Data-Driven Minicourse Design for Operational Research and Its Practice

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Abstract

This paper explores the data-driven minicourse design for operational research at Chongqing University of Arts and Sciences. Situating this article on literature review, numerical simulation and comparison analysis methods, it previously sets the minicourse objectives as "can operate data processing", beyond that "may build mathematics model to optimize real problems in engineering fields, especially in logistics engineering field". Then, this article rearranges course contents into twelve modules and delineates each module in a way of a brief explanation with numerical example. These examples are solved by Matlab or related software. To disseminate applicable skill, we also released these Matlab codes which may be served as templates for secondary development of operational research pedagogy. The data-driven minicourse may be carried out in ways of both offline classroom and online mobile internet classroom, of which some modules are especially suitable to be implemented in flipped classroom pedagogy. Comparing with operational research implemented in undergraduate majors at other universities, our minicourse design is characterized as data-driven style, logistics industry-focused, mini case study pedagogy, rich mobile internet resources, as well as applicable skill training. Learners' feedback confirmed that the minicourse design equipped them with model application and software skills helpful for a successful career.

Keywords

Operational Research, Data-Driven Minicourse, Minicourse Design, Online Course Design, Flipped Classroom Technique

1. Introduction

The Institute for Operations Research and the Management Sciences (INFORMS)

defines operational research as the scientific process of transforming data into insights for making better decisions (INFORMS, 2019). Ormerod (2014) accentuates that operational research is to hone three competences: 1) conducting analysis, 2) managing the process of intervention and, 3) understanding context. Grossman et al. (2016) report a student-centered approach to teach management science course at the University of San Francisco, and emphasize three teaching principles: real-world context, spreadsheet-native attitude and student self-efficacy. In line with the Asian Programme of Educational Innovation for Development (APEID), a minicourse is defined as an entire course of studies for a group similar to a conventional course but compressed into a few hours (Frankel & Gage, 2007). In 1982, APEID published a report on minicourse practice at Macquarie University, which was characterized by: a system approach, overt and exemplary strategies, clear objectives, structured program, self-contained, wide participation, varied learning activities and media, creative activity, feedback, follow-up, skill-oriented, and an educational technology design (APEID, 1982).

The minicourse reform of learning and teaching in operational research was piloted at Chongqing University of Arts and Sciences started in 2006. Since then, we have gradually rearranged and optimized course objectives, course content design, pedagogy as well as course resources. Concerning to foster applicable practitioners, our minicourse design previously emphasizes on "can operate data processing", beyond that "may build mathematics model to optimize real problems in engineering fields, especially in logistics engineering field".

Learner's interest is an important factor to carry out learning and teaching in operational research. Sert (2019) surveys operational research delivered by undergraduate in the Recep Tayyip Erdogan University, and suggests redesigning course content and reforming pedagogy to improve efficiency and effectiveness of the course. To creatively hone mathematical model application as well as addressing learning interest, DePuy and Taylor (2007) suggest the use of games as pedagogical tools in teaching operational research. Another article (Martonosi, 2012) reports a project-based operational research and management science (ORSM) course implemented at Harvey Mudd College, where students are obligated to learn both mathematical model formulation in a special field and the craft of practice of ORSM. Similarly, a problem-based course design is operated for a one-year MBA program at Duquesne University (Sroufe & Ramos, 2015). Recently, Alias et al. (2020) suggest that a combinatorial pedagogy practiced well in Malaysia can stimulate learning interest, as a consequence of that, intrinsically bringing about efficiency and effectiveness of operational research. This combinatorial pedagogy, based on the theory of constructivism (Cheng, 2018), is featured by inserting problem-based learning into flipped classroom approach.

With the emphasis area being shifted from theoretic mathematics to model-building and application, case study pedagogy is extensively adopted in course design (Drake, 2018; Winch & Yurkiewicz, 2014). Winch and Yurkiewicz (2014) report a class scheduling case implemented in management science course at

Pace University, which aims to hone modeling of integer linear programming, data collection and processing, as well as results explanation. More aggressively, article Frances and Terekhov (2019) reports a purely case-based operational research course design running in the industrial engineering program at the University of Toronto. This course requires undergraduates to solve mathematical model in Excel, Matlab or by AMPL language. To explore minicourse design, Penn et al. (2016) delineate a kind of mini case study running at Manchester Business School. As this approach is heavily biased towards application, it fits excellently with the learning objectives. However, it also provides challenges to students in areas of structuring problem and IT skills since lecturer has little time to instruct each group.

Despite of difficulty to master, employing IT skills to solve mathematical programming is highly attractive to learners because it has become a necessity for an operational manager. For example, in the United States labor market, individuals with graduate degrees in both operational research and computer science are equal attractive to employers seeking operational research analysts (Hardin et al., 2012). In literature, Mandelbaum and Zeltyn (2010) provide an explanation on service engineering course design at the Technion-Israel Institute of Technology. It operates in ways of data-driven as well as incorporation of state-of-the-art researches into lectures, training and tests. Considering operational research running at the Massachusetts Institute of Technology (MIT), it is composed of 8 modules and each module is heavily relied on R-language (Dunning et al., 2015). Hardin et al. (2012) summarizes foundational skills, core skills and recommended skills that operational research should train undergraduate students, also, these skills are extensively focused on mathematical modeling and computer science. Lu (2018, 2020) proposes a data-driven framework for extracting knowledge from data, of which applicable skills contain data management, data preprocessing, data modeling and business intelligence achievement. At an earlier time, Marr (2015, 2017) suggests a data-driven SMART model: strategy, measure data, apply analytics, results and transform business, to convert data into business application. It is valuable for students to be able to transform theoretical algorithm into efficient and high-performance codes (Dunning et al., 2015).

Situating on over a decade experience accumulation, our minicourse objective is highly in consistency with the aforementioned literature review and investigation of operational research implemented by other universities. With "can operate data processing" and "may build mathematics model to optimize real problems" course objectives in mind, our minicourse design not only provides plentiful opportunities to hone Matlab skill, but also assigns many tasks, such as writing cases, making simulation experiments, surveying logistics firm and related homework, to help learners familiar with the operations of logistics company. Learners' feedback confirmed that our minicourse design equipped them with model application and software skills helpful for their career.

This article reports and explores the data-driven minicourse design for operational research that has been successively implemented in undergraduate majors of logistics engineering, project management, and engineering cost near 15 years at Chongqing University of Arts and Sciences. The following work is organized as, section 2 delineates offline minicourse design, section 3 explores online mobile internet as a type of irresistible learning and teaching tool, section 4 completes a comparison analysis between our data-driven minicourse design and course design carried out by other universities, finally, a brief conclusion is presented in section 5. To disseminate applicable skill, we also released the Matlab codes of solution to the mathematical models through Appendices A1 to A5.

2. Data-Driven Minicourse Design

Our minicourse design takes a data-driven approach (Vista, 2020; Qian & Lehman, 2019) to learning and teaching. Hence throughout this section, minicourse module content will be illustrated with the help of simplified case carried out in computer environment. As revised by our previous work (Fu & Qin, 2015), **Figure 1** displays that each module focuses on forming mathematical model in practice and training algorithm in Matlab or related software.

2.1. Module 1—Linear Programming (LP)

This module is to learn simple LP model formulation and train graphic method by employing Matlab code. The former may be further extended to sensitivity analysis, parameter LP as well as duality problem. All of these problems are solved in Matlab environment, hence, it is also an opportunity for students to
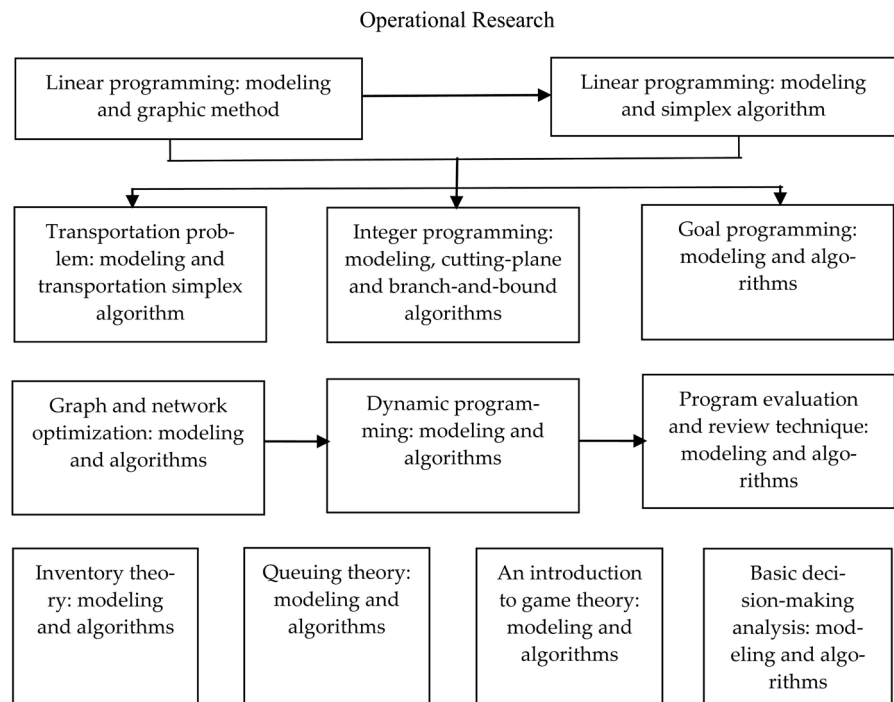
Figure 1. Minicourse modules design for operational research.

learn Matlab basic skills.

Here provides an example. Let's employ a graphic way to solve the following LP in Matlab environment.

$$\max Z = 3x_1 + 5x_2$$
$$st.$$
$$-2x_1 + x_2 \leq 100$$
$$5x_1 + x_2 \leq 200 \tag{1}$$
$$x_{1-2} \geq 0.$$

Through writing M-file codes as **Appendix A1** then compiling it, the graphic solution is displayed in Figure 2. Furthermore, sensitivity analysis, parameter LP and duality LP problems may be realized in a similar way using Matlab package. In contrast to manual graphic method, this data processing contributes a lot to training applicable skills, also brings an extra effect of attracting student's learning interest.

2.2. Module 2—Linear Programming (Continuation)

Module 2 brings learner to study generalized LP problem, containing complex model formulation, simi-manual realizing simplex algorithm in Excel and/or Matlab environment, as well as writing Matlab codes to solve sensitivity analysis and parameter LP problem.

To train complex LP modeling, lecturer may previously assign learning group to collect case materials through web search-engine such as Baidu, Bing, Wikipedia, Yahoo, Google or academic databases, etc. Alternatively, lecturer may simply hand out case study materials thereafter instruct learning group to analyze and
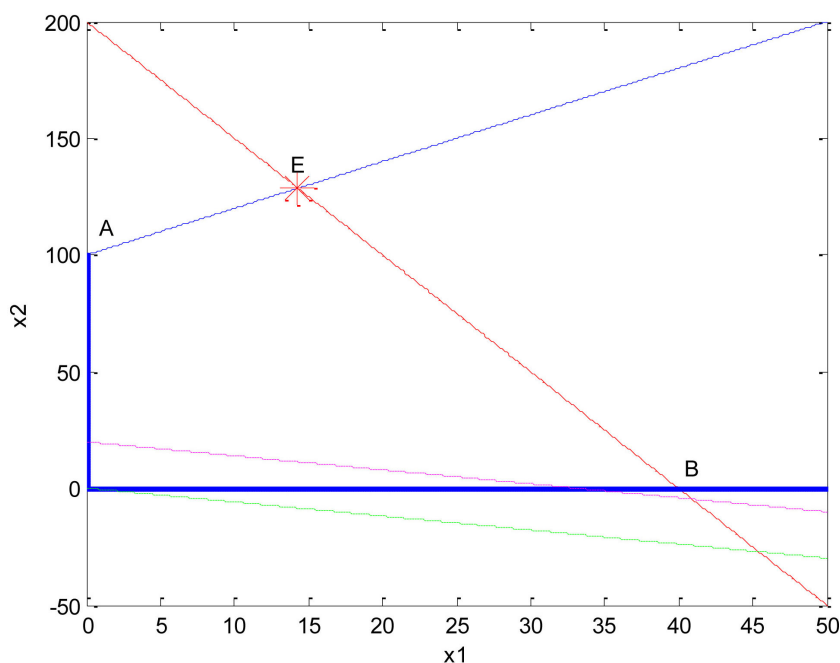

Figure 2. Solving simple LP problem by graphic method in Matlab environment.

formulate its LP model. Although the former takes more time and is difficult to be structured, it always hones a lot of applicable skills helpful to learner's career. The key point to complex LP modeling is information classification, including decision objective, resources restriction, technical coefficients and choice of variables. Usually, a tableau format to classify information can guarantee the correctness of model formulation.

To solve an LP model in Matlab environment, we can employ linprog() function. Its paradigm is,

$$
\begin{aligned}
&\min fX \\
&st. \\
&AX \le b \\
&Aeq.X = beq \\
&lb \le X \le ub \\
&[x, \text{fval}, \text{exitflag}, \text{output}, \text{lambda}] = \text{linprog}(f, A, b, Aeq, beq, lb, ub, x_0).
\end{aligned} \tag{2}
$$

For example, the codes of LP in section 2.1 can be written as **Appendix A2**. By compiling codes, the results are displayed as x = [14.2857; 128.5714], fval = −685.7143 and lambda.ineqlin = [3.1429; 1.8571]. Note that, the latter item displays the optimized solution of duality LP model, also indicates no residual resources exist under optimized condition.

For sensitivity analysis, changing value coefficients in objective function or resources restriction, the code of f-vector or b-vector needs to be adjusted correspondingly. Changing technical coefficients needs only to adjust A-matrix or Aeq-matrix. Adding another unequal restriction needs to adjust A-matrix and b-vector. Adding equal restriction needs to supplement Aeq-matrix and beq-vector. Simply adding another decision variable needs to adjust f-vector, A-matrix and Aeq-matrix. For solution to a parameter LP model, it can be operated as a series of sensitivity analysis, thus no technique problem exists there.

2.3. Module 3—Transportation Problem

As displayed in Figure 1, transportation problem is a special kind of LP, hence no extra modeling or solution problems exist. To deep understand this kind of LP, we set the objective of Module 3 as to exercise transportation problem modeling in reality and to carry out transportation simplex algorithm in Excel and/or Matlab environment. Lecturer may require each learning group to write a case of logistic distribution problem and collect related information through web search-engine, such as BaiduMap, GoogleMap, BingMap etc.; thereafter guide them to analyze and formulate its LP model.

Concerning transportation simplex algorithm, lecturer may employ an M-file to stepwise tutor its operation, or directly employ the intlinprog() function. For example, Table 1 provides a case of coal distribution among coal miners and power plants. The question is to find the minimum cost distribution schedule.

Its Matlab codes can be written as **Appendix A3**. The optimized distribution schedule is 5000 trucks transported from miner 1 to plant 3; 1000, 1000 and 4000

trucks transported from miner 2 to plant 1, 3 and 4 respectively; meanwhile, 2000 and 5000 trucks transported from miner 3 to plant 1 and 2 respectively. The total minimum cost is CNY 8,160,000. Similar to section 2.2, sensitivity analysis may be implemented through changing corresponding matrices or vectors.

2.4. Module 4—Integer Programming

Integer linear programming (ILP) is an LP restricted by partial or whole integer variables. Therefore, there is no modeling problem for learners. This module is to learn cutting-plane algorithm, branch-and-bound algorithm, and Hungarian algorithm solving assignment problem (also a special transportation problem), especially implemented in Matlab environment.

Considering the LP in section 2.1, let's supplement constraint $x_{1-2} \in N$. Its Matlab codes for graphic method and intlinprog() function may be written as **Appendix A4**. Compiling these codes, **Figure 3** displays the solution of graphic method. Through employing a cutting-plane equation, the optimized integer point is x = [14.0000; 128.0000] and fval = 682. The intlinprog() function still reports solution of its slack LP, which has an optimal objective value of 685.7143,

Table 1. Data on coal distribution among miners and power plants (unit: CNY/truck).

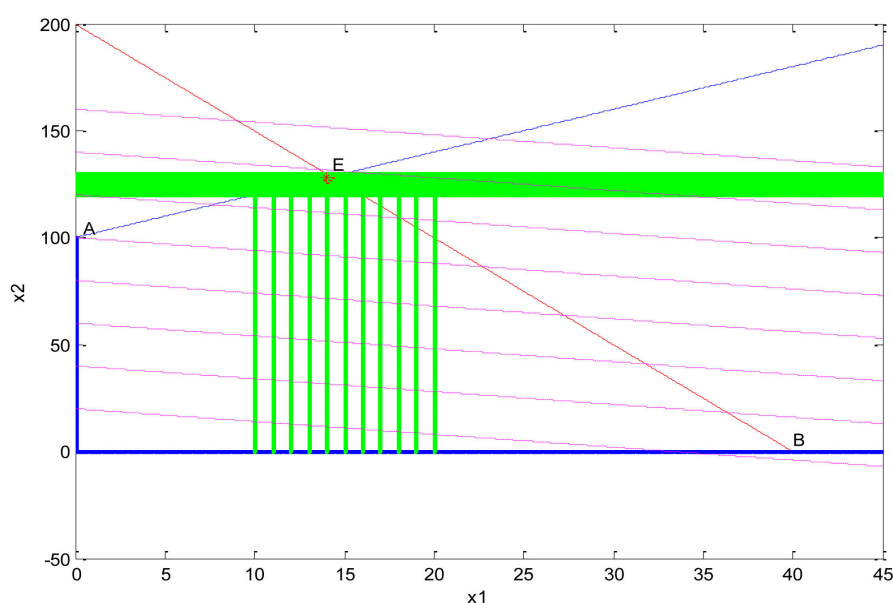|	Power plant 1	Power plant 2	Power plant 3	Power plant 4	Supply (trucks)
Coal miner 1	600	400	350	460	5000
Coal miner 2	400	600	450	520	6000
Coal miner 3	490	500	550	610	7000
Demand (trucks)	3000	5000	6000	4000	

Figure 3. Solving simple ILP by graphic method in Matlab environment.

higher than ILP's value.

For tutorial intuitiveness, the branch-and-bound method may be semi-manually realized in Matlab environment. The code of this method for the above ILP is also displayed in **Appendix A4**.

2.5. Module 5—Goal Programming

Goal programming, inspired by the management by objectives (MBO) approach, is a type of multiobjective linear programming. Its algorithm may be understood as a series of LPs or weighted LP. However, its modeling is somewhat difficult for learners because of introducing deviation variable, priority factor and weight coefficient. Module 5 sets its objective as training goal programming model formulation, solving this model through graphic method, sequential LP algorithm (or preemptive algorithm) and weighted LP algorithm (or Archimedean algorithm) in Matlab environment.

An effective way to train goal programming model formulation is firstly setting its rigid LP model, then rearranging it into the correct model through distinguishing absolute or goal restriction, adding deviation variable, choosing goal variable as well as priority factor and weight coefficient.

To exercise goal programming algorithms in Matlab environment, let's consider the following two-goal programming,

$$
\begin{aligned}
&\min\left\{P_1 d_1^-, P_2 d_2^+\right\} \\
&st. \\
&-2x_1 + x_2 \le 100 \\
&5x_1 + x_2 + d_1^- - d_1^+ = 200 \\
&x_1 + 3x_2 + d_2^- - d_2^+ = 150 \\
&x_i \ge 0; d_i^\pm \ge 0; d_i^- \cdot d_i^+ = 0; P_1 \gg P_2; i = 1, 2.
\end{aligned}
\tag{3}
$$

The codes of graphic method, sequential LP algorithm and weighted LP algorithm are attached in **Appendix A5**. Through compiling these codes, **Figure 4**
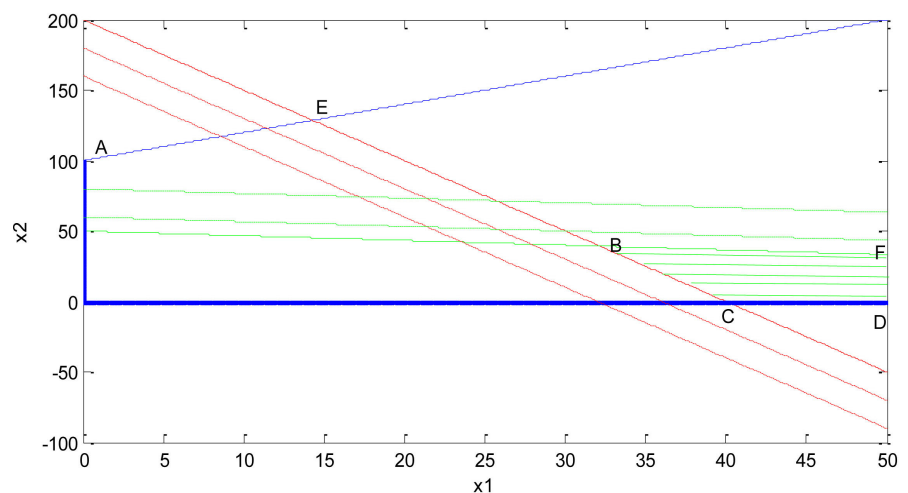

Figure 4. Solving simple goal programming by graphic method in Matlab environment.

shows that the optimized region is a triangle composed by lines BF, BC and CD, here displayed as a quadrilateral BCDF.

2.6. Module 6—Graph and Network Optimization

This module contains shortest path problem, minimum spanning tree problem, maximum flow problem and, minimum cost flow problem. The former two models may be transformed into binary integer programming, hence can employ intlinprog() or bintprog() function in Matlab environment to find their solution. The latter two models may be transformed into LP or double-objective LP, also no solution problem exists there. However, writing M-file codes for Dijkstra's algorithm to solve shortest path problem, for Kruskal's greedy algorithm to solve minimum spanning tree problem, for augmenting path algorithm to solve maximum flow problem and, for cycle-canceling algorithm to solve minimum cost flow problem, may be a challenge to learners. Therefore, training these skills is the key point of module 5.

2.7. Module 7—Dynamic Programming

Dynamic programming, because of many new concepts and its principle of optimality, is somewhat difficult to understand for undergraduates, both modeling and algorithms. To alleviate tediousness, this section chooses solving the shortest path problem in a directed acyclic graph to learn its backward/forward recursion algorithms through writing M-file codes in Matlab environment. Further modeling exercise of dynamic programming may choose machine scheduling problem or knapsack problem, which is also an effective way to inspire learning interest by offering applicability.

2.8. Module 8—Program Evaluation and Review Technique (PERT)

PERT technique is comprehensively applied in program management. The Technical Specification for Engineering Network Planning and Scheduling (JGJ/T 121-2015, JGJ/T 121-99) is an industrial standard of China architecture and building. Module 8 sets the objective as training activity-on-arrow (AOA) and activity-on-node (AON) network diagram manually according to the above standard, meanwhile operating a project in ProjectLibre or GanttProject environment. Since deterministic PERT network is also a kind of special binary linear programming, we may employ intlinprog() or bintprog() function to carry out critical path (CP) management, even making sensitivity analysis and resources optimization in Matlab environment.

2.9. Module 9—Inventory Theory

Inventory theory has many models, both deterministic and stochastic. Concerning applicability, it is necessary to understand theory's development, at least, to operate material requirements planning (MRP) and manufacturing resource

planning (MRPII) in computer environment, such as web-MRP and NetSuite software. Fortunately, it is easy to exercise these models semi-manually in EXCEL or Matlab environment.

For example, Table 2 provides a simplified MRP input information of product A. Suppose product demand is 100 units, Table 3 displays its optimized schedule for components in line with demand and ordering quantity implemented in EXCEL environment. This kind of exercise may be designated as skill-based homework.

2.10. Module 10—Queuing Theory

Queuing theory also has many models, however, their solution may be easily realized through writing Matlab code. Module 10 requires each learning group to collect a case of queuing model applied in reality, such as highway gate, canteen window, cyber-store payment, etc. Although this module is based on advanced mathematics theory, data-driven minicourse design may avoid complicated mathematical deduction, thereby focusing on the applicability of queuing theory.

Table 2. MRP product structure tree, production and assembly time.

	level 0		product A			
product structure tree	level 1	component X (2)[a]			component Y(1)	
	level 2	component U (1)	component V (2)		component U (2)	component W (3)
product and components	A	X	Y	U	V	W
production and assembly time (week)	1	2	2	2	1	1

Note: [a]data in parentheses is quantity of component required by per unit of immediate-up component.

Table 3. MRP components scheduling: demand and ordering quantity in time horizon.

product and components	week	1	2	3	4	5	6
A	demand						100
	ordering					100	
X	demand					200	
	ordering			200			
Y	demand					100	
	ordering			100			
U	demand			400			
	ordering	400					
V	demand			400			
	ordering		400				
W	demand			300			
	ordering		300				

2.11. Module 11—An Introduction to Game Theory

Module 11 is to understand basic game models, including prisoner's dilemma game, boxed pigs game, chicken game, etc. As a module of operational research course design, this section focuses on solving two-player zero-sum game with an LP approach. Up-to-date game theory model may be designated as extensive reading material.

2.12. Module 12—Basic Decision-Making Analysis

Basic decision-making models contain utility theory, mean-variance analysis, decision tree, analytic hierarchy process (AHP), data envelopment analysis (DEA), break-even analysis, etc. This section requires each learning team to write an applicable case study based on one of the aforementioned models, thereafter getting its solution in Matlab environment and making a brief explanation on the results. Our teaching experience supported that a flipped-classroom design (Alias et al., 2020; Swart & Wuensch, 2016; Herreid & Schiller, 2013) is an efficient way to hone these model formulation and algorithms.

3. Mobile Internet as a Complementary Tool

Miltenburg (2019) reports an online course design for management science taught at McMaster University, which contains how to create online documents, carry out quizzes, monitor student performance, and to collect student evaluation of the course. In contrast with Miltenburg (2019) entirely depending on online teaching and learning, Sharkey and Nurre (2016), Lepp et al. (2019) blend offline classroom teaching with online tutorial, and further explore the multitasking behavior phenomenon of learner under different pedagogical methods. Another article Kokic et al. (2013) explore how lecturer and administrator collaborate to facilitate multi-dimensional learning and teaching through an online course development. Earlier articles related to online course learning and teaching still include Davis et al. (2011), Bolliger and Wasilik (2009), Wilson and Stacey (2004), etc.

Our minicourse design extensively employs online communication tools such as QQ group, WeChat and Superstar platform to promote mobile teaching and learning. Figure 5 displays the online minicourse modules based on Superstar platform, which has abundant records of simultaneous activities and learning resources. As a complementary tool for data-driven operational research minicourse design, mobile internet has contributed a lot, not only to learning interest but also to learning efficiency and effectiveness.

4. Comparison and Discussion

This section presents a comparison between our data-driven minicourse design and course design implemented by undergraduate majors at other universities. In line with the emphasis area of course content, Table 4 displays that operational research course design may be classified as model-driven, knowledge-driven,
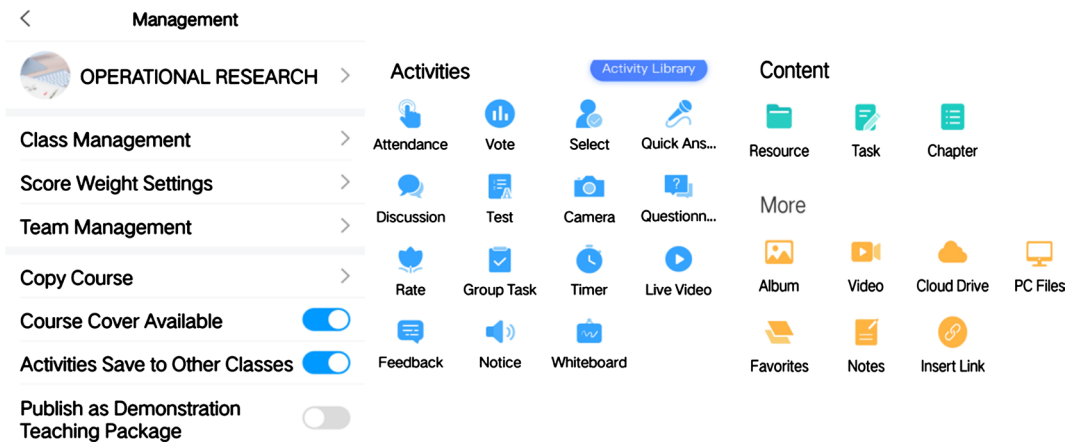
Figure 5. Online operational research minicourse modules.

Table 4. Style and features of operational research course design.

Style	Literature	Features	University	Software packages
question-driven	Frances and Terekhov (2019)	purely case-based course design	University of Toronto	Excel, Matlab or AMPL language
	Penn et al. (2016)	mini case studies	Manchester Business School	need computational software or IT skills
	Cochran (2000)	case-based course design	Louisiana Tech University	need computational software
	Sroufe and Pamos (2015)	problem-based course design	Duquesne University	_
model-driven	Dunning et al. (2015)	active learning, software algorithm-oriented	Massachusetts Institute of Technology	R-language
	DePuy and Taylor (2007)	games as pedagogical tools	University of Louisville	ILOG CPLEX
Knowledge-driven	APEID (1982)	principles and guidelines for minicourse design	Macquarie University	not mentioned
project-driven	Martonosi (2012)	project-based course design	Harvey Mudd College	need computational software
data-driven	Lu (2020), Lu (2018)	data-driven analytical framework	University of Winchester Business School	Excel, SPSS, Python-language or R-language
	Mandelbaum and Zeltyn (2010)	data-driven course development for service engineering	The Technion-Israel Institute of Technology	R-language
	Grossman et al. (2016)	Student-centered approach, spreadsheet-native modeling	University of San Francisco	Excel
	Miltenburg (2019)	Online teaching at a large scale	McMaster University	Excel

question-driven, project-driven and data-driven styles. Of which respective emphasized area is concentrated on applicable model construction, theoretical knowledge understanding, addressing cases in specific industry, training project management, and acquiring quantitative decision methods equipped with modern IT skills.

As described in section 2, our data-driven minicourse design is heavily relied on Matlab package to deal with data process. In fact, Matlab has become an important skill for learners, also effectively motivated their learning interest. Situating on software skill, the minicourse has designed many mini cases to hone

model formulation, solution and result explanation, in a way of offline or online teaching and learning activities. Our minicourse also designates learning group many tasks such as writing mini case, collecting information, online homework, online flipped classroom, etc., to train applicable skills. Similar to Mandelbaum and Zeltyn (2010) restricting cases in service field, our minicourse restricts cases in engineering field, especially in logistics companies. Learners' feedback confirmed that these skills equipped them with stronger competitive ability in workplace.

5. Conclusion

Because of model application diversity and solution tools development, operational research course design has experienced considerable changes in the last twenty years at universities around the world. This paper reported and analyzed the data-driven minicourse design for operational research at Chongqing University of Arts and Sciences. According to over a decade teaching and learning exploration, we refined course objective as previously "can operate data processing", beyond that "may build mathematics model to optimize real problems in engineering fields, especially in logistics engineering field". Section 1 and 4 display that this minicourse objective is highly in consistency with operational research course design carried out at many other universities.

Our minicourse divides course contents into 12 modules and each module has its offline and online version. Learning and teaching activities may be carried out in ways of offline classroom or online classroom, which leaves freedom for lecturer and learners to collaboratively achieve course objectives. The core task of lecturer is to instruct learner to formulate mathematical model and get its solution by Matlab package or related software. In section 2, we account each module design by a brief explanation with simple numerical examples. In fact, the Matlab codes of these examples may be employed to solve more general model as long as substituting input data and adjusting relative syntax. We also released these codes in Appendices A1 to A5 which may be served as secondary development templates for operational research course pedagogy and real-world production optimization. Comparing with operational research course of undergraduate majors practiced at other universities, our minicourse design is featured as data-driven style, logistics industry-focused, mini case study pedagogy, abundant mobile internet resources as well as applicable skills training. Evidence coming from learners' feedback supported that the data-driven minicourse of operational research may effectively motivate learning interest, enhance learning efficiency, in the long run, may equip them with quantitative modelling analysis and software skills helpful for a successful career.

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and omits.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix A1. Matlab Codes for Case in Section 2.1

```
x1=linspace(0,50,500);x2=2*x1+100;
plot(x1,x2,'b-'),hold on. % draw a feasible region.
x2=-5*x1+200;
plot(x1,x2,'r-'),hold on. % draw a feasible region.
x2=linspace(0,100,500);
plot(0,x2,'b-'), hold on. % draw a feasible region.
plot(x1,0, 'b-'),hold on. % draw a feasible region.
xlabel('x1'),ylabel('x2')
x2=(1-3*x1)/5;
plot(x1,x2,'g--'),hold on. % draw an objective function.
x2=(100-3*x1)/5;
plot(x1,x2,'m--'),hold on. % draw an objective function.
a = [-2 1;5 1];b = [100;200];
x=a\b; % solve optimized point.
x1=x(1,1),x2=x(2,1);
plot(x1,x2,'r*','markersize',15).
```

Appendix A2. Matlab Codes for Case in Section 2.2

```
f=[-3 -5];a=[-2 1;5 1];b=[100;200];
[x,fval,exitflag,output,lambda]=linprog(f,a,b,[],[],zeros(2,1)).
```

Appendix A3. Matlab Codes for Case in Section 2.3

```
f=[600 400 350 460 400 600 450 520 490 500 550 610]; intcon = [1,2,3,4,
5,6,7,8,9,10,11,12];
ae=[ones(1,4) zeros(1,8)
zeros(1,4) ones(1,4) zeros(1,4)
zeros(1,8) ones(1,4)
    1 zeros(1,3) 1 zeros(1,3) 1 zeros(1,3)
    0 1 zeros(1,2) 0 1 zeros(1,2) 0 1 zeros(1,2)
zeros(1,2) 1 0 zeros(1,2) 1 0 zeros(1,2) 1 0
zeros(1,3) 1 zeros(1,3) 1 zeros(1,3) 1]
be=[5000;6000;7000;3000;5000;6000;4000];
[x,fval,exitflag,output]=intlinprog(f,intcon,[],[],ae,be,zeros(12,1))
```

Appendix A4. Matlab Codes for Case in Section 2.4

```
x1=linspace(0,45,500);x2=2*x1+100;
plot(x1,x2,'b-'),hold on %draw a slack feasible region.
x1=linspace(0,40,500);x2=-5*x1+200;
plot(x1,x2,'r-'),hold on %draw a slack feasible region.
x1=linspace(0,45,500);x2=linspace(0,100,500);
plot(0,x2,'b-'), hold on %draw a slack feasible region.
plot(x1,0, 'b-'),hold on %draw a slack feasible region.
```

```
xlabel('x1'),ylabel('x2')
x2=linspace(0,130,500);
fori=10:1:20        plot(i,x2,'g--'),hold on
end %draw a series of feasible integer points.
for j=120:1:130        plot(x1,j,'g--'),hold on
end %draw a series of feasible integer points.
for z = 100:100:800        x2=(z-3*x1)/5;
plot(x1,x2,'m--'),hold on
end %draw a series of objective functions.
plot(14,128,'r*'),hold on %draw the optimized point.
fval1=[3 5]*[14;128]
%employ intlinprog() function to solve ILP.
f=[-3 -5];intcon=[1,2];a=[-2 1;5 1];b=[100;200];
[x,fval,exitflag,output]=intlinprog(f,intcon,a,b,[],[],zeros(2,1))
% module4:branch-and-bound algorithm
% solve LP.
f=[-3 -5];a=[-2 1;5 1];b=[100;200];
[x,fval,exitflag,output]=linprog(f,a,b,[],[],zeros(2,1))%x =[14.2857;128.5714]
% solve LP1:add x1<=14;
f=[-3 -5];a=[-2 1;5 1;1 0];b=[100;200;14];
[x,fval,exitflag,output]=linprog(f,a,b,[],[],zeros(2,1))%x
=14.0000;128.0000];fval=682.0000.
% solve LP2:add x1>=15;
f=[-3 -5];a=[-2 1;5 1;-1 0];b=[100;200;-15];
[x,fval,exitflag,output]=linprog(f,a,b,[],[],zeros(2,1))%x=[15.0000;125.0000];
```
fval=670.0000. In contrast to LP1, the optimal integer solution is $x^\star$ =[14.0000;128.0000].

Appendix A5. Matlab Codes for Case in Section 2.5

```
x1=linspace(0,50,500);
x2=2*x1+100;
plot(x1,x2,'b-'),hold on %draw a feasible region.
x1=linspace(0,50,500);
x2=-5*x1+200;
plot(x1,x2,'r-'),hold on %draw a feasible region.
x2=(150-x1)/3;
plot(x1,x2,'g-'),hold on %draw a feasible region.
x1=linspace(0,50,500);
x2=linspace(0,100,500);
plot(0,x2,'b-'), hold on %draw a feasible region.
plot(x1,0, 'b-'),hold on %draw a feasible region.
xlabel('x1'),ylabel('x2')
for k=20:20:40
```

```
x2=-5*x1+200-k;hold on
plot(x1,x2,'r--','linewidth',.5);hold on
end %draw the optimized region.
for k=30:60:120
x2=(150+k-x1)/3;hold on
plot(x1,x2,'g--','linewidth',.5);hold on
end %draw the optimized region.
% sequential LP algorithm.
% solve min{d1_}.
f=[zeros(1,2) 1 zeros(1,3)];a=[-2 1 zeros(1,4)];b=100;
ae=[5 1 1 -1 zeros(1,2);1 3 zeros(1,2) 1 -1];be=[200;150];
[x,fval,exitflag,output]=linprog(f,a,b,ae,be,zeros(6,1))% d1_ = 0
% solve min{d2+}.
f=[zeros(1,5) 1];a=[-2 1 zeros(1,4)];b=100;
ae=[5 1 1 -1 zeros(1,2); 1 3 zeros(1,2) 1 -1; zeros(1,2) 1 zeros(1,3)];be =
[200;150;0];
[x,fval,exitflag,output]=linprog(f,a,b,ae,be,zeros(6,1))% d2+ = 0
% weighted LP algorithm.
f=[zeros(1,2) 100 zeros(1,2) 1];a=[-2 1 zeros(1,4)];b=100;
ae=[5 1 1 -1 zeros(1,2); 1 3 zeros(1,2) 1 -1];be=[200;150];
[x,fval,exitflag,output]=linprog(f,a,b,ae,be,zeros(6,1))% d1_ = 0; d2+ = 0
```