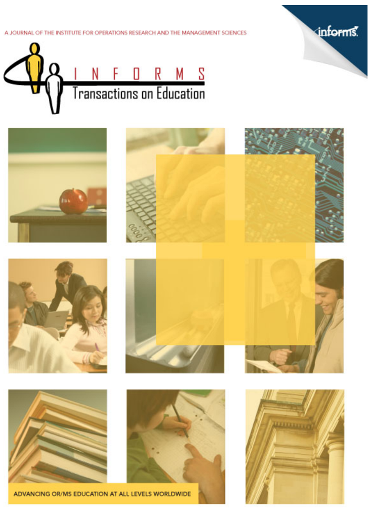

INFORMS Transactions on Education

Publication details, including instructions for authors and subscription information:
http://pubsonline.informs.org

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Vol. 13, No. 3, May 2013, pp. 129–137
ISSN 1532-0545 (online)
INFORMS Transactions on Education
http://dx.doi.org/10.1287/ited.2013.0105

Teaching Integer Programming Starting From an Energy Supply Game

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This paper presents an integer programming (IP) model for solving an online energy supply game. Instead of a traditional approach in which students are given a problem statement and asked to develop an IP model, both the problem and data are hidden in the game. The energy supply game can be used to illustrate many mathematical programming concepts including blending constraints, multiobjective programming, and the branch-and-bound method. In addition to developing IP modeling skills, students become familiar with the properties of several energy supply systems. The results of two experiments and the related evaluation questionnaires indicate that the game component motivates students more to build IP models as compared to classic approaches.

Key words: game; energy supply; spreadsheet modeling; integer programming
History: Received: January 2012; accepted: November 2012.

1. Introduction

One of the most difficult aspects of teaching integer programming (IP) is making students enthusiastic about developing optimization models. Many OR textbooks fail to motivate students to formulate, solve, and use IP models. The main reason for this is because the exercises to practice optimization modeling almost always take the form of an assignment that includes text that fully defines a fictional, small business problem in which the objective function and constraints are clearly described. This way of presenting modeling exercises has two important disadvantages.

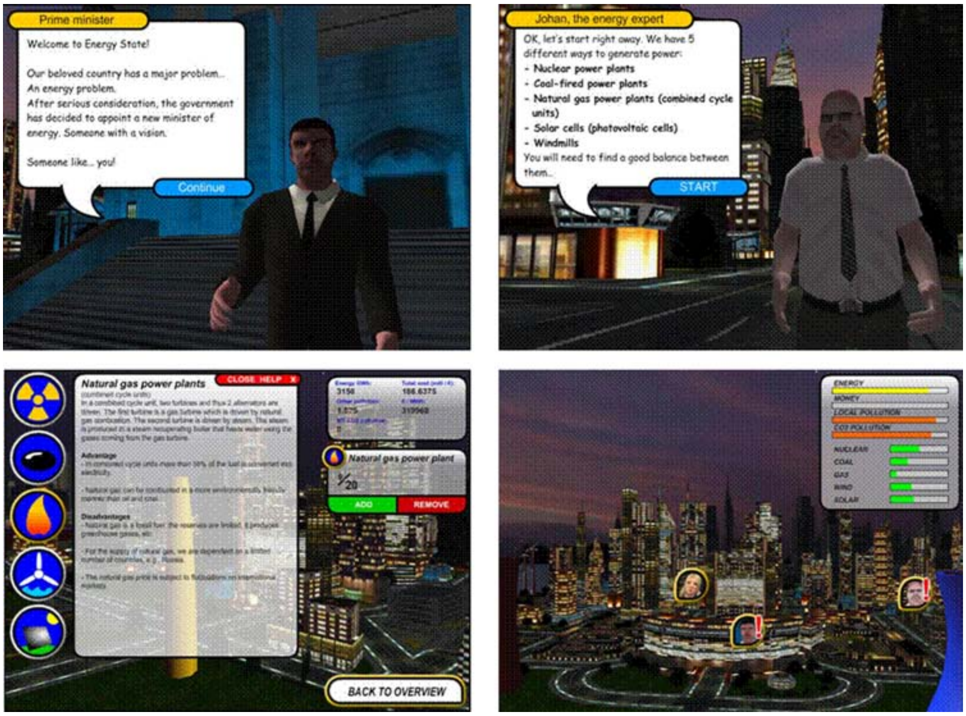
Firstly, real-life problems hardly ever have a clear, well-defined objective function and constraints. Assignments including text that fully defines the problem to be solved do not stimulate creative, out-of-the-box thinking. Consequently, students fail to apply optimization modeling in their business careers because they have never learned to *recognize* an optimization problem.

Secondly, most of these traditional textbook assignments are not exciting and therefore fail to awaken intrinsic motivation for many students. Students solve these exercises because they are asked to do so, not because they *want* to find the solution.

To make students more enthusiastic about IP, this paper presents an IP model that can be used to find the optimal mix of power plant types in an energy supply game, called the EnergyState game (Wouters et al. 2009). Both the game aspect and that energy supply is a very topical issue contribute to the motivation of students to build an optimization model.

Although the game can be used as an introductory example for teaching IP, realistic extensions allow instructors to illustrate more advanced concepts like branch-and-bound, blending constraints, and multi-objective programming models. The energy game can thus easily be reused in later moments during the course by introducing new restrictions or opportunities that lead to new model formulations. This increases teaching efficiency because no new problem

Figure 1 **Four Screenshots of the EnergyState Game**



examples need to be introduced and, consequently, more time and attention can go to teaching the new concept. Examples of such extensions are described in §3.

Today, the energy sector is one of the most important sectors in the world. Many countries are continuously evaluating and adjusting their energy supply plans, something that is often a complicated task because many factors have to be taken into account. Examples of recent problems are the nuclear disaster in Fukushima, Japan, and global warming caused by greenhouse gasses. In Belgium, for instance, two nuclear plants will be closed in 2015, followed by a nuclear phase-out in 2025 (Federal Government Belgium 2012), and Germany plans to shut all its nuclear reactors by 2022 (Breidthardt 2011). Nuclear energy is very cheap compared with renewable energy and, as opposed to fossil fuel power stations, does not produce CO_2. Does a nuclear phase-out create a budget problem or an excess of CO_2? Or is it possible to replace nuclear energy with alternative types of power generation? The online game EnergyState familiarizes students with the different types of power stations. Figure 1 depicts four screenshots of the English version of the game that can be played at the following URL: http://energierijk.be/game/index-EN.html.[1] In addition. a standalone version for Windows can be found at: http://www.energierijk.be/game/energystate.zip.

The aim of this single-player game is to find an energy supply plan for a fictional country, EnergyState, such that sufficient energy is produced while satisfying pollution limits and a budget constraint. One can choose between different types of power plants (nuclear, coal, gas, wind, solar). Students playing the game typically try to find a feasible solution (mix of plants) based on a trial-and-error approach. Note that as compared to other operations research (OR) games and puzzles (see, e.g., Chlond 2005, 2009, 2011; Meuffels and den Hertog 2010; Beliën et al. 2011), the input data of the optimization model are not given to the student in a very straightforward and clear way but have to be extracted out of the game by the students themselves.

We realize that realistic energy supply models are much more sophisticated than the model described in this paper. Nevertheless, this paper can serve as a basis for a better understanding of these realistic models. The purpose of this paper is not to construct a realistic energy model for a country but to show students, through a concrete example, the value of IP modeling. The IP models enable students to play the energy supply game in the most efficient manner. This paper examines whether students are more motivated to develop IP models when a game component and a problem of current interest such as energy supply are introduced into an OR course.

[1] Last accessed on March 7, 2013. Adobe Shockwave is required to play the game.

The remainder of this paper is organized as follows. Section 2 gives an overview of the related literature. Section 3 describes how the energy supply game can be used in a classroom to teach IP modeling. Section 4 presents our experience with the EnergyState game during the last two academic years. Section 5 concludes this paper. A teaching note with solutions and background material is available to instructors through the *INFORMS Transactions on Education* website (available at http://ite.pubs.informs.org).

2. Literature Review

We review two relevant literature streams: the use of case studies and games in the classroom and earlier studies of energy supply models.

2.1. Case Studies and Games

Similar to the approach presented in this paper, case studies often hide the relevant information for formulating an optimization problem instead of presenting that information explicitly and systematically. An example of a case in which IP can be used to optimize a distribution network design is given by Drake et al. (2011). Köksalan and Batun (2009) present a case at Pfizer Turkey in which IP can be used to optimally assign sales representatives to regions.

The value of games in a classroom has already been studied in the literature. Many studies show that students in traditional lectures, where a professor delivers a monologue in front of the class, quickly lose attention (Bonwell and Eison 1991, Prince 2004). To keep the students' attention, instructors should, studies such as Bonwell and Eison (1991) and Prince (2004) suggest, provide a more active form of learning. Active learning is more than just listening to a professor. To involve students more in a course, instructors should engage students in solving problems and thinking about what they are doing. By introducing active learning into an operations research course, business students will be more enthusiastic about IP. Sniedovich (2002) argues that games are a valuable source for students to visualize IP problems and they can motivate students to find the optimal solution.

Not all games contribute to the motivation and education of students. Games only designed to educate students are less popular than commercial games such as the strategy game *Age of Empires*. However, the use of commercial games in the classroom should be investigated carefully to prevent negative influences upon students (e.g., addiction) from exceeding the positive ones (e.g., increased motivation; Bakar et al. 2006). Squire (2005) proves through the game *Civilization III* that commercial games can strongly increase the motivation of students. However, they do not make a large educational contribution.

The commercial game that is most related to the EnergyState game (Wouters et al. 2009) is *SimCity*. A necessary part in this game is to provide a city with energy. The basic problem of supplying a city (country) with sufficient energy taking into account a budget restriction also occurs while playing *SimCity*. *SimCity* has already been used in some schools as an educational tool, although not for teaching energy-related topics or linear programming (LP) (Squire 2005).

The taxonomy of online games to teach operations provided by Wood (2007) distinguishes between insight games (allow students to quickly gain a conceptual background or key insights), analysis games (to acquire specific skills), and capstone games (provide a more comprehensive, less focused experience). In this taxonomy, the EnergyState game would be classified as an analysis game.

Many classroom games, developed to engage students in OR topics, can be found in the literature. These games are particularly useful in illustrating complex ideas that are not easily taught through traditional lectures (Griffin 2007). Because the EnergyState game can be used to teach IP, we only focus here on games that address IP. For instance, Beliën et al. (2011) present an IP model to find an optimal cycling team for the Gigabike game, addressing three types of modeling techniques: knapsack problems, multiperiod problems, and modeling if-then constraints. There are also many existing puzzles that can be solved using IP. For instance, Chlond proposes an IP formulation for well-known puzzles such as the minesweeper (Chlond 2011), a card trick puzzle (Chlond 2009), and Su Doku puzzles (Chlond 2005). Another example is the battleship puzzle in Meuffels and den Hertog (2010) that is solved by IP. According to DePuy and Taylor (2007), puzzle games are a useful tool to help students learn creative formulation and solution techniques. This way, they can enhance their understanding of these techniques in relation to more realistic problems. However, students are less interested in puzzle games, for they do not seem to be relevant to their career paths (Trick 2004). Formulating an IP for the EnergyState game is also a puzzle. However, since the energy supply of a country is a more realistic and recent topic than the above mentioned puzzles, the EnergyState game of Wouters et al. (2009) might better succeed in keeping the students' attention when compared with the earlier mentioned puzzle games. By playing the EnergyState game, students also get familiar with the different energy systems and their characteristics. Moreover, they gain insight into the energy supply problem and the main tradeoffs between energy production, costs, and pollution. As the green energy industry is growing rapidly, this kind of topic is likely to be more relevant to students' careers than artificial puzzle games.

2.2. Energy Supply Models

This section gives an overview of energy supply models that are most used in practice and have proven their value in achieving significant economic and environmental benefits in countries or regions where they have been implemented.

The most common energy supply model in practice is "the MARKet ALlocation" (MARKAL) model. It is an LP model that is developed for a long-term multiperiod energy technology optimization. The basic components are energy and environmental control technologies and demand for energy services. The MARKAL model can be used for a city as well as for a large country (Loulou et al. 2004). Belgium is one of the countries that has already applied the MARKAL model. It was used to evaluate the Belgian policy regarding climate change and the choice of technologies in the electricity sector (KU Leuven 2005). The Energy Flow Optimization Model (EFOM) is another energy supply optimization model that is specially developed for the European Commission (Grohnheit 1991). A more recent LP model for energy supply optimization is The Integrated MARKAL-EFOM System (TIMES). It combines the best features of MARKAL and EFOM (Loulou and Labriet 2007). Schrattenholzer (1981) gives a technical description of the Model for Energy Supply Systems And their General Environmental impact (MESSAGE), which is a well-known dynamic programming model that minimizes total costs of energy supply over a given time horizon. Recently, the MESSAGE model has been used to design a sustainable energy plan for Cuba (International Atomic Energy Agency 2008).

MARKAL, EFOM, TIMES, and MESSAGE are linked to this paper because they all optimize the energy supply of a country or region by using LP or IP. However, not all practical models use LP or IP. The National Energy Modeling System (NEMS), for example, is an energy-economy modeling system applied in the United States that uses simulation to forecast energy markets (Energy Information Administration 2003). Another example is Meta ∗ Net, which can solve complex economic models by representing the market economy as a network of nodes (Lamont 1994). Meta ∗ Net proves the importance of network modeling, which is a specific class of IPs discussed in this paper.

The main difference between realistic energy supply models and the energy supply model described in this paper is uncertainty. In realistic models, uncertainty is introduced by using stochastic variables and parameters instead of deterministic ones.

Possible methods of optimizing an energy system when planning under conditions of uncertainty include stochastic LP (e.g., Li et al. 2010) and fuzzy LP (e.g., Canz 1999). Wong and Fuller (2007) present a stochastic LP model that can be used for pricing in electrical energy and reserve markets. The model is illustrated on a test system representing the Ontario, Canada, network. Iran (Sadeghi and Hosseini 2006) and India (Jebaraj and Iniyan 2007) have illustrated the use of optimization models for their energy supply planning by using a fuzzy LP approach. Zhua et al. (2011), who studied energy systems planning in Beijing, present an IP model incorporating interval-parameter programming and full-infinite programming for dealing with uncertainty intervals.

3. Using the EnergyState Game to Teach IP Modeling

All the IP models can easily be solved with a basic MS Excel Solver installation (student version). The most effective way of using the EnergyState game in the classroom in order to teach IP modeling is through the concept of *mysterious homework*. The homework is mysterious in the sense that instead of being provided with a clearly described problem and data, the students are asked to use IP to solve the problem presented by the game. The students will have to find the problem, the data, the objective, and the constraints through playing the game. The EnergyState homework can be assigned to students who have had a basic introduction to IP. They should be familiar with defining decision variables; an objective function; simple constraints (demand constraints, capacity constraints, budget constraints); and integrality constraints on the decision variables. The EnergyState game can be assigned as an IP modeling task. Instead of a traditional assignment, in which students are given a problem statement as well as data, the EnergyState game itself is the homework assignment. Both the problem (what must be optimized, what are the relations, what are the restrictions?) and the data (e.g., what is the cost of a nuclear plant, what is the CO_2 contribution of a coal plant?) are hidden in the game.

One possibility is to ask your students to solve the EnergyState game using an IP model without any further explanations; i.e., the students are only provided with the link to the online game (http://energierijk.be/game/index-EN.html). The constraints are clearly indicated in the game (green bars indicate satisfaction of the constraints, red bars indicate violation). The different model parameters like the right-hand side values of the constraints are, however, hidden in the game. Creative students will have no problem in developing an IP model and deducing the values of these parameters when playing the game. This experiment is evaluated in §4.1.

Students might not be convinced of the additional value of an IP model in assisting with energy supply decisions. After all, finding a feasible solution to the EnergyState game may go faster by trial and error than by developing an IP model. To make your students aware of the benefits of a structured modeling approach, you can ask them to find, for instance, the feasible energy plant mix that maximizes power generation or that minimizes CO_2 pollution. Your students will quickly realize that finding these specific solutions (instead of just any feasible solution) is very hard without using an optimization model. To this end, you can divide your students into different groups, each having a different objective. The first group must find the maximum power solution, i.e., the energy plant mix that maximizes power production while satisfying the budget and pollution constraints. The second group must find the lowest cost solution, the third group the minimal "CO_2 pollution" solution, the fourth group the energy plant mix that minimizes "other pollution," the fifth group the solution that minimizes the number of coal plants, etc. Compared with the first approach, this approach is more student friendly because you already reveal a concrete objective function to each student group. It lies closer to the traditional way of teaching IP, i.e., let the students develop a problem formulation starting from a clear problem description. A benefit of this second approach is that you can assign different, "individual" tasks to several groups. This experiment is evaluated in §4.2.

By turning all the stakeholders' hard constraints into soft constraints, the game can be used to teach *multiobjective programming models*. We distinguish between three types of multiobjective models: the nonpreemptive feasible goal programming model, the nonpreemptive infeasible goal programming model, and the preemptive goal programming model. A nonpreemptive feasible goal programming model maximizes the deviations of the goals according to their weights; a nonpreemptive infeasible goal programming model minimizes the deviations of not reaching the goals according to their weights (because not all goals can be achieved simultaneously); the preemptive goal programming model proceeds in successive stages, starting by optimizing the most important goal, followed by the second most important goal, etc. Section 2 of the teaching note presents the different model formulations and provides spreadsheet implementations.

Additional constraints or new opportunities can dramatically complicate the optimization problem, making it nearly impossible for students to find a solution by trial and error.

An example of an additional constraint is the requirement that at least x% of the energy must be generated using renewable energy sources (wind or solar). This is a very realistic extension because these kinds of "green constraints" are currently imposed by the European standards. This restriction can be modeled through a blending constraint, which is addressed in almost all introductory LP courses. An example of an opportunity is the case in which excess power, i.e., power that is not consumed by EnergyState, can be sold to neighbor countries.

All these extensions are summarized in a case assignment on the EnergyState game, which can be found in the file "EnergyState_case.pdf" supplied with this paper. Model implementations can be found in the spreadsheets supplied with the teaching notes.

Other possibilities include *sensitivity analysis questions*, e.g., "by how much should the cost of solar panels or wind turbines be decreased to facilitate a solution without nuclear plants?" Students will not be able to solve these kinds of questions by simply playing the game.

After having introduced the *branch-and-bound method* for solving IP models, the EnergyState models can be used as exercises in using the branch-and-bound method. Students can be asked to find the optimal IP solution to one of the models without imposing integrality constraints in the Excel Solver. This way, students are forced to add the branching constraints themselves, thereby eventually leading to the optimal IP solution. More details on applying the branch-and-bound method on the EnergyState problem can be found in §3 of the teaching note.

4. Classroom Experience

4.1. Evaluation Questionnaire 2010–2011

The EnergyState game serves as an educational tool to teach IP modeling to students in an introductory LP course. We set up an experiment in order to examine whether students appreciate the use of a topical matter such as energy supply and of the active learning aspect, namely introducing IP through a game. Three homework assignments were given to 41 undergraduate students of the commercial engineering program (a combination of business and engineering) at the Hogeschool-Universiteit Brussel, who were following the LP course. The LP course is a required course that introduces LP and IP. Hence, the students following this course have never seen optimization modeling. The first two assignments addressed traditional examples of optimization problems: a multiperiod modeling bank checks exercise and a production process modeling exercise. The third homework assignment was to solve the EnergyState game using IP where students were only provided with the link to the online game. Subsequently, we sent them an online questionnaire, which was filled out by 30 of 41 students (anonymously). The questionnaire consisted of eight questions, each evaluating the effectiveness of the energy supply exercise with respect to

Table 1 Results Evaluation Questionnaire 2010–2011

Question	Responses (%)		
	Homework 1	Homework 2	EnergyState homework
(1) Which of the three homework assignments motivated you most to find the solution?	11	20	69
(2) Which of the three homework assignments taught you the most?	14	55	31

	Strongly agree (%)	Agree (%)	Neither agree nor disagree (%)	Disagree (%)	Strongly disagree (%)
(3) I liked the fact that the assignment of homework 3 was hidden in a game.	40	43	7	7	3
(4) I liked the fact that the assignment of homework 3 covered a topical matter such as the energy issue.	30	54	16	0	0
(5) Thanks to the energy game homework, I better understand the use of LP in solving practical problems.	43	54	0	0	3
(6) Thanks to the energy game homework, I better understand the use of LP in energy policy decisions by the government.	20	67	10	0	3
(7) I would like to get more examples, exercises, homework with a game component in the LP course.	40	27	27	3	3
(8) I would like to get more examples, exercises, homework about the energy issue or the environmental issue in the LP course.	7	27	53	13	0

its motivation (questions 1 and 5); game aspect (questions 3 and 7); energy supply topic (questions 4, 6, and 8); and instruction power (question 2). The questions together with the response scores are reported in Table 1. These questions have been translated from Dutch (the original language of the questionnaire) into English.

The most remarkable results can be summarized as follows. No less than 69% of the students were most motivated by the energy game exercise (question 1) and almost all of the students confirmed that this energy game exercise had increased their belief in the usefulness of LP in solving practical problems (question 5). In addition, 87% of the students had a better understanding of the use of LP in energy policy decisions by the government because of the energy game exercise (question 6). However, only 31% of the students learned most from the energy game exercise (question 2), compared to 55% of the students that learned most from homework assignment 2. The energy game exercise only addresses a very basic IP model, which could be a reason for this lower rate. More than 80% of the students like that the assignment for the energy game exercise was hidden in a game and covered the energy topic (questions 3 and 4). Two thirds of the students (67%) would like to get more exercises with a game component in the LP course (question 7), in contrast to only one third of the students (34%) who would like to get more exercises about the energy or environmental issue (question 8). One reason for this could be that there are already many environment-related courses in the commercial engineering program at the Hogeschool-Universiteit Brussel, whereas there are almost no professors who introduce a game component into their courses.

4.2. Evaluation Questionnaire 2011–2012

In order to get more evidence of the extent to which students are more motivated by the EnergyState game as compared to a classic assignment, we performed a second experiment where we split the new group of commercial engineering students 2011–2012 (by coincidence also 41 students, which is the same number as the preceding year) into two groups. These students never had the energy game before. The students were divided in a random way. The first group of 20 students got the energy game assignment for their third homework: five students had to find the solution that maximizes the energy production, five students had to find the solution that minimizes the cost, five students had to find the solution that minimizes the "CO_2 pollution," and five students had to find the solution that minimizes the "other pollution." The second group of 21 students got a traditional assignment of an energy supply problem, which basically consisted of the same IP model as the model required to solve the energy game, except for the

Table 2 Results Evaluation Questionnaire 2011–2012

Question	Homework 1	Homework 2	EnergyState homework
(1) Which of the three homework assignments motivated you most to find the solution?			
Game assignment	2 (16.7%)	2 (16.7%)	8 (66.7%)
Traditional assignment	3 (42.9%)	2 (28.6%)	2 (28.6%)
(2) Which of the three homework assignments taught you the most?			
Game assignment	1 (8.3%)	4 (33.33%)	7 (58.3%)
Traditional assignment	3 (42.9%)	2 (28.6%)	2 (28.6%)

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
(3) I liked the fact that the assignment of homework 3 was given through a game. (Only answered by students who got the game Assignment.)	5 (41.7%)	5 (41.7%)	2 (16.7%)	0	0
(4) I liked the fact that the assignment of homework 3 covered a topical matter such as the energy issue.					
Game assignment	2 (16.7%)	5 (41.7%)	5 (41.7%)	0	0
Traditional assignment	4 (57.1%)	3 (42.9%)	0	0	0
(5) The energy homework helped me to better understand the use of LP in solving practical problems.					
Game assignment	3 (25%)	8 (66.7%)	0	1 (8.33%)	0
Traditional assignment	2 (28.6%)	4 (57.1%)	1 (14.3%)	0	0
(6) The energy homework helped me to understand the use of LP in energy policy decisions by the government.					
Game assignment	1 (8.3%)	9 (75%)	1 (8.3%)	1 (8.3%)	0
Traditional assignment	1 (14.3%)	6 (85.7%)	0	0	0

input data, which were provided to the students. The classic assignment for this second group can be found in §4 of the teaching note.

Note that the homework was not compulsory and students were not evaluated on this homework. For the first group (game assignment), 12 out of the 20 students handed in a solution, whereas for the second group (classic assignment) only 7 out of 21 students handed in a solution. The difference is significant at the 0.10 level (p-value is 0.09 using a standard two-sided hypothesis test for equal proportions). This already suggests that a game motivates students more to develop IP models than does a classic assignment.

Afterward, we asked the students to complete an online questionnaire (anonymously). The questions together with the students' responses are listed in Table 2. For each question, Table 2 compares the response scores of the two students groups (game assignment versus traditional assignment). Because question 3 measures the extent to which the game aspect is appreciated by the students, this question was only given to the students who got the game assignment and, therefore, no comparison could be made to the traditional assignment.

The percentage of students that was most motivated by the homework 3 (EnergyState) was more than twice as high in case of the game assignment as compared to the traditional assignment (66.67% versus 28.57%). Moreover, when asked which of the three assignments taught you the most, 58.33% of the students who got the game assignment indicated the EnergyState homework, whereas only 28.57% indicated this homework given as a traditional assignment. Both the results to questions 1 and 2 have been subject to a chi-square test for independence between the type of assignment and the homework that was most motivating or taught the most. No statistically significant dependence was found (probably because of the small numbers).

The results of the other questions confirm our findings of the preceding year, namely, that students greatly appreciate the game aspect (question 3) and that it helped them to understand the use of LP in solving practical problems (question 5) and in energy policy decisions by the government (question 6). Note also that questions 4 and 6 show that a topical matter as energy supply is slightly more appreciated (question 4) and creates a better understanding of the usefulness of LP in policy decision making (question 6) for traditional assignments as compared to game assignments. That is probably because the game aspect tends to disconnect students from reality to a certain extent. However, in general we may conclude from this second evaluation questionnaire that the game aspect strongly dominates the aspect of a topical matter in motivating and teaching students.

5. Conclusions and Future Work

This paper has presented a creative form of an IP modeling assignment. Instead of a classic assignment that includes text that fully defines the problem to be solved, students are given a game assignment. The game can easily be formulated as an IP model by students who have had a basic introduction to IP. The EnergyState game provides a good illustration of how a structured model formulation approach eventually outperforms a trial-and-error approach.

Besides the game aspect, this paper addresses an up-to-date topic, namely, energy supply. Today, energy is very important and students are concerned about the growing energy costs and the impact of, e.g., fossil fuels on our environment or the risks related to nuclear energy.

The results of the two experiments and related evaluation questionnaires confirm our belief in the effectiveness of the EnergyState game in teaching IP modeling. The results indicate that the game concept is crucial to the students' motivation for developing IP models. The energy topic turned out to be less important. However, the EnergyState game also serves as a basis for a better understanding of realistic energy supply models and the trade-offs between costs, pollution, and power generation.

Many other economic concepts and OR models could be illustrated using the EnergyState game and energy supply decision problems in general. For instance, the EnergyState game could be used to demonstrate the concept of Pareto efficiency. Each Pareto-efficient solution with respect to two dimensions, e.g., energy production and costs, can be generated by solving a specific IP model. Each model optimizes one criterion (e.g., maximize energy production) while imposing a certain limit to another criterion, e.g., the costs (budget constraint). By varying this limit from the lowest possible value to the highest available budget, all Pareto efficient solutions with respect to energy production and cost can be generated. The same can be done for each pair of criteria (energy production, cost, CO_2 pollution, and other pollution). Three-dimensional Pareto efficient curves are also possible.

A second, interesting extension is a dynamic multiperiod model. One possible way to transform the static energy supply problem into a dynamic problem is through CO_2 emission rights. In order to mitigate global warming, the European Commission introduced in 2005 an emission trading system (ETS). Under this system, large CO_2 emitting installations and companies are required to surrender every year emission permits to cover their actual emissions of CO_2. Emission permits are, up to now, given for free and are fully tradable. The European standards dictate that CO_2 emissions should decrease significantly in the coming years. Thus, each year, the permitted level of CO_2 pollution decreases. If a company emits less (more) CO_2 than imposed by the European standards, it can sell (buy) the remaining emission rights at the prevailing market price. The multiperiod linkages aspect could also be introduced through purchasing (selling) emission permits from (to) other companies in certain years; multiperiod emission account balance requirements; yearly depreciations of, e.g., nuclear plants and energy storage; and changes over time in prices of energy, emission permits, operation and investment costs, etc.

Other models that can be illustrated through energy supply problems include fixed charge IP models (with fixed costs for building an energy plant and variable costs for every unit of power production), set covering models (where to place the energy plants so that the whole country is provided with energy) and transportation models (which plants supply which regions given energy transportation costs and limited plant capacities), etc. Examples of such models can easily be created starting from the model for the EnergyState game.

Supplemental Material

Supplemental material to this paper is available at http://dx.doi.org/10.1287/ited.2013.0105.

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