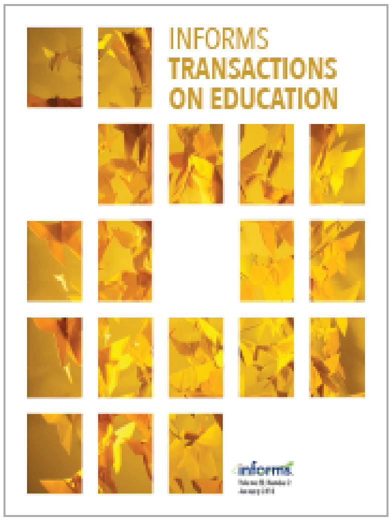

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Extending "Lego® My Simplex"

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Almost 20 years have passed since Pendegraft described his use of Lego® toys to teach students basic modeling skills and linear programming concepts. Since then, many instructors of operations research (including the author) and their students have benefited from his contribution. In this article, the author describes a series of extensions he has developed since originally implementing Pendegraft's active learning exercise in the introductory operations courses he teaches. Through these extensions, the author integrates the concepts of sensitivity, integer programming, and LP formulation and extends the modeling experience beyond the original exercise.

Keywords: active learning; classroom games; teaching optimization; developing analytical skills; developing critical thinking skills
History: Received: September 2011; accepted: December 2014.

1. Introduction

In 1997, Pendegraft (1997) wrote in the "Issues in Education" column of *ORMS Today* of his use of Lego® toys as part of an active learning exercise that was designed to teach students basic modeling skills and linear programming concepts. Through this active learning exercise, students quickly develop an understanding of the basic components of a linear programming formulation, the algebraic representation of linear programs, and the relationship between the algebra and geometry of linear programming models.

After initially implementing Pendegraft's active learning exercise into the introductory operations courses he teaches, the author found several opportunities to extend the exercise and increase the breadth of concepts that students understand as a result of participating in the exercise. In this article, the author first reviews the concept of active learning, and then provides a brief overview of Pendegraft's exercise. He follows by describing his extensions of Pendegraft's original exercise and describes how these extensions expand the modeling experience beyond the original exercise and support the development of student understanding of sensitivity, integer programming, and LP formulation.

2. An Overview of and Motivations for Active Learning

Active learning has been defined by several authors in a variety of ways. The definition preferred by the author, which is a hybrid of definitions provided by other authors in their writings on active learning, follows:

> Instructional strategies and exercises designed to engage students through participation in exercises that involve them in higher-order thinking tasks such as analysis, synthesis, and evaluation of course material.

Instructors who integrate active learning into their classrooms frequently cite as motivation their beliefs that learning is a naturally active process and that understanding of a complex concept is most effectively developed through student interaction with concepts, the instructor, and other students.

While a quality lecture can result in the efficient transfer information or demonstration of simple concepts, from the student perspective, it is a relatively passive activity that generally does not fully engage him or her in the subject matter (Hartley and Cameron 1967, McLeish 1968). One who has earned advanced degrees in operations research may not agree with this assessment, recalling instead the fascination with the concepts of operations research he or she felt when attending lectures on the subject. This can lead an instructor of operations research to neglect the profound differences between his or her/ perspective and that of a typical student enrolled in an introductory operations research course.

A great majority of students will not follow the paths of their instructors and pursue graduate studies in operations research, which is a clear indication that most students and their operations research instructors differ greatly in their aptitude for and/or interest in the subject. An instructor of operations research (or any other relatively technical discipline) must avoid the common trap of assuming he or she and his or her students learn in similar ways.

Results of a study conducted by Russell et al. (1984) suggest that a student's retention of information presented by lecture is higher when the density of new material is low, and these authors propose that instructors devote no more than half of any class meeting to coverage of new concepts or material. McKeachie (1999) asserts that few instructors are capable of the difficult task of holding a student audience's attention throughout a long lecture. McKeachie's claim is consistent with the results of Hartley and Davies (1978), who found that a typical student's level of attention steadily increases during the first 10 minutes of a typical lecture and then diminishes rapidly. These results suggest that an instructor's overdependence on lectures may quickly create a torpid learning environment in which students become lethargic and fail to question ideas or think critically about concepts. Not surprisingly, Russell et al. (1984) find that students leave such learning environments with only a superficial understanding of the concepts and ideas that were discussed.

Chilcoat (1989) summarizes several research studies in which each report that a change in the classroom environment during a lecture can enable an instructor to recapture the attention of his or her student audience. Several studies (Cashin 1985; Brown and Atkins 1988; Campbell and Smith 1995; Cochran 2001a, b) extend this finding, and their results suggest that a break featuring a relevant and effective active learning exercise will be far more effective. Chickering and Gamson (1987, p. 1) summarize this perspective on learning and education in the following way:

> Learning is not a spectator sport. Students do not learn much just by sitting in class listening to teachers, memorizing prepackaged assignments, and spitting out answers. They must talk about what they are learning, write about it, relate it to past experiences, apply it to their daily lives. They must make what they learn part of themselves.

Several experienced operations research educators have written on integration of active learning strategies into introductory operations research courses. *ORMS Today*, the Institute for Operations Research and the Management Sciences' bimonthly membership magazine, has published several articles on effective active learning exercises in its "Issues in Education" column. Examples include Liebman (1996), Pendegraft (1997), and Cochran (2001a). In these columns, the authors argue persuasively for the effectiveness of simple but thought-provoking active learning exercises. Their suggestions are inexpensive and easy to use and extend, and these suggestions also often transfer readily across cultures.

In contrast, Mattson (2005) expresses strong skepticism about active learning and the philosophy he argues that it represents, maintaining that the active learning movement has masked the need for greater resources and meaningful reform of the education system. Whereas this author will not deny the needs identified by Mattson, he respectfully disagrees with Mattson's assertion that active learning masks these needs. Indeed, the author believes the modern active learning movement is actually born of these needs.

Several authors have also published articles on the use of active learning in operations research courses in *INFORMS Transactions on Education* (http://ite.pubs.informs.org/). These include but are not limited to Cochran (2001b), Hannibalsson (2001), Taras and Grossman (2003), Teich et al. (2005), Brimberg and Hurley (2007), DePuy and Taylor (2007), Villalobos (2007), Talluri (2009), Behara (2010), Robb et al. (2010), Gray (2011), Devia and Weber (2012), Gorman (2012), D'Amours and Rönnqvist (2013), Beliën et al (2013), and Sauré and Puterman (2014). Griffin (2007) also guest edited a special issue of *INFORMS Transactions on Education* in September 2007 that was devoted to educational games (Volume 8, Number 1), and the journal has featured several articles by Chlond on the use of puzzles to demonstrate operations research concepts.

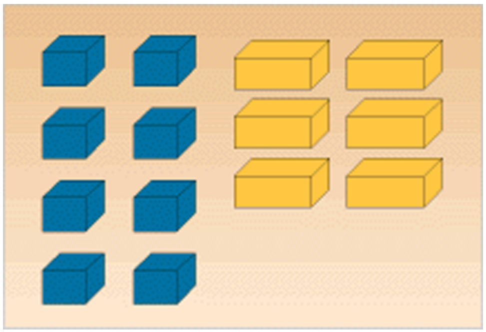
3. The Original Lego™ My Simplex Active Learning Exercise

Pendegraft (1997) initiates his active learning exercise by dividing his class into small groups and distributing one bag that contains eight small (2 × 2) Legos® and six large (2 × 4) Legos® (Figure 1) to each of the student groups.

Pendegraft then demonstrates construction of a table and a chair (Figure 2).

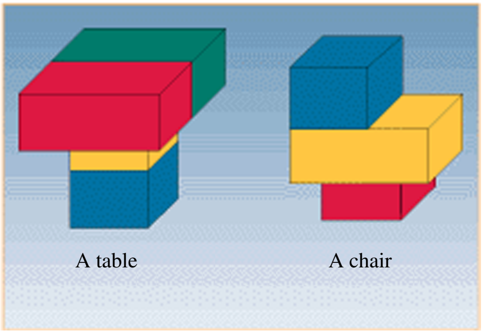
Pendegraft proceeds to announce that a chair sells for \$10 and a table sells for \$16, and then instructs

Figure 1 **The Available Resources**[a,b]



[a]Figures 1–3 have been reproduced with the permission of the editorial staff of *ORMS Today*.
[b]Figures 1–10 are available in editable form in Figures.pptx.

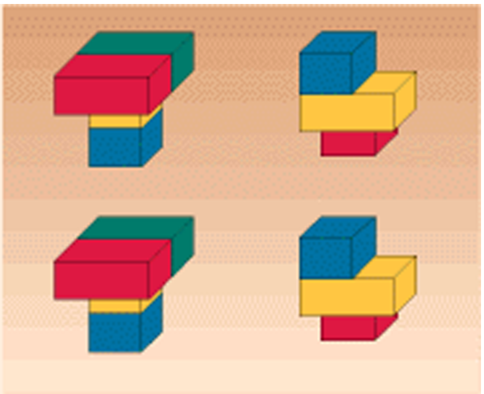
Figure 2 Construction of Tables and Chairs Using the Available Resources



the class to select a product mix that maximizes their revenue using the available resources (Lego® pieces). Within a few minutes, most teams of students will find the optimal mix; produce two tables and two chairs (Figure 3) and generate a revenue of \$52 with no remaining Lego® pieces; other student groups may report a suboptimal solution of three tables and a resulting revenue of \$48 with two leftover small (2×2) Lego® pieces.

Finally, Pendegraft uses these two solutions to illustrate basic sensitivity analysis by explaining how the student groups that decided to build three tables and generate a revenue of \$48 can increase their profit to \$52 by disassembling a table. This frees two large (2×4) Lego® pieces and two additional small (2×2) Lego® pieces at a cost of \$16 in revenue. The students can then build two chairs from the remaining Lego® pieces and generate \$20, thereby increasing the revenue associated with their solution by \$4. Pendegraft also uses this approach in conjunction with a discussion of extreme points to motivate discussions of the Fundamental Theorem of Linear Programming and the simplex algorithm.

Figure 3 The Optimal Solution



4. Extensions of the Original Lego® My Simplex Active Learning Exercise

In this section, we review extensions that support greater development of student modeling skills and their understanding of integer programming, LP relaxation, and sensitivity analysis.

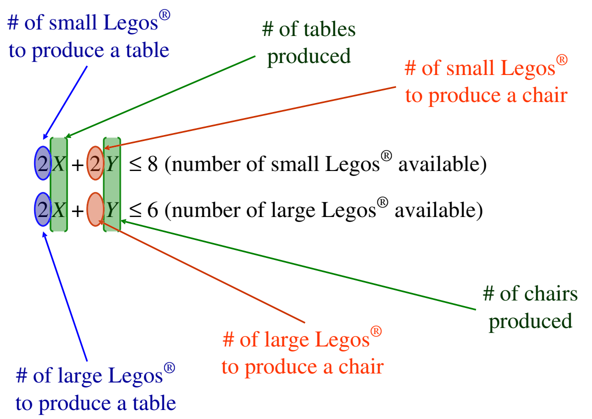
4.1. Extending the Modeling Experience

The author has implemented Pendegraft's Lego® exercise and the author's extensions in required introductory operations research courses for undergraduate students (junior level) and students in MBA programs. Students in the undergraduate course generally have not been exposed to linear programming, whereas a few of the MBA students have covered some basic linear programming concepts in an undergraduate course. Enrollment in the undergraduate course ranged from 40 to 50 students, whereas the MBA course enrollment ranged from 15 to 25. The exercise generally takes between 30 and 45 minutes, depending on how many of the concepts discussed in this paper are introduced. One advantage of this approach over many other active learning exercises is that it scales well; with the exception of the time it takes to distribute the Lego® pieces at the beginning of the exercise and to collect the Lego® pieces at the conclusion of the exercise, the amount of time that must be devoted to this exercise varies little as the size of the class increases.

The author initiates his exercise in the same manner as Pendegraft; he divides his class into small groups and distributing one bag that contains eight small (2×2) Legos® and six large (2×4) Legos® (Figure 1) to each student group. However, the author's approach now diverges from the approach taken by Pendegraft, as the author instructs the class to build "the best-possible collection of tables and chairs" from the Lego® pieces he has provided. Students typically work for a few minutes trying to build tables and chairs (with no instruction on how to do so), until one notices the variety of designs being used around the classroom. At this point, a curious student may ask how he or she is to build tables and chairs from the Lego® pieces the instructor has provided. This is a critical juncture in the development of student modeling skills; this simple variation from the original Lego® exercise forces students to confront the process of recognizing the need for and requesting additional information when modeling a real problem.

The author then provides the students with the same instructions provided by Pendegraft; tables are constructed from two large (2×4) Lego® pieces and two small (2×2) Lego® pieces, whereas chairs are built from one large (2×4) Lego® piece and two

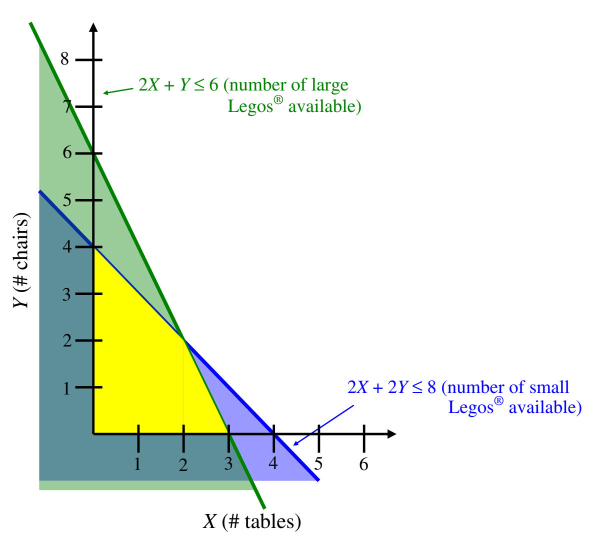
Figure 4 **Algebraic Representation of the Constraints**



small (2×2) Lego® pieces (illustrated previously in Figure 2). He also works with the students to identify limitations (or constraints) that these instructions and the available number of small (2×2) and large (2×4) Lego® pieces imply. He lets X represent the number of tables produced and Y represent the number of chairs produced, and the students can quickly and easily surmise the following algebraic formulation (note that the blank oval in Figure 4 is used to emphasize that the coefficient of 1 is understood).

Furthermore, this is an excellent opportunity to introduce the concept of a feasible region and to show the relationship between the algebra and geometry of a linear program with two decision variables. After ensuring that students also recognize that they cannot produce a negative number of tables or chairs, the students quickly understand the concept of a feasible region and can draw a diagram of the feasible region for this problem (Figure 5, in yellow).

Figure 5 **Graph of the Constraints and Resulting Feasible Region (in Yellow)**



Students are now instructed to resume the process of building tables and chairs.

Within a few minutes, several teams of students will find one of two common solutions; produce two tables and two chairs with no remaining Lego® pieces, or produce three tables and no chairs with two leftover small (2×2) Lego® pieces. Students are now motivated to ask for a basis on which they can determine which solution is superior, and here again the author diverges from Pendegraft's approach. He tells the students that

- Tables sell for \$32.00
- Chairs sell for \$21.00
- Small (2×2) Legos® cost \$3.00 each
- Large (2×4) Legos® cost \$5.00 each.

Now, the students face a quandary; should they maximize revenue, minimize costs, or maximize profit? This extension provides an opportunity for the instructor to discuss various scenarios under which each of these objectives would be most appropriate, which is another important modeling lesson.

Ultimately, the author encourages the students to maximize profit, which they quickly calculate for the two products produced to be

- \$32.00 − 2(\$5.00) − 2(\$3.00) = \$16.00 for a table and
- \$21.00 − 1(\$5.00) − 2(\$3.00) = \$10.00 for a chair.

Now, student teams almost always find the optimal mix (produce two tables and two chairs and generate revenue of \$52 with no remaining Lego® pieces). The class works through the geometry (drawing an iso-profit line through the feasible region, parallel shifting the iso-profit line in the direction of improvement as shown in Figure 6 until the iso-profit line is tangent to the feasible region, and solving for the point of tangency).

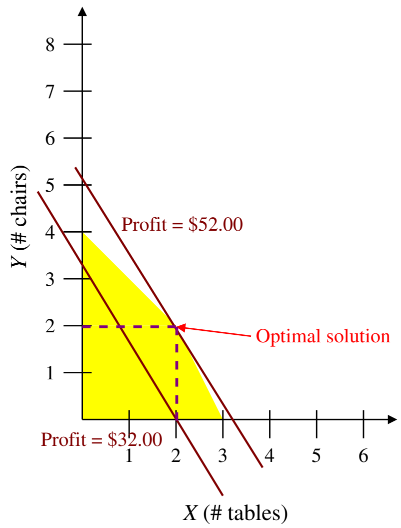
The class can then proceed with Pendegraft's discussion of the Fundamental Theorem of Linear Programming, the logic of the simplex algorithm, and sensitivity/the value of an additional unit of either a small (2×2) or large (2×4) Lego® piece.

4.2. Introducing Sensitivity Analysis

The author now proceeds by offering one large (2×4) Lego® piece in an auction. The students know the optimal solution to the original problem is to produce two tables and two chairs and generate revenue of \$52 with no remaining Lego® pieces. Because they have no actual physical resources (Lego® pieces) remaining, students generally do not think this newly available large Lego® piece has value, and so they are not inclined to bid.

At this point, the instructor can emphasize that the model is conceptual rather than physical, and that much of the value in modeling comes from the relative ease with which the modeler can alter model

Figure 6 **Graph of the Feasible Region, Iso-Profit Lines, and Optimal Solution**



characteristics and observe the ramifications of these changes. To underscore this point, the instructor disassembles one chair from one student group's optimal solution. He shows the class that this group now has one large (2 × 4) Lego® piece and two small (2 × 2) Lego® pieces available, and that the group has forfeited $10 of profit to free these resources. Students now see that if they purchase the one large (2 × 4) Lego® piece that is up for auction, they could create another table and earn $16 of profit. Thus the value of the one large (2 × 4) Lego® piece that is being auctioned is $6.00.

The instructor can also introduce the geometry of sensitivity analysis at this juncture by showing that when another large (2 × 4) Lego® piece is added to the available resources, the boundary of the constraint on the number of large (2 × 4) Lego® pieces available shifts away from the origin and remains parallel to the boundary of the original constraint. The instructor can show how, because the constraint on the large (2 × 4) Lego® pieces available is binding, the optimal solution and associated objective function value change will change with the availability of this additional large (2 × 4) Lego® piece. In addition, the instructor can emphasize various aspects of sensitivity through this exercise by

- Adding a nonbinding constraint (perhaps labor) that becomes binding as more units of another resource (perhaps large (2 × 4) Lego® pieces) are acquired;
- Changing the per unit sales price (and so the per unit profit) of one of the products to be produced (perhaps small (2 × 2) Lego® pieces) and noting the effect on the objective function, optimal solution, and optimal values of the decision variables;
- Changing the cost of one resource (perhaps large (2 × 4) Lego® pieces) and noting the effect on the objective function, optimal solution, and optimal values of the decision variables;
- Changing the number of units required to produce one of the products (perhaps increasing the number of small (2 × 2) Lego® pieces required to produce a table) and noting the effect on the small (2 × 2) Lego® pieces constraint, objective function, optimal solution, and optimal values of the decision variables;
- Adding an additional decision variable (perhaps footstools), demonstrating the impact on the geometry of moving to three dimensions, and noting the effect on the objective function, optimal solution, and optimal values of the decision variables.

Each such example also provides an opportunity to further explore the geometry of sensitivity analysis.

4.3. Adding Integer Programming and LP Relaxation and Extending Sensitivity Analysis

It is important to note that the solution to this linear programming model is naturally integer. To introduce students to the nuances of integer programming, the author now perturbs the original problem in a way that results in a noninteger optimal solution. The author allows each student team access to three additional small (2 × 2) Lego® pieces and instructs them to resolve the problem. The initial inclination of the student teams is to solve this new formulation

$$\begin{aligned}
\text{Max}\ & \{16X + 10Y\} \\
\text{s.t.}\ & 2X + 2Y \le 11 \ (\text{number of small Legos}^{\circledR} \text{ available}), \\
& 2X + Y \le 6 \ (\text{number of large Legos}^{\circledR} \text{ available}), \\
& X, Y \ge 0 \ (\text{nonnegativety}),
\end{aligned}$$

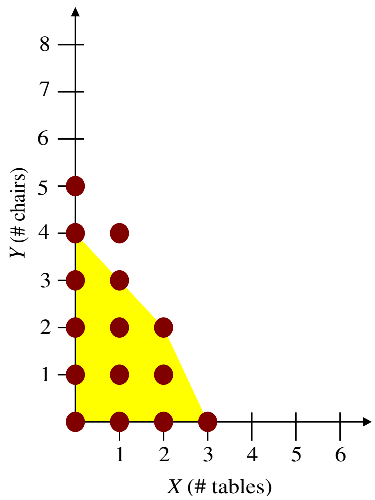
in the same manner as the previous problem. This yields an optimal solution of 0.5 tables, 5 chairs, and a profit of $58. Students are distressed by this solution (How can one build a half table?), which leads to consideration of integer restrictions on the decision variables (number of tables and chairs to produce) and the addition of these restrictions to the formulation.

$$\begin{aligned}
\text{Max}\ & \{16X + 10Y\} \\
\text{s.t.}\ & 2X + 2Y \le 11 \ (\text{number of small Legos}^{\circledR} \text{ available}), \\
& 2X + Y \le 6 \ (\text{number of large Legos}^{\circledR} \text{ available}), \\
& X, Y \in N.
\end{aligned}$$

It is also instructive to note here that nonnegativity constraints are subsumed by the integer restrictions as stated in this formulation, and so are redundant and can be removed.

As expected, students are strongly inclined to find their integer solution by rounding the solution to the LP relaxation. This is an opportune time to consider

Figure 7 **Graph of Feasible Integer Solutions Overlaid on the LP Relaxation Feasible Region**



the geometric implications of the integer restrictions on the feasible region of this problem. In Figure 7, we overlay the feasible integer solutions on the feasible region with the LP relaxation to allow the students to better understand the relationship between the feasible region with and without the integer restrictions enforced.

Rounding the optimal LP relaxation solution up to the nearest integer solution takes the solution from 0.5 tables, 5 chairs, and a profit of $58 to 1 table, 5 chairs, and a profit of $66 (Figure 8).

Here, a student may note that although profit has improved, the solution is not feasible. The student will point out that it was impossible to achieve a profit that is superior to the optimal profit achieved ($58) before adding the integer restrictions to the problem. This naturally leads to discussions of (i) LP relaxations and (ii) the concept that adding constraints to a mathematical program cannot result in

Figure 8 **LP Relaxation Solution Rounded Up (Point in Blue)**

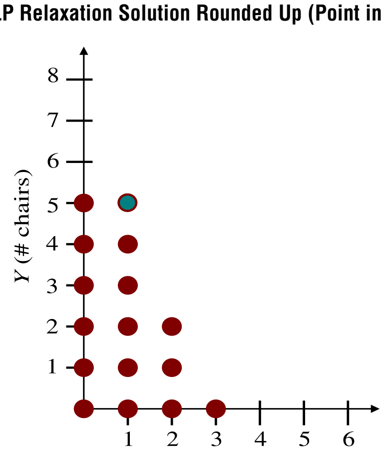
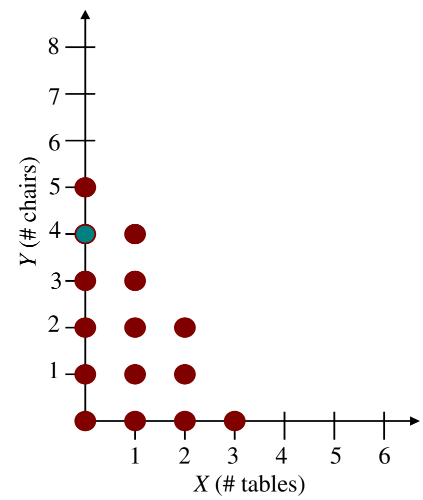


Figure 9 **LP Relaxation Solution Rounded Down (Point in Blue)**



improvement to the resulting optimal value of the objective function. The geometry of rounding up the optimal solution to the LP relaxation to this problem is also helpful.

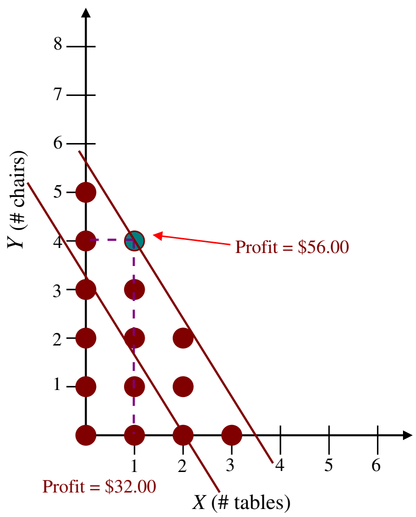
Students now are inclined to round the solution to the LP relaxation down from 0.5 tables, 5 chairs, and a profit of $58 to 0 tables, 5 chairs, and a profit of $50 (Figure 9).

Although this is clearly feasible, a clever student will note that this solution generates less profit than the solution to the problem prior to the acquisition of the three additional small (2 × 2) Lego® pieces (a solution that happened to yield integer values for both decision variables). Another important realization comes out of this step; relaxation of a constraint cannot result in degradation of the optimal value of the objective function, which, in turn, leads to a discussion of the use of bounding to find portions of the feasible space that will not yield an optimal solution and exclude these portions of the feasible space from the search for the optimal solution. Ultimately, the class returns to the reliable iso-profit approach (Figure 10).

Now, the students can proceed with a discussion on how they went from building two chairs and two tables at $52 profit to building four chairs and one table at $56 profit after they acquired three small (2 × 2) Lego® pieces. Specifically, they should note that

- They couldn't use these additional small (2 × 2) Lego® pieces because they had no available large (2 × 4) Lego® pieces;
- They could use these additional small (2 × 2) Lego® pieces to make another table if they took the large (2 × 4) Lego® pieces from two chairs, which would result in a $16 profit for the table and a $20 loss for the two chairs (i.e., a net loss = $4);

Figure 10 Graphical Solution Technique Applied to Integer Restricted Problem (Optimal Solution in Blue)



• They could use these additional small (2 × 2) Lego® pieces to make two additional chairs if they took the large (2 × 4) Lego® pieces from a table, which would result in a $20 profit for the two chairs and a $16 loss for the table (i.e., a net gain = $4).

After this discussion, the class can consider (i) why the addition of integer restrictions on values of the decision variables can actually (and generally do) make the problem more difficult to solve to optimality and (ii) the marginal value of small (2 × 2) and large (2 × 4) Lego® pieces. Each of these problems can also be solved to optimality in Excel using Solver.

5. Student Reactions

The instructor has used Pendegraft's exercise and the author's extensions in five undergraduate (junior level) sections of introductory operations research for business majors; this includes two sections at a university in France. The instructor has also used the exercise and extensions in two sections of introductory operations research for MBA students. The exercise and extensions appeared to be effective with undergraduate and MBA students as well as with American and French students.

Although the instructor has not undertaken an experiment designed to assess the impact of his extensions to Pendegraft's (1997) Lego® toys active learning exercise on student learning and comprehension, he has received a great deal of anecdotal evidence of their efficacy. Typical student comments on anonymous end of academic term instructor evaluations include:

> I thought this stuff was supposed to be hard, but the Lego example at the beginning of the quarter effectively established the basics and made the rest of the material much easier to understand.
>
> I was scared of this class (I waited as long as I could to take it), but the Lego game made me feel like I could get it! And then I did!
>
> The class was fun without being stupid. The Lego game was simple but not trivial, and I felt like I understood linear programming in about 20 minutes—amazing!
>
> I don't like math because I never see how I can use it, but the Lego game helped me see how operations research could be used on real problems.

The author's experience suggests that students enjoy and derive great educational benefit from participation in this exercise.

6. Conclusion

The author has provided brief reviews of the concept of active learning and Pendegraft's (1997) original Lego® toys active learning exercise, and he has demonstrated several novel and useful extensions to Pendegraft's exercise. These extensions provide instructors with greater opportunity to use this simple game/problem to enhance students' comprehension of linear programming, modeling, problem formulation, and sensitivity whereas also providing students with a tangible example of integer programming and LP relaxations.

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