AN INQUIRY-BASED APPROACH FOR TEACHING STUDENTS TO FORMULATE LINEAR PROGRAMMING MODELS

Emma Jane Riddle, College of Business, Winthrop University, Rock Hill, South Carolina, 29733, **riddlee@winthrop.edu**

ABSTRACT

Linear programming (LP) is a standard topic in management science and operations management courses. This paper presents a simple, inquiry-based approach to teaching formulation of linear programming models. The inquiry-based activity is based on a simple LP problem, requires students to use critical thinking skills, and can be used as a foundation for teaching the formulation of more complex LP models. This activity is an important component of an instructional package that has enabled most students to formulate simple LP models.

INTRODUCTION

Linear programming (LP) is a standard topic in management science and operations management courses. In most operations management textbooks, the discussion of LP begins with a definition of optimization and a summary of the uses of LP. Then the concepts of decision variables, objective function, and constraints are introduced. Next, a two-variable LP problem is introduced, set up in standard format, and solved using the graphical method. Finally, at least one other solution method, such as the simplex method or Excel/Excel Solver, is demonstrated.

In the author's experience, this approach often works well for students with strong mathematics skills. However, this method is less effective for students who struggle with math. The major contribution of this paper is to present an inquiry-based approach to teaching LP model formulation. The inquiry-based approach seems to help struggling students learn the topic and gives all students an opportunity to practice critical thinking skills. This approach has been used for the past four semesters. Classroom experience will be discussed. Both theory and assessment data will be used to evaluate the inquiry-based activity. Plans for improving both the activity and student performance will be discussed.

REVIEW OF LITERATURE

One objective of inquiry-based learning is to help students develop critical thinking skills. Bloom's taxonomy, which is often used to classify critical thinking skills, will be presented first. Then inquiry-based learning and its benefits will be described. Finally, literature related to the design of the inquiry-based LP activity will be discussed.

Bloom's Taxonomy

For more than fifty years, educational researchers have recognized that there are different levels of cognitive reasoning. Bloom's taxonomy [3] identified six types of cognitive reasoning: knowledge, comprehension, application, analysis, synthesis, and evaluation. Analysis, synthesis, and evaluation were generally considered to be critical thinking skills.

Anderson and Krathwohl [1] revised Bloom's taxonomy to be more consistent with recent learning research. The six categories in the new taxonomy are described below [1, p. 31].

- *Remembering* is the retrieval of knowledge from long-term memory. Remembering includes recognizing and recalling information.
- *Understanding* occurs when meaning is constructed from oral, written, or graphic information. Examples of understanding include interpreting, exemplifying, classifying, summarizing, inferring, comparing, and explaining in one's own words.
- *Application* means carrying out a procedure, such as a computational procedure or a set of work instructions.
- *Analysis* involves breaking information into parts and determining how they relate to each other or to some structure or purpose. Examples of analysis include distinguishing between relevant and irrelevant information, organizing information, and determining an author's point of view.
- *Evaluation* is the process of making judgments, based on criteria or standards. This includes both the application of standards and the determination of which standards are appropriate.
- *Creating* is the process of putting elements together to form a coherent or functional whole, or reorganizing elements into a new pattern. Creating involves generating, planning, or producing something; examples include generating a hypothesis about the cause of a quality problem, planning a project, and developing a new human resources manual.

The first four categories in the revised taxonomy are roughly equivalent to the first four categories in the original Bloom [3] taxonomy. The new taxonomy defines *evaluation* more narrowly; evaluation is now the fifth category, rather than the sixth. *Creating*, which is now the sixth category, is similar to the old *synthesis* category. In the revised taxonomy, critical thinking includes analysis, evaluation, and creating.

Inquiry-Based Learning and Its Benefits

Inquiry-based learning is a teaching method that presents students with a real-world challenge, such as a problem to be solved or a business case to be analyzed [12]. Real-world tasks are used because they have a greater ability to motivate students [12]; Oliver [10] found that students dislike tasks that they consider irrelevant. The information needed to meet the inquiry-based challenge has not been explicitly covered in previous class sessions or earlier course work. However, the learning activity is designed so that students can extend their existing knowledge and skills to meet the requirements of the activity. The scope of inquiry-based activities may range from a single class session or a brief assignment, to a project that lasts throughout the semester. Some activities are designed to be completed by individuals, while others require a team effort.

Audet [2] states that some course activities do not qualify as inquiry-based learning:

> What distinguishes inquiry from other classroom activities is the attempt to draw meaning out of experience. Without driving, answerable questions and an emphasis on sense making, no classroom experience has a true connection with the process of inquiry [2, p.7].

DeBoer [7] noted that inquiry-based learning requires students to use inductive reasoning, which involves drawing general conclusions from particular instances or situations; consequently, inquiry-based learning is also called inductive learning [12].

Many business faculty are already familiar with some inquiry-based activities, such as case teaching, problem-based learning, project-based learning, and field experience courses. A case problem is also an inquiry-based activity if it requires "sense-making" activities, such as analysis, recommendations, or developing a new problem-solving strategy. Some case problems only require students to apply a specific or obvious problem-solving strategy that has already been taught; those problems can provide a useful learning experience, but they do not meet Audet's definition of an inquiry-based activity.

Prince and Felder [11, 12] have reviewed a significant body of research that documents the benefits of inquiry-based learning. A number of research studies have found that inquiry-based learning improves students' skills in critical thinking and problem solving [11, 12]. Other benefits depend on the subject matter, the nature of the inquiry-based task, and the extent to which the activity challenges students [11, 12]. The research studies reviewed by Prince and Felder [11, 12] are generally based on an activity, or a sequence of activities, that are done throughout a semester. The benefits of a single inquiry-based activity, as described in this paper, are probably much smaller.

Designing an Inquiry-Based Activity

Researchers have also provided advice about designing inquiry-based activities. Lundeberg and Yadev [9] found that tasks which require high levels of knowledge and critical thinking have the greatest impact on student learning. Colburn [6] suggested that tasks should be challenging but not so difficult that most students cannot do them. Oliver [10] found that students dislike tasks with unclear instructions; this raises the issue of how much structure the faculty member should provide to students. Instructions with too little detail may leave students floundering, but instructions that are too specific may eliminate the need for students to think critically about the assignment. The teacher must also decide what assistance should be available to students as they do the task, and whether that help should come from peers, the teacher, or both. Here again, the goal is to maximize student learning without leaving some students behind [15].

The inquiry-based exercise presented in this paper is based on two techniques taught by Harvey Brightman [5]. The first is a set of principles for presenting a topic in a way that is clear and understandable to students; Brightman calls these the "Big 5". The "Big 5" were developed in response to research by Feldman [8], who found that presentation clarity is one of the most important factors in student learning. The "Big 5" principles are listed below:

1. Why before what: Help students understand why a topic is important before teaching the topic. Remember that the students' "why" may be different from the teacher's "why".
2. Simple to complex: Start with simple ideas, and move toward more complex ideas.
3. Familiar to unfamiliar: Begin with everyday principles or ideas, and move toward new concepts or unfamiliar words.
4. Concrete to abstract: Start by analyzing a situation, dataset, or question. Use the analysis to introduce definitions, concepts, theory, and formulas.
5. Multiple languages: Translate between words, diagrams, and symbols.

The "why before what" principle is a reminder to motivate students by making the material seem important and relevant; this is consistent with the research of Prince and Felder [12] and Oliver [10], which was mentioned earlier. Brightman's [5] technique for implementing the "why before what" principle will be described in the next paragraph. The second, third, and fourth principles are designed to make the presentation clear and understandable, while also presenting complex material. The "concrete to abstract" principle is consistent with inquiry-based learning. Both are based on beginning with a specific example, reasoning inductively, and drawing conclusions. The last principle, multiple languages, recognizes that communicating in words, diagrams, and symbols will make the presentation clear to a larger number of students.

The second Brightman [5] technique that is used in this paper is called a "hook". A hook is an activity that is designed to serve two purposes: (1) to make the topic seem relevant to students, and (2) to serve as a "spine", or organizing device, for the presentation of the topic. The hook can be an exercise, a short quiz, a small case, or a demonstration [4]. Some hooks, like the one presented in this paper, also provide opportunities for students to engage in problem solving and use critical thinking skills. Those hooks are simple inquiry-based activities.

AN INQUIRY-BASED ACTIVITY FOR FORMULATING LP MODELS

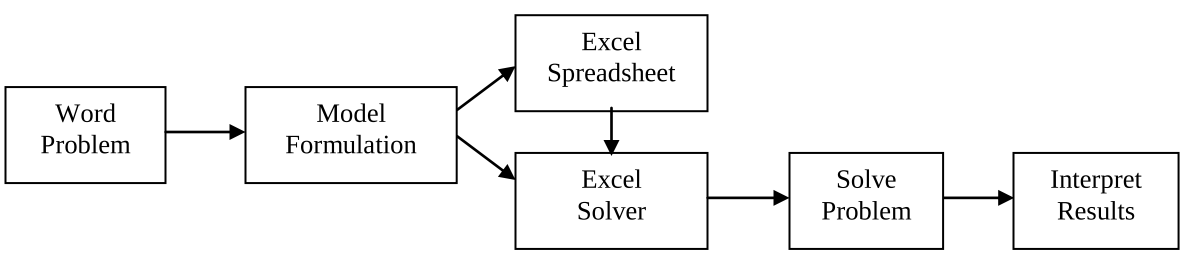
The teaching challenge that prompted the development of the inquiry-based activity will be discussed first. Then the hook will be presented. Finally, a teaching strategy for using the hook will be described.

Analyzing the Teaching Challenge

The author regularly teaches an undergraduate core course in operations management, which all business students must take in their junior or senior year. Since no management science course is offered, linear programming and several other management science topics are taught in the operations management course. Typically, two 75-minute class periods are allocated to linear programming. The objective of linear programming coverage is to teach students to formulate LP problems in standard form, solve them in Excel and Excel Solver, and interpret the results. Since time is so limited, manual methods of solving LP problems are no longer taught.

The process for solving an LP problem is shown in Figure 1. The word problem must be translated into a standard algebraic formulation. Some information from the model formulation is used to set up a spreadsheet, while other information is entered directly into Solver. If all those steps have been done correctly, the problem can be solved quickly. The last step is to interpret the results. The remainder of this paper will focus on the first step: translating the word problem into a standard algebraic formulation

FIGURE 1: PROCESS FOR SOLVING AN LP PROBLEM



Brightman's Big 5 principles [5] were used to analyze the way that LP model formulation had been taught in the past.

- Why before what: Several uses of LP were discussed near the beginning of the first class on LP, but students seldom remembered this information when they were tested on it. This was a case of the teacher's "why", not the students' "why".
- Simple to complex, familiar to unfamiliar, and concrete to abstract: After the uses of LP were discussed, decision variables, objective function, and constraints were introduced. These abstract, unfamiliar concepts were presented before a concrete example was introduced.

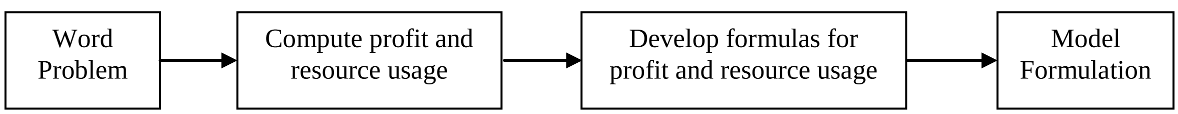
- Multiple languages: Words were translated into algebraic symbols, but some students had difficulty making this translation, and some never mastered the translation.

On the basis of this analysis, a decision was made to test the use of a hook and the "Big 5" principles to teach linear programming. LP was an ideal test case for these methods. It is an important topic in operations management, and it is a difficult topic for many students. Finding a problem to use as a hook would be easy. Business students understand the importance of maximizing profit and minimizing costs; there are a multitude of LP problems that require students to do one of those two things.

The Hook

The inquiry-based learning activity for LP was based on the principle of going from a concrete situation to abstract concepts. The underlying hypothesis was that many students understand calculations better than they understand algebraic functions and constraints. Students who had trouble setting up objective functions and constraints might be able to compute profit and resource usage for a specific combination of bowls and mugs. After they had practiced with those calculations, the model formulation could be taught more easily. The process is shown in Figure 2.

FIGURE 2: THE TRANSLATION PROCESS FOR THE HOOK



The plan was to have students attempt to solve a two-variable product mix problem by trial and error. Students would be instructed to try various combinations of the two products, checking each time to see whether the constraints were met. They would be asked to make the profit as large as possible, without violating any constraints. No formulas would be given for profit or resource usage; students would have to figure out how to compute those quantities. To assist weak students, students would do the exercise in pairs. It was expected that working in pairs would also help students develop better strategies for finding the optimal solution.

The problem below was selected as the basis for the hook:

> A craft shop makes and sells pottery bowls and mugs. The shop makes a profit of $40 per bowl and $50 per mug. A bowl requires 1 hour of labor and 4 pounds of clay. A mug requires 2 hours of labor and 3 pounds of clay. 40 labor hours are available each day. The shop can obtain only 120 pounds of clay per day. Find the maximum profit per day, and determine how much of each product should be made. (Adapted from [14], pp. 217-218)

Students were given a sheet with the following information: the problem, a table for recording data, and instructions for the activity. Figure 3 is a shortened version of the data table; the table used in class has more rows. The row of calculations is intended to show students what to do; it also gives them a way to check their computational methods before proceeding with the exercise. The instructions are shown in Figure 4.

The problem, instructions, and data table are distributed on one sheet of paper. Students are given 15 to 20 minutes to complete the exercise.

FIGURE 3: DATA TABLE FOR LP LEARNING ACTIVITY

Number of bowls	Number of mugs	Profit	Hours of Labor Used	Labor $\leq$ 40	Pounds of Clay Used	Clay $\leq$ 120
4	6	$460	16	Yes	34	Yes

FIGURE 4: INSTRUCTIONS FOR LP LEARNING ACTIVITY

Work with a partner on this exercise.

Procedure:

(a) Select a combination of bowls and mugs to make. Enter the number of bowls and mugs in the table. Complete the information in the rest of the row. Both you and your partner should complete the information and compare your answers.
(b) Repeat step (a), with different combinations of bowls and mugs until time is called. Try to get as high a profit as you can.

Using the Hook

This lecture begins with a short discussion of optimization and what is meant by an optimal solution. Students are told that we will study an optimization method called linear programming and that we will begin with a short exercise. When the exercise is distributed, the teacher briefly discusses the instructions and answers any questions about them. During the next few minutes, the teacher's coaching is usually limited to clarifying the instructions. The few students who have trouble with the computations usually get help from their partners; if necessary, the teacher also helps struggling students. About halfway through the exercise, some students begin asking advice on solution strategy or inquiring whether they have the optimal solution. If a student pair asks for advice or has not found the optimal solution, they will be encouraged to try another problem-solving strategy. If the optimal solution has been found, this will be confirmed; the students will be asked not to share their solution, so that other students can discover it on their own.

The first two times this exercise was used, almost all coaching was requested by students. With that procedure, five to ten percent of the student pairs in each class found the optimal solution. Then the teacher began approaching students who were not asking for help and asking to see their work. Students were given feedback on whether they had found the optimal solution, were getting close, or could still do much better. When all student pairs received feedback, forty to fifty percent of the pairs in each class found the optimum. This teacher-initiated coaching also increased the time needed for the exercise from 15 minutes to about 20 minutes. Without teacher-initiated coaching, some students apparently stopped work when they had achieved a significant improvement over the initial example given in the data table or when a particular solution strategy had reached its limits.

While students are working on the exercise, the teacher divides the chalkboard into four vertical sections. The first three are labeled profit, labor, and clay; the fourth section is not labeled. When the students have worked about 20 minutes, the teacher calls time and begins a dialogue with the students about their results. Most of the information required for the model formulation will be developed during this dialogue. At each step, information provided by the students is listed on the chalkboard. The four sections of the chalkboard are filled one row at a time, from left to right. The steps in the dialogue are listed below; the filled-in chalkboard is depicted in Figure 5.

1. Call on a student to give the optimal solution and explain the profit calculation.
2. Call on two other students to give the calculations for labor used and clay used.
3. Set up two variables to represent the amount of each product to make. Ask the student pairs to develop a formula for profit. Call on a student to give the answer. Explain the answer for the benefit of those who did not get it.
4. Ask the student pairs to develop formulas for resource usage. Call on students to give those formulas.
5. Write the right-hand sides of the constraints on the chalkboard, next to the formulas for resource usage. Ask the students whether the signs between the formulas and the right-hand sides should be $\leq$ or $\geq$. Write the signs on the board.
6. Introduce the terms decision variables, objective function, and constraints. Write them on the chalkboard as shown in Figure 5.

FIGURE 5: FILLED-IN CHALKBOARD FOR THE LP MODEL EXERCISE

Profit	Labor	Clay	
Optimal solution: 24 bowls, 8 mugs			
24($40) + 8($50) = $1,360	1(24) + 2(8) = 40 hrs.	4(24) + 3(8) = 120 lbs.	Let x = number of bowls to make Let y = number of mugs to make
40x + 50y	x + 2y $\leq$ 40	4x + 3y $\leq$ 120	
Objective function	Labor constraint	Clay constraint	Decision variables

At this point, most of the model formulation has been developed; only the non-negativity constraints are lacking. It is now time to summarize what has been done, and introduce the standard model formulation. Here are the steps:

7. In a convenient spot on the chalkboard, note that every linear programming problem has three elements.
8. Write the model formulation, except for the non-negativity constraints, on the chalkboard.
9. Explain why the non-negativity constraints are needed, and help the students develop them. Add them to the model.

The final chalkboard is shown in Figure 6.

FIGURE 6: FINAL CHALKBOARD FOR LP MODEL EXERCISE

Profit	Labor	Clay	Model formulation in standard form
Optimal solution: 24 bowls, 8 mugs 24($40) + 8($50) = $1,360 40x + 50y Objective function	 1(24) + 2(8) = 40 hrs. $x + 2y \leq 40$ Labor constraint	 4(24) + 3(8) = 120 lbs. $4x + 3y \leq 120$ Clay constraint	Decision variables Let x = number of bowls to make Let y = number of mugs to make Objective function 40x + 50y Constraints Labor: $x + 2y \leq 40$ Clay: $4x + 3y \leq 120$ Non-negativity: $x \geq 0$ $y \geq 0$

It is now time to summarize what has been done and explain what still needs to be done.

10. Draw the diagram in Figure 2 on the chalkboard, or display it in PowerPoint. Use the diagram to summarize what the class has done.
11. Draw the diagram in Figure 1 on the chalkboard, or display it in PowerPoint. Use the diagram to explain what still needs to be done.

The exercise and steps 1-11 can be done in about 50 minutes. After these activities, the author distributes notes on linear programming. The notes present linear programming in a traditional way, explain how to solve LP problems using Excel and Excel Solver, and discuss the formulation of more complex LP problems. The notes are necessary because the textbook used in this course [13] does not include LP coverage. Information that was previously skipped, such as the uses of LP, is now discussed. An induction approach is used to help students develop Excel formulas for profit and resource usage. The remainder of the LP coverage is handled in a traditional way.

Before a test is given, students have several opportunities to reinforce what they learned in class. First, self-study problems, with answers, are distributed; students have a week to work on these problems and get help from the teacher. Second, a quiz on LP model formulation is given, and students receive written feedback on their errors. Third, students have an out-of-class assignment, which requires formulating an LP model, solving it, and interpreting the results. Students also get written feedback on the assignment. Therefore, classroom instruction is only one of several course activities that influences student performance on the test.

EVALUATING THE INQUIRY-BASED APPROACH

First, the inquiry-based activity will be evaluated from a theoretical point of view. Then assessment data will be presented. Finally, plans for further assessment and improvement will be discussed.

Theoretical Evaluation

The instructor's observation was that the exercise created a sense of excitement in the classroom and seemed to motivate students to learn linear programming, as predicted by Brightman [5], Oliver [10], and Prince and Felder [11]. For most students, the activity appeared to be challenging but not too difficult; this is consistent with the recommendations made by Colburn [6]. In terms of the revised Bloom taxonomy, checking to see that the LP constraints are being met is an evaluation (level 5) task. Some student pairs have mentioned well-developed strategies for finding the optimal solution; those students are using creation (level 6) skills. Even those students who are using only evaluation skills are doing critical thinking.

The exercise conforms to Brightman's (2005) "Big 5" principles:

- Why before what: Business students understand the importance of profit and are motivated to increase profit.
- Simple to complex: The exercise begins with calculations that students already understand. A fair number of students can make the translation from arithmetic to algebra by themselves.
- Familiar to unfamiliar: The exercise proceeds from arithmetic to algebra, and then to the concepts of decision variables, objective function, and constraints.
- Concrete to abstract: The exercise begins with a specific word problem. The class discussion of the exercise is used to introduce the model formulation and new concepts.
- Multiple languages: Students translate from a word problem to calculations, and then to algebra.

Student reactions to the exercise suggest that the "hook" and the "Big 5" principles worked well in this case.

Assessment Data

At the author's university, one of the learning goals for the BSBA program is: "Students will be able to demonstrate rational decision making using quantitative tools, strategies, and data". This goal is assessed in several courses, using both multiple choice tests and quantitative tasks in each course. The authors were asked to develop a task and a rubric for assessing this goal in the undergraduate operations management course. The assessment task is defined as follows:

Assessment will be based on a test question that requires students to formulate a linear programming problem in standard form. The student should be prompted for the decision variables, the objective function, and the constraints. The problem must be a product mix problem with 2 variables, 2 resource constraints, and one additional constraint – such as a contract, booked orders, or a market size limitation. The problem must prompt the student for the decision variables, objective function, and constraints. Students must be required to set up the problem from scratch. Multiple choice questions cannot be used for this assessment.

Faculty teaching an operations management course are required to include this task in one of the tests given in the course. The rubric used to assess student performance on the task is shown in Figure 7.

FIGURE 7: RUBRIC FOR ASSESSING PERFORMANCE ON LP MODEL FORMULATION

Item	Characteristics of Student's Answer	Points
1	Decision variables are defined correctly and used consistently throughout the problem setup.	0 - 1
2	The formula for the objective function is present and correct	0 - 2
3	The student correctly states whether the objective function should be maximized or minimized.	0 - 1
4	Two resource constraints are present. The left-hand sides of the resource constraints are correct. (0 – 3 points for each constraint)	0 - 6
5	Both resource constraints have correct signs	0 - 1
6	Both resource constraints have correct right-hand sides	0 - 1
7	Both non-negativity constraints are present and correct.	0 - 2
8	The additional constraint is present and correct.	0 - 2
	Total points	0-16

For the past two semesters, detailed assessment data has been collected using this rubric. During those semesters, the author taught four sections of undergraduate operations management, with a total of 134 students. Student scores, based on the rubric, are summarized in Figure 8.

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FIGURE 8
SUMMARY SCORES FOR STUDENT PERFORMANCE ON LP MODEL FORMULATION

Raw Score	% Score	Number of Students	% of Students
16	100	96	71.6%
15	94	12	9.0%
14	88	7	5.2%
13	81	4	3.0%
12	75	5	3.7%
0 – 11	0 - 74	10	7.5%
TOTAL		134	100%

More than 70% of the students earned a perfect score on the model formulation task; 92.5% earned a score of 75% or more on the task. The remaining 7.5% received raw scores of 11 or less; their percentage scores were less than 70%. As stated earlier, classroom instruction is only one factor that influences student performance on the test. However, there is anecdotal evidence that students who attended class on the day that model formulation was taught generally received higher scores than those who did not.

Student performance on various parts of the LP formulation task was also analyzed. The results are shown in Figure 9. In five of the eight categories, the average score was 95% or more of the maximum score. Students had the greatest difficulty with the signs for the resource constraints; the non-negativity constraints; and the additional (non-resource) constraint. Plans for improving performance in these areas will be discussed in the next section.

FIGURE 9
STUDENT PERFORMANCE ON VARIOUS PARTS OF THE LP FORMULATION TASK

Item	Characteristics of Student's Answer	Maximum Points	Average Points	Average % Score
1	Decision variables are defined correctly and used consistently throughout the problem setup.	1	0.95	95.0%
2	The formula for the objective function is present and correct	2	1.91	95.5%
3	The student correctly states whether the objective function should be maximized or minimized.	1	0.98	98.0%
4	Two resource constraints are present. The left-hand sides of the resource constraints are correct. (0 – 3 points for each constraint)	6	5.75	95.8%
5	Both resource constraints have correct signs	1	0.90	90.0%
6	Both resource constraints have correct right-hand sides	1	0.95	95.0%
7	Both non-negativity constraints are present and correct.	2	1.74	87.0%
8	The additional constraint is present and correct.	2	1.75	87.5%
	Total points	16	14.93	93.34%

Instructional Improvement and Additional Assessment

The assessment results in Figure 9 will be used to improve instruction. The meaning of the $\leq$ and $\geq$ signs will be reviewed in class. Students will also be given more practice with the non-negativity constraints and non-resource constraints. We will continue to use the rubric in Figure 7 to assess student learning.

For research purposes, the effectiveness of the inquiry-based activity will be assessed using quiz performance and the rubric in Figure 7. Quiz performance is a better measure of effectiveness than test performance, which is influenced by quiz questions, feedback on the quiz, the assignment, and feedback on the assignment.

In the theoretical evaluation of the inquiry-based activity, it was suggested that students were excited about the activity; that the activity was sufficiently challenging but not too difficult; and that some students developed strategies for finding the optimal solution. In the future, students will be surveyed about their reactions to the inquiry-based activity and strategies they may have used during the activity. They will also be asked to rate the impact of each LP-related activity on their learning. In addition, attendance records will be compared with student scores on the quiz-based and test-based LP assessments to see whether attendance affected learning. These evaluations will provide additional measures concerning the effectiveness of the inquiry-based activity and other instructional components. Also, this additional research will provide more data for improving instruction.

SUMMARY

An inquiry-based approach to teaching LP model formulation has been presented. This activity is an important component of an instructional package that has enabled most students to formulate simple LP models. Anecdotal evidence suggests that students enjoy the inquiry-based activity. The activity also gives students a chance to practice critical thinking skills. Plans for instructional improvement and further assessment of the activity were discussed.

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