33	TOTAL cost	=SUM(B28:B32)	=SUM(C28:C32)	=SUM(D28:D32)			

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