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Katta G. Murty
Editor

Case Studies in Operations Research

Applications of Optimal Decision Making

Springer

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Foreword

History of Optimum Decison Making Techniques and Their Applications

During my High School education, I had a mathematics teacher who used to prove one theorem after another in his class. In that class I got the impression that his aim, and in fact the aim of mathematics as a subject, is to maximize the number of theorems proved. After seeing what felt like close to 100 theorems, I thought of the question, *what is the very first mathematical result realized by mankind?* The textbook did not discuss this aspect at all. So one day, I picked up enough courage to ask the teacher about it. He thought about it for a long time, and then said that he does not know the answer, but will discuss with other colleagues and let me know. My question went up all the way to the level of the Head Master, but none of the teachers knew the answer.

Thinking about that question now, I believe that the discovery of the first mathematical result realized by mankind goes back well over 100,000 years ago. In those days people used to live in caves, and they needed to fetch water from the nearby river for their living. So they faced the problem of finding the shortest route from the center of their cave entrance to the nearest point to it on the river bank (an instance of an unconstrained decision-making problem, as there are no constraints on the route taken), and they realized that this shortest route is the straight line joining the two points. This, I believe, is the first mathematical result realized by man.

In this way, I believe that the human urge to find optimum solutions to the decision-making problems that they faced in their daily living provided the motivation for the development of mathematics.

Solving a decision making problem optimally involves the following steps: (1) Construct an appropriate *mathematical model* for it, (2) then select an efficient *algorithm* for solving that model, and (3) finally implement the solution obtained by the algorithm.

History of Mathematical Modeling

For the first step above, both Chinese and Indians can feel proud that their ancestors pioneered the development of mathematical modeling over 2500 years ago. It involves representing the quantities that we want to determine by symbols—usually letters of the alphabet like *x, y, z* (the symbols representing the unknown quantities to be determined are nowadays called *unknowns*, or *variables*, or *decision variables*) then express the relationships between the quantities represented by these symbols in the form of equations, or other functional relationships. This process is called *modeling* or *mathematical modeling*. The earliest mathematical models constructed were *systems of linear equations*.

The Chinese text *Chiu-Chang Suanshu* (*Nine Chapters on the Mathematical Art* (a summary of this ancient Chinese text can be seen at the website: http://www-groups.dcs.st-and.ac.uk/history/HistTopics/Nine-chapters.html) composed over 2000 years ago describes the modeling process using a problem of determining the yield (measured in units called "tou") of an alcoholic drink made from rice. Rice grain produced by farmers contains three grades of grain: inferior, medium, and superior. Yield data from rice grain procured from three different farmers, Farmers 1, 2, and 3 are given. The composition of rice from these farmers (in terms of the percentage by weight of the three grades) and the yield from it is given in the following table:

Rice from farmer	Weight percent of grade			Yield of drink in tou/unit
	Inferior	Medium	Superior	
1	50	30	20	6
2	45	25	30	8
3	30	30	40	9

The problem considered is to determine the yield of the drink if it is made from pure inferior, medium, and superior grades of rice. Denote these quantities by the symbols:

$$x_1 = \text{yield in tou from one unit of inferior grade rice}$$
$$x_2 = \text{yield in tou from one unit of medium grade rice}$$
$$x_3 = \text{yield in tou from one unit of superior grade rice}$$

Then the mathematical model for determining the values of these variables is:

$$\begin{aligned} 50x_1 + 30x_2 + 20x_3 &= 6 \\ 45x_1 + 25x_2 + 30x_3 &= 8 \\ 30x_1 + 30x_2 + 40x_3 &= 9 \end{aligned}$$

Ancient Indian texts *Sulabha suutrah* (*Easy Solution Procedures*), and the *Bakshali Manuscript*, with origin during the same period describe the process in terms of models consisting of systems of two (three) linear equations in two (three) variables; for information on these texts, and a summary see: http://www.tlca.com/adults/origin-math.html. One of the problems considered deals with a fruit seller in a farmer's market. She is selling the following bundles of fruit:

Bundle	Price
8 citrons + 5 mangoes	20
5 citrons + 4 mangoes	15

The problem is to determine how much she is charging for each individual citron, mango respectively. So, it is to detrmine the values of the following variables:

$$x_1 = \text{ price in Rs. of an individual citron}$$
$$x_2 = \text{ price in Rs. of an individual mango}$$

Then the mathematical model for determining the values of these variables is:

$$8x_1 + 5x_2 = 20$$
$$5x_1 + 4x_2 = 15$$

The Chinese and the Indians developed the *elimination method* for solving linear equation models, independently around that same period, more than 2000 years ago. This method was almost unknown in Europe until the German mathematician Gauss rediscovered it in the eighteenth century, hence it is now-a-days called the Gaussian elimination method.

History of the Word "Algorithm"

Methods for solving mathematical models are called *algorithms*. This word itself has a very strange connection to India. For many centuries, Muslim, Arabs, and Persians have invaded India. Many of these invaders settled down in India, but a few of them also returned to their home lands after some stay in India. One of those is a Persian, Muhammad ibn-Musa Alkhawarizmi, who left India after learning mathematics from Indian teachers in the ninth century CE. Then in 825 CE, he wrote a book *Kitab al-Jam'a wal-Tafreeq bil Hisab al-Hindi*, in Arabic, the lingua-franca in the Middle East in those days. This book appeared in a Latin translation under the title *Algoritmi de Numero Indorum*, meaning *Al-Khwarizmi Concerning the Hindu Art of Reckoning*; it was based on earlier Indian and Arabic treatises. Today this book survives only in its Latin translation, because all the copies of the original Arabic version have been lost or destroyed. The word *algorithm* (meaning procedures for solving algebraic systems) originated from the title of this Latin translation. Algorithms seem to have originated in the work of ancient Indian mathematicians on rules for solving linear and quadratic equations.

What Steps to Take Before Implementing an Algorithm in Practice

When an algorithm is developed for a decision-making problem, we need to make sure, either through a mathematical analysis of its performance, or through a computational test, that it outputs a guaranteed optimal or near optimal solution.

I will relate my experience once. I was talking with the DMs (Decision Makers) at a company on the benefits their company can gain by using optimal decision-making techniques for the decisions they make. They told me "Prof. Murty, for every decision we have to make, we use the following approach: we list all possible *actions* we can take for it, and estimate the profit we can get by taking each of those actions. Among all these actions, we select for implementation, one that is associated with the maximum expected profit. Because of this, we do not see how your optimal decision-making techniques can improve on our performance. If you like, you can try to convince us using an example."

I constructed the following example for them. It deals with a marketing company. The company divided their marketing area into six different zones, Z_1–Z_6, based on the background and other characteristics of people living there. For example the residents of zone Z_1 are administrators and other relatively well-off people. Zone Z_2 houses academic communities, etc. Then, they selected six experienced candidates, C_1–C_6 with different marketing backgrounds, and other experiences, etc.

Now they are faced with the very important decision-making problem of allocating one candidate as Director of Marketing Operations per zone. These are high level positions with the responsibility of maximizing the growth in company's profit.

Considering the background, experience, and other relevent characteristics of the candidates, and information obtained by market surveys, company's statisticians have come up with the following estimates of the profit to the company/year by the allocation of each candidate to (the Director of Marketing Operations position in) each zone.

	cij = Expected annual profit in \$million if candidate Ci is assigned to zone Zj					
Zone =	Z_1	Z_2	Z_3	Z_4	Z_5	Z_6
Candidate = $C1$	29	10	1	17	6	2
$C2$	36	31	26	32	28	27
$C3$	35	24	18	25	21	19
$C4$	30	11	3	20	8	4
$C5$	34	16	13	23	15	14
$C6$	33	12	5	22	9	7

Each candidate can be allocated to any of the six zones, so there are six possible actions associated with each candidate (allocating her/him to the position in zone $j = 1$ to 6). Since there are 6 candidates, there are $6 \times 6 = 36$ possible actions the company can take ((C_i, Z_j) = allocating C_i to the position in Z_j; $i, j = 1$ to 6). The above table gives the annual expected profit to the company associated with each of these 36 actions.

To apply the procedure described by the DMs at the company, we look for the action corresponding to the highest annual expected profit, it is (C_2, Z_1) yielding \$ 36 million in expected annual profit. After taking this action, we are left with candidates C_1, C_3 to C_6, and zones Z_2–Z_6. Among the actions available at this stage, the one corresponding to the maximum profit is (C_3, Z_4), leading to \$ 25 million in expected annual profits. Continuing the same way, leads to the solution of allocating candidates $C_2, C_3, C_5, C_6, C_4, C_1$ to the position in zones $Z_1, Z_4, Z_2, Z_5, Z_6, Z_3$ respectively, yielding total annual expected profit of \$ $36+25+16+9+4+1=91$ million.

To check how good this solution is, we generate a random solution. It allocates candidates $C_1, C_2, C_3, C_4, C_5, C_6$ to the position in zones $Z_4, Z_3, Z_5, Z_6, Z_1, Z_2$ respectively; which yields an annual total expected profit of \$ $17+26+21+4+34+12=114$ million; higher than the annual expected profit corresponding to the solution produced by the company's procedure!

Actually, by developing a mathematical model for this problem, and solving it by an algorithm guaranteed to solve the problem exactly, it can be verified that the solution given by the company's procedure, instead of maximizing the total annual expected profit as required, in fact minimizes it!!!

The optimal solution maximizing the total annual expected profit allocates candidates $C_1, C_2, C_3, C_4, C_5, C_6$ to the position in zones $Z_1, Z_3, Z_6, Z_4, Z_5, Z_2$ respectively, leading to an annual expected profit of \$ $29+26+19+20+15+12=121$ million.

This shows that optimal decision-making problems are tricky, and procedures for solving them based on instinct and simple hunches may often lead to poor solutions. Hence, the importance of developing an appropriate mathematical model for them, and solving the model using an algorithm guaranteed to produce a good solution for implementation. In this book we discuss applications of this approach in a variety of areas.

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9 September 2012.

Katta Gopalakrishna Murty

Preface

In their OR (Operations Research) curricula, most universities place a lot of emphasis on teaching algorithms for solving a variety of standard mathematical models for solving optimum decision-making problems like linear programming, nonlinear programming, integer programming, etc. and the mathematical analysis of their convergence properties and computational complexity. But they do not put much emphasis on helping their students cultivate the essential skill of constructing an appropriate mathematical model for real world decision-making problems, before these algorithms can be applied to solve them.

Textbooks used in optimization courses do contain some simple modeling examples, but each of them is specially prepared to illustrate the application of a specific algorithm under discussion. But when students graduate and start working, they face the reverse situation, they face unstructured real world problems for which they have to construct appropriate mathematical models, and decide on which algorithms to use for solving them to get good solutions. From simple examples in their textbooks, and college courses, these students cannot learn how to model the unstructured real world problems that they will face. Since a fundamental goal of education is to train students to be able to comfortably handle the work they will face on their job after graduation, we have here a contradiction in present day practices.

One remedy for this situation is to provide students a textbook of a collection of real cases of applications of optimum decision-making techniques from a variety of application areas which can, by examples, help them develop the modeling skill, that students can also use for self-study and self-learning. This is the main purpose of this book.

Applications of OR and optimization techniques are usually quantitative and data intensive. Obtaining satisfactory solutions for them needs specialized data handling and data analysis strategies. Surprisingly, so far, OR departments have not yet developed for OR curricula collections of cases of data intensive quantitative work amenable to OR techniques for optimum decision making. I, and the contributing authors, hope that this book addresses this pressing need for such good and realistic cases

Style of the Book and Its Goals

Each chapter in the book will be a detailed case study of some challenging real world application of OR techniques, with all the data provided in a companion website that Springer has set up and maintains for this book. There will be two files: File 1 and 2 associated with each chapter. File 1 will only reside on the website for the book at Springer, with access given by Springer to all the readers of the book; it contains a brief description of the area of application, and of the problem, and the required outputs, and provides links to access all the data in the problem.

File 2 for the chapter is the book chapter. It contains a detailed description of the area of application (to make the readers familiar with the area), the scope for optimum decision-making techniques in the area, how to take advantage of any special structure in the data for the problem to construct a simpler mathematical model for it, different approaches for modeling and selecting algorithms for solving it, comparisons of the solutions obtained by these different approaches, and finally a recommendation on the best among them for implementation. If the problem is one that occurs periodically, the chapter describes how a DSS (Decision Support System) can be developed for solving it at the organization. As far as possible, the chapter should be in a style that students find engaging.

Methods for solving problems, considered in the book, will include not only ones like linear, nonlinear, integer programming with theoretically well established convergence criteria discussed in OR textbooks, but also simulation, heuristic methods like the greedy method with appropriately set up "greediness criterion;" which are not theoretically guaranteed to give the best solution, but have been verified to give good results in practice. In the book all methods including heuristics that give good solutions are considered.

So, the overall goals of this textbook are:

- To provide the readers with descriptions of the history and other background information on a variety of industries, and service or other organizations in which decision making is an important component of their daily operations. Also, in each of these organizations, give a list of possible applications of optimum decision-making techniques that can improve performance of these organizations.
  This information will provide very useful knowledge to students in their job interviews, and for them to settle in their jobs when they start working.
- To expose students to a variety of applications in a wide variety of areas.
  Since we clearly explain how each application is modeled and solved, and a variety of real applications are discussed, it helps the students develop the skill of modeling and solving the problems that they will face in their jobs.
- To teach students how to choose an appropriate model and algorithm to solve decision making problems.
- To teach students how to look for and take advantage of any special structure in the problem and the data for it, to simplify the model and algorithm used to solve it.

- To provide in each chapter some project exercises for students to practice what they have learnt in the chapter. These could be some variants of the problem discussed in the chapter. Faculty can also use these exercises as project assignments in their courses.

Brief Summaries of Chapters

Chapter 1 titled "Intelligent modeling essential to get good results" describes a project carried out at HIT (Hong Kong International Terminals) in the Port of Hong Kong by K. G. Murty in collaboration with colleagues from Hong Kong University of Science and Technology and HIT, to optimize decision making in daily operations at the terminal, with the aim of increasing the productivity of the terminal measured by the GCR (Gross Crane Rate, the number of lifts (moves of the shore cranes either downloading an incoming container from a vessel, or loading an outgoing container into a vessel))/shore crane hour. The only models discussed in published literature at that time are 0–1 models. They found that these models are inappropriate for the problem, since the data used in the model changes even before the software outputs the solution of the model. The second model tried for this problem is a multicommodity flow model which was easier to solve, but produced poor results. Finally a real time model using a substitute objective function technique gave excellent results, and the team received the Edelman finalist award of INFORMS for this work.

Chapter 2 on the Locomotive Fueling Problem (LFP) is a contest problem set up by RAS (Railway Applications Society) of INFORMS in 2010. It deals with a decision-making problem faced by a railroad company using diesel locomotives, to determine which yards should be selected as locomotive fueling yards, and how many refueling trucks should be hired at those yards to minimize fuel related operating costs of the company. The original contest problem can be seen at the website: http://www.informs.org/Community/RAS/Problem-Solving-Competition/2010-RAS-Competition.

Chapter 3 deals with the problem of organizing national elections in the Indian Republic, a societal application. Due to concerns about terrrorist disruptions at polling booths, there is a restriction that at each polling booth, 4 CPF (Central Police Force) personnel must be posted while polling is going on, and only 1.5 million CPF personnel are available for this. Hence polling over the whole country cannot be completed in a single day. The problem is to determine, subject to the specified constraints, the scheduling of different states of the country to different polling days, to minimize the number of polling days and the cost of moving CPF personnel from one set of states to the next over these polling days.

Chapter 4 deals with the decison making problems at a large Milk Producers Cooperative in India, the country that produces and consumes the maximum quantity of milk among all countries in the world.

Chapter 5 discusses an important application in the Health-care area. It deals with developing a DSS for use by a hospital to help new patients select for their care a PCP

(Primary Care Physician) from their PCP doctors, with the objective of equalizing the workload on these doctors; and for allocating appointment times to patients calling for service, with the aim of minimizing delays and waiting times.

Chapter 6 features decision-making problems faced by an NPO (Non-Profit Organization) distributing solar cooking stoves to poor families in tropical countries.

Chapter 7 is another societal application. It deals with the civil engineering problem of finding an optimum design for an earth dam across a river, to minimize the cost of constructing it, subject to safety constraints that the dam will not collapse during heavy flooding situations.

Chapter 8 features the optimum scheduling of a multiunit pumped strorage hydro power station during a short-term planning horizon, to maximize revenue at the prevailing market clearing price.

Chapter 9 deals with the problem of rebuilding the decaying water distribution infrastructure in municipalities to replace all the pipes using the same network topology to achieve present day pressure demands at junctions of the network at minimum cost.

Chapter 10 discusses an important application in the paper and paper board manufacturing industry. The major raw material in paper production is wood logs of a variety of species (conifers, casurina, eucalyptus, subabul, etc.). This chapter discusses the problem of making various decisions in the procurement of wood and the feeding of wood to the production line optimally.

Chapter 11 deals with the problem of finding an optimum design for the heat exchanger network to minimize the cost of hot and cold utilities used for bringing fluid streams in given sets of hot and cold streams to their target temperatures. This is a common problem in oil refineries and chemicals manufacturing industries.

Chapter 12 is a warehousing application. It deals with the problem of developing a DSS for a warehouse to store cuboidal boxes using storage space optimally.

Chapter 13 deals with the problem of determining the number of floating oil rigs to rent, route, and allocate for the drilling oil wells in the oil and gas fields in production in the North Sea to maximize the profit made by recovery and processing of oil/gas reserves.

Over the period of a 24-h day, the demand for electric power is higher during daylight hours than nighttime. The peak demand occurs during late afternoon; and its magnitude is nearly twice the demand level at 5:00 A.M., which is known as the base load level. Power companies usually have generators operating on cheaper fuel, producing power continuously throughout the day at base load level. It takes a long time to turn on these generators operating on cheaper fuel, that is why they are kept operating continuously once they are turned on. During daytime as demand for power increases (for airconditioning mostly, and other daytime uses), they turn on other generators running on more expensive fuels, to meet demand over the base load level, and switch these off in the evening as demand drops. If demand for power is at the same level throughout the day, meeting the demand would be much cheaper. The problem of meeting power demand over base load level economically is known as the "peak power problem." Chapter 14 discusses a strategy for solving this peak power problem to meet extra demand for power for airconditioning needs during hotter day time hours using thermal energy storage.

Chapter 15 on "Optimal flight planning and performance for a jet aircraft" discusses the optimum choice of pilot inputs: thrust level, elevator deflection, and bank angle by quantifying them, and determining how their values affect the flight conditions and its route; and then using this framework for determining optimal flight conditions.

While the freight railroad industry has been in existence for about 200 years, the procedure used for aggregating freight railcars into "blocks" based on their destination yards and other attributes, and then assembling blocks into trains has essentially remained the same. This "Train design problem" discussed in Chapter 16 is a very important and difficult combinatorial optimization problem encountered in the freight railroad industry. This case study is based on a simplified real-life problem set-up under the 2011 RAS Problem Solving Competition by RAS (Railway Applications Society) of INFORMS, see https://www.informs.org/Community/RAS/Problem-Solving-Competition/2011-RAS-Problem-Solving-Competition.

Chapter 17 discusses efficient tools for solving 2D cutting stock problems in the sheet-metal products industry, and 1D cutting stock problems in the paper industry.

Chapter 18 features the problem of managing inventories of blood products in a blood bank efficiently.

Chapter 19 discusses the application of optimization techniques for packing cells inside traction batteries used for operating forklifts in companies, to maximize their lives.

An "operating room" is a unit in a hospital where surgical procedures are performed, it is estimated that they generate over 42 % of hospital revenues. Chapter 20 discusses the important and complex problem of managing operating rooms in hospitals to minimize the idle time of both operating rooms and surgeons. The later part of this chapter on sequencing the various surgeries to be performed by a surgeon over the time of the day is based on the 5th AIMMS-MOPTA Optimization Modeling Competition 2013, see http://www.aimms.com.

Chapter 21 deals with the efficient scheduling of image acquisition, and image downlinking operations in satellite mission planning for earth observing satellites. It is a case study of mission planning operations of Canada's Earth Observing Synthetic Aperture Radar (SAR) satellite RADARSAT-2.

In some coastal regions, they have ferry service carrying people and automobiles between various ports in the region. Companies operating the ferrry service are often confronted with the problem of routing and scheduling the ferries to meet the travel demand between the various ports in the region during the planning horizon (typically from 5:00 A.M. to midninght in a day), while minimizing the cost of operations and any passenger dissatisfaction. Chapter 22 is a case study of such a ferry scheduling problem.

File 1s for the Various Chapters

For each chapter we have a File 1. It briefly explains the setting and the statement of the optimum decision-making problem discussed in the chapter, either provides all the data for the problem, or gives a link from where it can be accessed, and clearly describes the desired outputs.

For each chapter, File 1 is prepared so that instructors can modify some data elements in the problem, and then use it as a project exercise in their courses. File 1s for the various chapters can be accessed by users of the book on the book's website at Springer.com; the link to which is: http://www.springer.com/business+%26+management/operations+research/book/978-1-4939-1006-9

A Final Caution

Clearly, making decisions optimally brings competitive advantages to the performace of organizations. But it is so easy to introduce an inappropriate or wrong model, and wrong equations into the model. To illustrate this, I mention the following puzzle:

" Three Ladies went to a hotel to share a room. The clerk asked for \$ 300. Each Lady paid \$ 100, making up the \$ 300.

The hotel keeper then decided to allow a discount for the day, charging only \$ 250 for the room. He told the clerk to return \$ 50 to the three Ladies. The clerk pocketed \$ 20 for himself. He gave the remaining \$ 30 back to the three Ladies. Each Lady took back \$ 10. Therefore, each Lady paid $100 - 10 = \$ 90$ to the hotel.

$\$ 90 \times 3 = \$ 270 +$ the clerk's $\$ 20 = \$ 290$. Question: Where has the remaining \$ 10 gone?"

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