INFORMS TutORials in Operations Research

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

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TUTORIALS IN
OPERATIONS RESEARCH
INFORMS 2007

 | ISBN 13 978-1-877640-22-3
DOI 10.1287/educ.1073.0034

Trends in Operations Research and Management Science Education at the Introductory Level

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Abstract The last 40 years have seen major changes in operations research and management sciences education at the introductory level. This tutorial traces the changes that have occurred, describes what subjects are currently being taught, and assesses the changes that can be expected in the near future.

Keywords education; educational trends; OR/MS education

1. Introduction

Although its roots go back much further, the beginning of the activity called *operations research* (or *operational research* in certain parts of the world) is generally attributed to teams of scientists who conducted research on how to perform military operations more effectively during World War II.[1] The activity of conducting research on how to perform activities of any kind more effectively then began to spread to business and industry during the years following World War II. Courses in operations research (OR) and then degree-granting programs in the field moved into colleges and universities during the 1950s and 1960s. Textbooks for teaching operations research at the introductory level also began to be available during the same period.

Of these initial textbooks, *Introduction to Operations Research* by Frederick S. Hillier and Gerald J. Lieberman [6] (now in its eighth edition) is still widely used today. We use the evolution of the many editions of this textbook since its initial publication in 1967 as a vehicle to describe the trends in OR education at the introductory level for students in engineering and the mathematical sciences.

Although in its early years this textbook was also widely used in business schools, specialized textbooks aimed directly at business students later were developed and used in courses that typically were entitled "Management Science" (MS) or "Quantitative Methods." A prominent example is the Anderson-Sweeney-Williams textbook [1], *An Introduction to Management Science: Quantitative Approaches to Decision Making*, that now is in its 12th edition. Early MS textbooks such as this one covered many of the same topics as the Hillier-Lieberman textbook, including substantial coverage of algebraic modeling and basic OR algorithms, but at a mathematical level appropriate for business students. Over the past decade or so, a new generation of MS textbooks[2] has appeared that greatly deemphasizes this

[1] See Gass and Assad [4] for an informal history of operations research and its precursors dating as far back as 1564.

[2] The first of these new-generation textbooks, *Management Science: A Spreadsheet Approach*, by Donald Plane [8], was published in 1994.

kind of coverage and instead emphasizes spreadsheet modeling. Typical is our textbook [5], *Introduction to Management Science: A Modeling and Case Studies Approach with Spreadsheets*. We will use the just-published third edition of this textbook in §3 to illustrate current trends in MS education at the introductory level.

Before discussing these trends in MS education for students in business school, we first will focus on trends in introductory OR education, that is, trends in introductory OR courses for students in engineering and the mathematical sciences.

2. Trends in Introductory OR Education

Gass and Assad [4] identify a few important OR books that were published during the early years of the field. Notable among these were *Methods of Operations Research* by Morse and Kimball [7] and *Introduction to Operations Research* by Churchman et al. [3]. Although these

Origins of the Hillier-Lieberman Textbook

As the first co-author of both this paper and the Hillier-Lieberman textbook, let me now present for the record a first-person account of the origins of this textbook [6].

When I arrived at Stanford University as a freshman in September, 1954, I had the great good fortune to have Jerry Lieberman assigned as my freshman advisor. Jerry took me under his wing and continued as my advisor all the way through both my undergraduate and graduate programs. During my total of seven years of study, Jerry put me into many wonderful courses with top-notch faculty. In addition to the regular undergraduate engineering courses and the full industrial engineering curriculum, I took 17 statistics courses, 13 math courses, 5 economics courses, a technical writing course, etc., as well as every operations research course given in any department. During my graduate study, Jerry also arranged for me to teach a couple of courses, including the "Introduction to Operations Research" course that had so excited me when I took it from Jerry a few years before. After auditing Harvey Wagner's version of the same course, I threw myself into the course preparation with meticulous care and thoroughly enjoyed the experience. These class notes later were to provide the foundation for my part of the first edition of our textbook.

After receiving my Ph.D. in June of 1961, I accepted an offer to join the Stanford faculty. Jerry and I soon began discussing the need for a new introductory textbook in operations research. We decided that we wanted to develop a path-breaking textbook that would help establish the direction of education in this emerging field. I was very excited about this prospect, because of both my enthusiasm for the material and the opportunity to be a co-author with Jerry, who was already a well-known book author.

Immediately on my return from a leave at Cornell for the 1962–1963 academic year, we began working on the book. It was a labor of love that would go on for over three years, including much class testing and feedback from colleagues. The first edition then was published in 1967. The publisher was Holden-Day, a small publishing company for whom Jerry was serving as a series editor.[3]

Jerry and I continued to work together on the next four editions of the book published in 1974, 1980, 1986, and 1990. Tragically, in 1991, Jerry received the horrible news that he had amyotrophic lateral sclerosis (Lou Gehrig's disease), which eventually took his life in 1999. When Jerry became ill, I promised myself that I would continue to devote myself to subsequent editions of the book. The sixth, seventh, and eighth editions were published with copyright dates of 1995, 2000, and 2005; and I am currently working on the ninth edition to be published in January, 2009. God willing, I plan to continue future editions until at least the 50th anniversary of the book in 2017, and hopefully much longer. I look forward to the challenge of continuing and enhancing the Hillier-Lieberman tradition.

[3] McGraw-Hill purchased the rights to our book from Holden-Day in 1988, so McGraw-Hill has been the publisher since that time.

books did not contain exercises and therefore were not fully designed for use as a textbook, the Churchman et al. book in particular did serve as a basic text for a considerable number of years. The first edition of *Introduction to Operations Research* by Hillier and Lieberman [6] followed a decade later and quickly became a standard introductory textbook. Through various editions, it maintained this status over the next 40 years to the present. The sixth edition won honorable mention for the 1995 Lanchester Prize and the eighth edition was awarded the 2004 INFORMS Expository Writing Award. The eighth edition continues to be the market leader in both the United States and internationally (various editions have been translated into well over a dozen other languages). A ninth edition is scheduled for publication in January 2009.

2.1. Contents of the First Edition (1967) of the Hillier-Lieberman Textbook

The first edition of the Hillier-Lieberman textbook seems somewhat quaint now, 40 years later, in light of both all the subsequent advances in the field and all the subsequent refinements in pedagogical approaches to teaching OR at the introductory level. However, it is of interest to briefly set the stage for beginning to trace the subsequent trends in OR education. (The reviewer of this tutorial commented that the first edition also is of interest because "many people argue that the 17 chapters of this edition defined OR for a generation of students.")

Table 1 shows the table of contents of the first edition. After two introductory chapters, the next two chapters provide primers or reviews of fundamentals for dealing with probabilistic

TABLE 1. Table of contents of the first edition of the Hillier-Lieberman textbook.

Chapter	
Part I	Methodology
1	Introduction
2	Planning an Operations Research Study
Part II	Fundamentals
3	Probability Theory
4	Statistical Inference and Decision Theory
Part III	Techniques: Mathematical Programming
5	Linear Programming
6	Special Types of Linear Programming Problems
7	Network Analysis, Including PERT
8	Dynamic Programming
9	Game Theory
Part IV	Techniques: Probabilistic Models
10	Queueing Theory
11	The Application of Queueing Theory
12	Inventory Theory
13	Markov Chains and Their Applications
14	Simulation
Part V	Techniques: Advanced Topics in Mathematical Programming
15	Advanced Topics in Linear Programming
16	Integer Programming
17	Nonlinear Programming
Appendices	Convexity
	Classical Optimization Methods
	Matrices and Matrix Manipulations
	Simultaneous Linear Equations
	Tables

OR models. Chapter 4 provides an introduction to such decision analysis topics as Bayes procedure and posterior probabilities but most of the chapter is devoted to traditional topics of statistical inference.

Chapters 5 to 9 give an introduction to some basic areas of mathematical programming. Chapter 5 presents the linear programming model and its underlying assumptions, describes the simplex method (including the Big M method and a brief mention of the two-phase method), and briefly introduces duality theory and sensitivity analysis. Chapter 6 covers the transportation problem, the transshipment problem, and the assignment problem, including specialized algorithms for solving these problems. Chapter 7 presents the maximum flow and shortest path problems (but not the general minimum cost flow problem), as well as the minimum spanning tree problem and PERT. Chapter 8 describes the general characteristics of dynamic programming problems and presents various examples of both deterministic and probabilistic dynamic programming. Chapter 9 focuses almost exclusively on two-person, zero-sum games.

Chapters 10 to 14 then turn to an introduction to basic types of probabilistic models. Chapter 10 focuses mainly on Markovian queueing models, including even priority models, but only briefly mentions queueing networks. Chapter 11 then deals with various aspects of applying queueing theory, including cost models for designing queueing systems. Chapter 12 presents a variety of classic inventory models, including both deterministic and stochastic models. Chapter 13 is devoted mostly to discrete-time Markov chains, but also includes a relatively brief discussion of both Markov decision models and continuous-time Markov chains. Chapter 14 introduces the various techniques of simulation, including the generation of random numbers, the generation of random observations from a probability distribution, and variance-reducing techniques.

Chapters 15 to 17 turn to some "advanced topics" in mathematical programming, so the implication is that these topics need not be included in a basic introductory survey course. Chapter 15 expands substantially on the treatment of duality theory and post-optimality analysis in Chapter 5. It also covers such topics as the revised simplex method, the dual simplex method, the decomposition principle, stochastic programming, and chance-constrained programming.

What is perhaps most striking about the table of contents in Table 1 is that such basic topics today as integer programming and nonlinear programming are relegated to the "advanced topics" at the end of the book. However, back in the mid-1960s, these were indeed fairly new and relatively advanced topics. Chapter 16 features Gomory's cutting plane algorithm but also introduces the branch-and-bound approach to integer programming that was quite new at the time. Chapter 17 presents the Kuhn-Tucker conditions (now known as the Karush-Kuhn-Tucker or KKT conditions), applies these conditions to quadratic programming with Wolfe's modified simplex method, and discusses separable programming. It then briefly surveys algorithmic approaches to convex programming, including Fiacco and McCormick's then-new sequential unconstrained minimization technique.

The pedagogical style of the first edition is a fairly formal one. Many chapters or sections begin with a mathematical statement of the general model being considered and then attention is turned to an algorithm for solving the model. One or more numerical examples are used to illustrate the formulation of the model and the application of the algorithm. This relatively concise treatment of the material results in a trim 6" $\times$ 9" book of 639 pages.

2.2. The Evolution of Subsequent Editions of This Textbook

Subsequent editions underwent numerous revisions, both large and small, to reflect developments in the field and changing pedagogical tastes. We will briefly summarize the most important changes.

Starting with the second edition, the pedagogical style of the book was changed fairly substantially from the one of the first edition. Much more emphasis was given to developing interesting and relatively realistic examples. Rather than beginning many chapters or sections with a general mathematical statement of the model being considered, a fairly elaborate prototype example was used instead to introduce the topic and then to illustrate the formulation of the model and the execution of an algorithm. The more expansive treatment of the material and the addition of many more problems (and then cases) considerably increased the size of the book.

Many new topics also were added to new editions of the book. Some of these involve well developed, but fairly specialized, areas of operations research, including goal programming, the minimum cost flow problem, the network simplex method, forecasting, reliability theory, and the theoretical foundations of the simplex method. Other topics were added to reflect important new developments in the field. These include the interior-point approach to solving linear programming problems, the branch-and-cut approach to solving integer programming problems, constraint programming, metaheuristics, and multiechelon inventory models for supply chain management. In §2.3, we will discuss the importance of these five new topics and why instructors should consider at least briefly including them in introductory OR courses.

Some topics that were covered only briefly in the first edition were greatly expanded and revised in subsequent editions. These include such key topics as decision analysis, duality theory and sensitivity analysis, simulation, Markov decision processes, and project management with PERT/CPM.

In addition, the rather short chapters on integer programming and nonlinear programming that were relegated to the back of the book as "advanced topics" in the first edition subsequently were greatly expanded and brought forward as mainstream chapters. After deleting the section on Gomory's cutting plane algorithm, the integer programming chapter now includes a section describing some real-world applications, two sections on model formulation, and extensive coverage of the branch-and-bound approach, as well as sections on the branch-and-cut approach and the incorporation of constraint programming. Similarly, the nonlinear programming chapter was expanded into a relatively comprehensive survey of the area.

Table 2 shows the timeline for when various major new topics were added to a new edition for the first time. (In a few cases, these topics were subsequently moved to the supplements on the CD-ROM in the most recent editions to save space.) Thus, the table gives an indication of the trends in OR education at the introductory level over the last few decades.

All these changes greatly increased the size of the book. Up to the seventh edition, each new edition was significantly larger than the preceding one. In contrast to the first edition that has 639 pages, the seventh edition had grown to 1,214 pages with trim size expanded from 6" $\times$ 9" to 8" $\times$ 9". Although the expanded material provides considerable flexibility to instructors for what to cover, a somewhat smaller size might be preferable for a textbook for introductory survey courses. Therefore, a strong effort was made to reduce the size of the book. This succeeded in reducing the eighth edition to 1,061 pages (with an 8" $\times$ 10" trim size), despite adding nearly 100 pages of new material on recent developments in the field. This reduction was accomplished largely by transferring various little-used sections and chapters in preceding editions (as well as many cases) to the book's CD-ROM and website as supplements.

The fifth edition introduced another key change by packaging software with the book for the first time. For the first four editions, the students had been expected to use paper and pencil to do their homework for learning how to execute the various algorithms. Mark S. Hillier then developed a tutorial software package to accompany the fifth and sixth editions. This package featured demonstration examples, interactive routines, and automatic routines for the various algorithms in the book. Each interactive routine enables the student to execute the corresponding algorithm interactively, making the needed decision at each

Table 2. Major new topics in new editions of the Hillier-Lieberman textbook.

Edition	Major new topics
Second (1974)	Tabular form of the simplex method
	A "fundamental insight" for the simplex method
	Multidivisional and multitime period problems
	Forecasting
	A complete chapter on decision analysis
	A complete chapter on Markov decision processes
	Reliability
	Regenerative method of statistical analysis for simulation
	Branch-and-bound algorithms for binary and mixed integer programming
	Gradient search procedure for unconstrained optimization
Third (1980)	Goal programming
	Special formulation techniques for linear programming
	Special formulation techniques for integer programming
	One-dimensional procedure for unconstrained optimization
Fourth (1986)	A complete chapter on reliability
	Greatly expanded chapter on nonlinear programming
	A continuous-review stochastic inventory model
Fifth (1990)	Interior-point approach to solving linear programming problems
	Use of microcomputer software
	Minimum cost flow problem
	Network simplex method
	Branch-and-cut approach to solving integer programming problems
	Jackson queueing networks
	Forecasting with seasonal effects
Sixth (1995)	Case studies of real applications
	Several case problems
	Utility theory
Seventh (2000)	Incorporation of MPL, CPLEX, LINDO, LINGO, Excel spreadsheets, etc.
	Eight new sections on the practice of operations research
	Many case problems
	A complete chapter on project management with PERT/CPM
Eighth (2005)	Metaheuristics (a complete new chapter)
	Constraint programming
	Multiechelon inventory models for supply chain management
	Spreadsheet modeling
	Hungarian algorithm for the assignment problem
	Newton's method for unconstrained optimization
	Many supplementary "worked examples" on the CD-ROM
	A test bank for instructors

step while the computer does the needed arithmetic. The result is a far more efficient and effective learning process that also is more stimulating to the student.

For the seventh and subsequent editions, a professional software company (Accelet Corp.) further enhanced this package of interactive and automatic routines and implemented it in Java 2, so it is platform independent. Michael O'Sullivan implemented the package of demonstration examples in JavaScript. Starting with the seventh edition, a wealth of other professional software packages were bundled with the book together with numerous illustrations of their use. The packages accompanying the eighth edition (and anticipated for the ninth edition) include the following:

- Interactive Operations Research (IOR) Tutorial (the package of interactive and automatic routines described above).

- OR Tutor (the package of demonstration examples of various algorithms mentioned above).
- Several Excel add-ins, including Premium Solver for Education (an enhancement of the basic Excel Solver), TreePlan (for decision analysis), SensIt (for probabilistic sensitivity analysis), RiskSim (for simulation), and Solver Table (for automating sensitivity analysis in optimization problems).
- Student versions of MPL (an algebraic modeling language) and three of its solvers: CPLEX (the most widely used state-of-the-art optimizer), CONOPT (for convex programming), and LGO (for both global optimization and convex programming).
- Student versions of LINDO (a traditional optimizer) and LINGO (an algebraic modeling language).
- Queueing Simulator (for the simulation of queueing systems).
- Crystal Ball Professional Edition (for risk analysis, including especially simulation).

2.3. Some Key New Topics for Introductory OR Courses

Over the 40 years since the publication of the first edition, many important new developments have occurred in the field. We highlight five here that we feel deserve strong consideration for inclusion at least briefly in even an introductory OR survey course. Thus, all five are covered in some detail in the most recent edition(s) of the Hillier-Lieberman textbook.

- **Interior-Point Approach to Linear Programming**

The most significant new development during the 1980s was the discovery of the efficiency of the interior-point approach to solving linear programming problems. Much more progress has been made in more recent years in developing algorithms of this type (commonly referred to as *barrier algorithms*). Although this approach did not supplant the simplex method (or dual simplex method) as the method of choice for problems of moderate size, it often is the most efficient method (and perhaps the only tractable method) for solving huge problems. Therefore, although its technical details are quite complicated, it is appropriate to introduce introductory students to its main concepts.

- **Branch-and-Cut Algorithms for Integer Programming**

For many years, *branch-and-bound algorithms* provided the most efficient way of solving integer programming problems. However, in more recent years, this kind of algorithm has been supplanted by branch-and-cut algorithms that incorporate the branch-and-bound approach into a much broader framework that also includes automatic problem preprocessing and the generation of cutting planes. Students should be made aware that this kind of algorithm now provides the state-of-the-art approach to solving integer programs.

- **Constraint Programming Techniques for Mathematical Programming**

An exciting recent development is the discovery of constraint programming techniques that are beginning to greatly expand our ability to formulate and solve certain kinds of mathematical programming problems, including integer programming and combinatorial optimization problems. Although the further development of this approach is still an active area of research, it is time to begin briefly introducing this key new concept in introductory courses.

- **Metaheuristics for Complex Problems**

Despite the continuing progress in developing more efficient algorithms, the problems that arise in practice often are too large and complex to be solved to optimality. Therefore, *heuristic methods* are frequently used to search for a very good, but not necessarily optimal, solution. This has led to the development of several powerful metaheuristics (e.g., tabu search, simulated annealing, and genetic algorithms), which are general solution methods that provide both a general structure and strategy guidelines for developing a specific heuristic method to fit a particular kind of problem. Because of their wide usage in practice, it is important for students to be made aware of the existence of these metaheuristics and perhaps to be introduced to their general concepts. Therefore, the eighth edition of the Hillier-Lieberman textbook added a complete new chapter on metaheuristics.

- **Multiechelon Inventory Models**

In our growing global economy, effective *supply chain management* is now a key success factor for many leading companies. Therefore, multiechelon inventory models are a vital tool for managing the inventories at the stages of a company's supply chain in a coordinated way. Consequently, any survey of inventory models in an introductory course now should at least introduce multiechelon models.

In addition to these five key topics, there are other recent developments that also warrant some consideration for inclusion in an introductory OR survey course. At the time of this writing, several of these are being considered for addition to the ninth edition.

3. Trends in Introductory MS Education

Section 2 focused on trends in introductory OR education. We now turn to discussing the trends in business schools, where the corresponding courses commonly replace the name "operations research" (OR) by "management science" (MS). After briefly describing the history of introductory MS education, we will use our own [5] textbook (the third edition of *Introduction to Management Science: A Modeling and Case Studies Approach with Spreadsheets*) to illustrate the current trends, including current progress in spreadsheet modeling.

3.1. A Brief History of Introductory MS Education

Management science topics were introduced into the curriculum of many business schools as early as the 1960s (and even earlier in some cases). The Hillier-Lieberman OR textbook (among others) was widely used in business schools during the early years after its initial publication in 1967. However, it then began to be replaced during the 1970s as textbooks directly aimed at business students (such as the classic Anderson-Sweeney-Williams [1] textbook) started to appear. These MS textbooks covered most of the same topics as the Hillier-Lieberman OR textbook (including coverage of basic algorithms), but at a considerably lower mathematical level and with more emphasis on examples of business applications.

In one sense, the 1980s were the glory days for introductory MS education in the United States. Because the Association to Advance Collegiate Schools of Business (AACSB) required the inclusion of a management science course in the core MBA curriculum to obtain accreditation, huge numbers of business students were taking a management science course (sometimes labeled "quantitative methods") and a considerable number of management science faculty were being hired to teach these courses. However, it seemed that an increasing number of students were struggling unsuccessfully to penetrate the "algebraic curtain" that was raised in many of these courses when presenting the algebraic models and algorithms of operations research, and there was considerable skepticism among both the students and other faculty about the relevance of these courses. Perhaps one factor, according to a common perception of instructors and the periodic results of international testing of the mathematical ability of students in various countries, was that the mathematical background and ability of typical American business students was becoming progressively weaker over time.

A catastrophic event occurred in 1991 when the AACSB dropped management science from its core body of knowledge needed to receive accreditation. Over the next several years, most business schools dropped the requirement that its students must take a management science course. A smattering of management science concepts might appear in other courses (such as a required operations management course) or even as one portion of a core course, but that was all. A management science course usually was still available as an elective, but most students were not taking it at most schools. The size of many management science faculties began to shrink.

As a result, the management science community was forced to take a hard look at what went wrong with old ways of teaching management science and what changes needed to be made. In 1996, INFORMS Business School Education Task Force issued a report that included the following statement.

> There is clear evidence that there must be major change in the character of the (introductory management science) course in this environment. There is little patience with courses centered on algorithms. Instead, the demand is for courses that focus on business situations, include salient nonmathematical issues, use spreadsheets, and involve model formulation and assessment more than model structuring. Such a course requires new teaching materials. ([9], p. 40)

This statement implied several key messages:

1. "There is little patience with courses centered on algorithms" suggests that it was a mistake for traditional courses and textbooks to focus largely on algorithms because they are not relevant for future managers (typical business students).
2. Teaching algorithms only succeeds in turning off these students and diverting attention from the relevant concepts of management science.
3. "The demand is for courses that focus on business situations (and) include salient nonmathematical issues" suggests that a **case studies approach** would be an appropriate way to consider the business and nonmathematical issues when applying management science.
4. "The demand is for courses that . . . involve model formulation and assessment more than model structuring" suggests that a **modeling approach** is appropriate, but it should be one that focuses on modeling on a conceptual and evaluation level rather than on the algebraic details of the model.
5. "The demand is for courses that . . . use spreadsheets" seems to suggest that the emphasis should be on **spreadsheet modeling** instead of algebraic modeling.

The statement ends with the plea that the kind of course being recommended "requires new teaching materials." This plea was answered in the mid-to-late 1990s with the publication of several new introductory management science textbooks that emphasize spreadsheet modeling. In most cases, the approach is to present a large number of relatively brief examples of the application of the mechanics of spreadsheet modeling to a variety of business problems, but not to present case studies (except for end-of-chapter cases) that illustrate the role of this process in an overall managerial study. However, other books also were being published that provide this broader perspective from the viewpoint of a corporate general manager. One notable example is the book by Peter Bell [2] entitled *Management Science/ Operations Research: A Strategic Perspective*.

We believe that our own textbook (first published in 1999 and now in its third edition), provides a unique, thoroughly modern approach. As implied by its title, *Introduction to Management Science: A Modeling and Case Studies Approach with Spreadsheets*, we feature the use of spreadsheet modeling within the context of case studies. We draw on our own experience with this book when describing the current trends in introductory MS education in the next subsection.

Before concluding this brief history of introductory MS education, we should point out that the AACSB again revised its accreditation standards in 2003 to require the coverage of "statistical data analysis and management science" in MBA courses. However, the standard does not require that a full course be devoted to management science, or even to both statistical data analysis and management science. It is still unclear in 2007 how much impact this revised guideline will have on the resurgence of management science in business school curricula.

3.2. Current Trends in Introductory MS Education

In this section we elaborate further on the current trends in introductory MS education and their rationale as illustrated by our own textbook.

- **Use Spreadsheets**

The modern approach to teaching of management science clearly is to use spreadsheets as a primary medium of instruction. Inasmuch as both business students and managers now live with spreadsheets, they provide a comfortable and enjoyable learning environment. Modern spreadsheet software, including Microsoft Excel, can now be used to do real management science. In addition to Excel's Solver and Frontline System's premium versions of Solver for doing optimization within spreadsheets, add-ins to Excel such as TreePlan or Precision Tree for decision trees and Crystal Ball, @RISK, or Risk Solver for simulation allow performing decision analysis and simulation modeling efficiently within the spreadsheet environment. For student-scale models (which include many practical real-world models), spreadsheets are a much better way of implementing management science models than traditional algebraic solvers. The algebraic curtain that was so prevalent in traditional management science courses and textbooks now can be lifted.

However, with the new enthusiasm for spreadsheets, there is a danger of going overboard. Spreadsheets are not the only useful tool for performing management science analyses. Occasional modest use of algebraic and graphical analyses still have their place and it would be a disservice to not develop the skills of students in these areas when appropriate. Furthermore, a management science textbook should not be mainly a spreadsheet cookbook that focuses largely on spreadsheet mechanics. Spreadsheets are a means to an end, not an end in themselves.

- **Use a Modeling Approach**

Model formulation lies at the heart of management science methodology. Therefore, it is appropriate to emphasize heavily the art of model formulation, the role of a model, and the analysis of model results. The modern approach is to do this by primarily (but not exclusively) using a spreadsheet format rather than algebra for formulating and presenting a model.

Some instructors have many years of experience in teaching modeling in terms of formulating algebraic models (or what the INFORMS Task Force called "model structuring" in the statement quoted in §3.1). Some of these instructors feel that students should do their modeling in this way and then transfer the model to a spreadsheet simply to use the Excel Solver to solve the model. However, most business students find it more natural and comfortable to do their modeling directly in a spreadsheet. Furthermore, by using the best spreadsheet modeling techniques, formulating a spreadsheet model tends to be considerably more efficient and transparent than formulating an algebraic model.

Another break from tradition is to virtually ignore the algorithms that are used to solve the models. There is no good reason why typical business students should learn the details of algorithms executed by computers. Within the time constraints of a one-term management science course, far more important lessons are to be learned. High on this list is the art of modeling managerial problems on a spreadsheet.

Formulating a spreadsheet model of a real problem typically involves much more than designing the spreadsheet and entering the data. Therefore, it is important to work through the process step by step: understand the unstructured problem, verbally develop a structure for the problem, gather the data, express the relationships in quantitative terms, and then lay out the spreadsheet model. The structured approach highlights the typical components of the model (the data, the decisions to be made, the constraints, and the measure of performance) and the different types of spreadsheet cells used for each. Consequently, the emphasis should be on the modeling rather than spreadsheet mechanics.

- **Use a Case Studies Approach**

However, an emphasis on spreadsheet modeling would be quite sterile if a course involved little more than examining a long series of brief examples with their spreadsheet formulations. In addition to examples, it is helpful to include case studies patterned after actual applications to convey the whole process of applying management science. By drawing the student into the story, a case study can bring the application of management science to life in a context that illustrates its relevance for aiding managerial decision making. This case-centered approach should make the material more enjoyable and stimulating while also conveying the practical considerations that are key factors in applying management science. Case studies are a key to preparing students for the practical application of management science in all its aspects.

3.3. Some Key New Topics for Introductory MS Spreadsheet Modeling Courses

With the increasing emphasis on spreadsheet modeling in modern introductory MS courses, it now is useful to introduce a few new topics into these courses that take advantage of the full power of modern spreadsheet technology. We describe some key topics of this kind below.

- **Spreadsheet Engineering**

As spreadsheet modeling has matured and become the dominant medium of instruction in MS education, there has been an increased emphasis on the design of spreadsheets, commonly referred to as spreadsheet engineering. Although one of the greatest benefits of spreadsheets is their flexibility, this benefit also leads to one of their greatest dangers as a modeling tool. It is extremely easy to create unorganized spreadsheet models that are difficult to interpret, difficult to understand, and difficult to debug. This unorganized approach often leads to spreadsheets that contain critical errors. An entire chapter of our textbook is devoted to the art of modeling with spreadsheets. The chapter discusses the process of modeling and provides tips on creating good spreadsheet models that are well organized, easy to interpret, and simple to debug. The tips include (1) how to organize or sketch out a spreadsheet, (2) start small before expanding to full size, (3) separate the data from the formulas, (4) use borders or shading to distinguish data cells, changing cells (decision variables), and the target cell (objective function), and (5) use range names to make formulas easier to read.

- **Automated Sensitivity Analysis**

Traditionally, teaching sensitivity analysis in linear programming has emphasized the interpretation of shadow prices for the constraints and the allowable ranges for changes in the objective coefficients as determined by using a sensitivity report. Although this information is still important and useful, one of the great assets of spreadsheets is how easy it is to make changes to a model. The new solution is then just one click of the Solve button away. Moreover, many current textbooks come with add-ins to Excel such as Solver Table in our book, which can automate this type of sensitivity analysis. The add-ins make it easy to build a table that shows how the solution changes over a range of possible values for one or two of the parameters of the problem. Solver Table also works with integer or nonlinear programming problems and can analyze the impact of changes in *any* parameter of a model, not just objective coefficients or constraint right-hand sides.

- **Search Procedures**

Frontline Systems, the original developer of the standard Solver that Microsoft includes with Excel, developed premium versions of Solver. They graciously made the Premium Solver for Education available with many textbooks, including our own. This solver includes a new search procedure called Evolutionary Solver that uses a genetic algorithm to solve difficult nonlinear problems (e.g., nonsmooth and/or discontinuous problems). Because this new search procedure uses the same simple Solver interface, it is easy to incorporate the use of these advanced algorithms into even introductory MS courses.

- **Simulation with Spreadsheets**

Much like the incorporation of optimization algorithms like Solver into spreadsheets has revolutionized the way optimization is taught to business students, software packages like Crystal Ball, @RISK, and Risk Solver that bring Monte Carlo simulation into the spreadsheet environment have revolutionized the teaching of simulation to business students. It is easy to take any financial spreadsheet and add the power of simulation to analyze the effect of uncertainty. An exciting new topic in MS education is doing optimization with simulation. For example, the OptQuest module in Crystal Ball uses a combination of scatter search, tabu search, and neural networks to optimize a set of decision variables where the objective function is based on simulation outcomes.

4. Conclusions

Over the last few decades, there has been a steady evolution in the content of introductory OR and MS courses. During the early years, heavy emphasis was given to the mathematical models and algorithms of operations research. This has continued to be the emphasis in courses directed to students in engineering and the mathematical sciences, but with some updating to include such new developments as the interior-point approach to linear programming, branch-and-cut algorithms for integer programming, constraint programming techniques for mathematical programming, metaheuristics for complex problems, and multiechelon inventory models. However, there has been a growing realization over the years that this emphasis on mathematical models and algorithms is not the appropriate one for typical business school students who will become managers rather than applied mathematicians. Since the mid-1990s, the new wave in the teaching of management science is to emphasize spreadsheet modeling and perhaps case studies instead.

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