SIMULATION AND MODELING

Current Technologies and Applications

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Simulation and Modeling:
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Preface

Introduction

Nowadays, technology advances in sync with the speed of light, noting that simulation is a practice, which extends to take into account factors concluded from scientific research emanating in the U.S. since the late 1940s, yet simulation is unanimously viewed as a science; therefore, the book tackles the current technologies and applications in simulation and modeling in a systematic, comprehensive manner.

Due to the high costs of network infrastructure and the constant rising of unanswered questions regarding technology, simulation has become a good choice for estimation of the performance of networks. Additionally, such methodology for requirements determination can be extended to serve as a blueprint for business (or management) simulation by providing an initial model for creating a business simulation to subsequently show how it can be incorporated into an application.

This allows one to capitalize on conceptual models in a business that have been created for requirements determination by extending them with the conceptual model of runtime management, thus covering the core decision-taking science, particularly in view of the well-known fundamental economic decision theory, to which individuals attribute rational choices from a range of alternatives.

The Challenges

The need to define what appropriate path to follow at any given crossroad triggers the concept behind this project, as any attempt to deal with a problem demands an adequate understanding of the challenges that exist. Such challenges can be further illustrated, as addressed in this book:

First, simulation of a system with limited data is challenging, as it calls for a certain degree of intelligence built in to the system.

Second, the overall employment of remotely controlled vehicles functioning in the ground, air, and marine domains requires investigating the critical issues in the command and control of such vehicles.

Third, a proper understanding of the simulation tools, underlying system algorithms, and user needs is challenging.

Fourth, healthcare systems pose many of the challenges, including difficulty in understanding the system being studied, uncertainty over which data to collect, and problems of communication between problem owners.

Searching for a Solution

Solutions to the problem of defining simulation technologies and application are tackled in this book: for instance, the book presents various based simulation methodologies that may be customized and used in the simulation of a wide variety of problems. Additionally, the book presents a model-based approach resulting in simulation architecture that integrates proven design concepts, such as the model-view-controller paradigm, distributed computing, Web-based simulations, cognitive model-based high-fidelity interfaces and object-based modeling methods.

Moreover, the book shows how simulation allows the identification of critical variables in the randomized clinical trial (RCT) by measuring their effects on the simulation model's "behaviour."

Organization of the Book

The book is organized into 15 chapters. A brief description of each of the chapters follows:

Chapter I provides a comprehensive explanatory platform of simulation background, reviewing simulation definitions, forms of models, the need for simulation, simulation approaches and modeling notations.

Chapter II offers an overview on the distributed simulation in industry, in view that, although the observance of a distinction between continuous and discrete simulations has long been a practice in the simulation community at large, human interactivity in simulation ("human-in-the-loop") *HL1* literature often uses a different terminology and refers to *time-stepped* and *event-driven* simulation.

In addition, Chapter III presents the object-oriented approach for the development of an optical burst switching (OBS) simulator, called OBSim, built in Java.

Subsequently, Chapter IV illustrates how natural language modeling (NLM), a conceptual modeling language, methodology for requirements determination can be extended to serve as a blueprint for business (or management) simulation by providing an initial model for creating a business simulation.

Consequently, Chapter V presents a suggested system development life cycle, "relay race methodology" (RRM). The RRM is based on the philosophy of a relay race, where each runner in the race must hand off the baton within a certain zone, usually marked by triangles on the track race.

On another note, Chapter VI sets forth a new model-based simulation methodology that may be customized and used in the simulation of a wide variety of problems involving multiple source-destination flows with intermediate agents. It explains the model based on a new class of neural networks, called differentially fed artificial neural networks, and the system level performance of the same.

Additionally, Chapter VII presents a model-based approach that the authors adopted for investigating the critical issues in the command and control of remotely operated vehicles (ROVs) through an interactive model-based architecture.

Furthermore, Chapter VIII reports on the use of simulation in supporting decision-making about what data to collect in a randomized clinical trial (RCT). The chapter shows how simulation also allows the identification of critical variables in the RCT by measuring their effects on the simulation model's "behavior."

In the same token, Chapter IX addresses the problem of modeling finished products and their associated sub-assemblies and/or raw materials. A production system is a set of policies that monitors and controls finished products and raw materials, as it determines how much of each item should be manufactured or be kept in warehouses, when low items should be replenished, and how many items should be assembled or ordered when replenishment is needed.

Chapter X illustrates the use of mathematical modelling and simulation to discover the reasons for data to behave in certain ways, as it suggests the use of simulation and modeling of knowledge-mining architecture by using recurrent hybrid nets; particularly in view that hybrid nets combine arithmetic and integrator elements to and from nodes for modeling the complex behavior of intelligent systems.

Likewise, Chapter XI demonstrates the development of a novel compromise linear programming having fuzzy resources (CLPFR) model as well as its simulation for a theory-of-constraints (TOC) product mix problem using MATLAB® v. 7.04 R.14 SP.2 software. The product mix problem considers multiple constraint resources. The developed CLPFR model helps in finding a robust solution with better profit and product mix solution in a non-bottleneck situation. The authors simulate the level-of-satisfaction of the decision maker (DM) as well as the degree of fuzziness of the solution found using the CLPFR model. Simulations have been carried out with MATLAB® v. 7.04 R.14 SP.2 software.

However, Chapter XII provides mainly an overview of the ongoing technology shift inside the vehicles and couples this to simulation possibilities and thereby introduces the business process simulator-based design (SBD). The perspective in this chapter is human-machine interaction (HMI) and therefore addresses human-in-the-loop simulators, keeping in mind the fact that simulation could and even must be used on other levels in order to optimize and verify more technical functions.

On another note, Chapter XIII tackles business aspects of simulation, amongst other things: describing the relationship between business process reengineering (BPR) and change management, the role of simulation in supporting BPR, notwithstanding the future challenges of business process simulation, along with an illustration of simulation technology limitations in reengineering business processes, characteristics of successful simulation and some simulation applications.

While Chapter XIV introduces virtual reality and augmented reality as a basis for simulation visualization. within this context, it shows how these technologies can support simulation visualization and gives important considerations about the use of simulation in virtual and augmented reality environments. Hardware and software features, as well as user interface and examples related to simulation, using and supporting virtual reality and augmented reality. are discussed, stressing their benefits and disadvantages. The chapter discusses virtual and augmented reality in the context of simulation, emphasizing the visualization of data and behavior of systems. The importance of simulation to give dynamic and realistic behaviors to virtual and augmented reality is also pointed out. The work indicates that understanding the integrated use of virtual reality and simulation should create better conditions for the development of innovative simulation environments as well as for the improvement of virtual and augmented reality environments.

In conclusion, Chapter XV aims to develop artificial mechanisms that can play the role emotion plays in natural life, in order to build agents with the mission to "to bring life" to several applications, amongst other things: information, transaction, education, tutoring, business, entertainment and e-commerce. In light of the fact that artificial emotions play an important role at the control level of agent architectures, emotion may lead to reactive or deliberative behaviors, it may intensify agent's motivations, it can create new goals (and then sub-goals) and it can set new criteria for the selection of the methods and the plans the agent uses to satisfy its motives. Since artificial emotion is a process that operates at the control level of agent architecture, the behavior of the agent will improve if the agent's emotion process improves.

Acknowledgment

The editors would like to extend their deepest appreciation for the efforts of all participants in the collation and review process of the book. Additionally, the editors would like to acknowledge their support, as this project could not have efficiently been completed without their significant participation. A further special note of thanks goes also to all the staff at IGI Global, especially Kristin Roth, Jan Travers, and Mehdi Khosrow-Pour; whose contributions throughout the whole process, from inception of the initial idea to final publication, have been invaluable.

In this regard, the editors would also like to acknowledge the authors of chapters included in this book that served as referees for articles written by other authors. Thanks goes to all those who provided constructive and comprehensive reviews.

In closing, we would like to our families and loved ones for their patience, love, and support throughout this project. May they be blessed with eternal happiness.

Editors,
Evon M. O. Abu-Taieh, PhD
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Chapter XI

Simulating Theory-of-Constraint Problem with a Novel Fuzzy Compromise Linear Programming Model

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Abstract

This chapter demonstrates development of a novel compromise linear programming having fuzzy resources (CLPFR) model as well as its simulation for a theory-of-constraints' (TOC) product mix problem using MATLAB® v. 7.04 R.14 SP 2 software. The product-mix problem considers multiple constraint resources. The developed CLPFR model helps in finding a robust solution with better profit and product mix solution in a non-bottleneck situation. The authors simulate the level of satisfaction of the decision maker (DM) as well as the degree of fuzziness of the solution found using the CLPFR model. Simulations have been carried out with MATLAB® v. 7.04 R.14 SP 2 software. In reality, the capacities available for some resources are not always precise. Some tolerances should be allowed on some

constraints. This situation reflects the fuzziness in the availability of resources of the TOC product mix problem.

Introduction

Simulation is a method that allows the analysis of complex systems through mathematically valid means. Through a software interface, the user creates a computerized version of a model (Peterman, 2006). Among other things, "model abstraction is a method for reducing the complexity of a simulation model while maintaining the validity of the simulation results with respect to the question that the simulation is being used to address" (Frantz, 2006). Model abstraction is the intelligent capture of the essence of the behaviour of a model without all the details of how that behaviour is implemented in code (Frantz, 1996). Researchers in the field of artificial intelligence (AI) have also been developing techniques for simplifying models, determining whether model results are valid and developing tools for automatic model selection and manipulation (Frantz, 2006).

Vast literature exists in the field of modelling and simulation. Fishwick and Zeigler (1992) reported substantial parallels between their work and the researches in qualitative simulation. Miller et al. (1992), Fishwick (1992) and Fishwick et al. (1994) provide general rationale and approaches for synergizing traditional simulation and AI modelling & simulation techniques. Weld (1992) reported model sensitivity analysis for qualitative models to formalize an approximation approach. Nayak (1992) described an alternative approximation approach based on the causal relationships of model parameters.

It is to be noted that simulation and modelling has a wide applicational range in military sciences. Sisti and Farr (2005) dealt with the wide variety of research issues in simulation science addressed by government, academia and industry, and their application to the military domain, specifically to the problems of the intelligent analyst.

Advancement in model abstraction research deals with the application and adaptation of the concept of "qualitative reasoning" which is borrowed from the field of AI (Sisti & Farr, 2005). Qualitative simulation concerns itself with getting away from the idea of "exactness" (Sisti & Farr, 2005). Some of the ancillary topics of research in qualitative simulation, as suggested by Sisti & Farr (2005), are: fuzzy modelling, random set theory, possibility theory, rough sets and Dempster-Shafer theory (DS theory) and ordinal optimisation. The common factor among all of these fields is that all of these strive to represent "intermediate degrees of truth" (uncertainty) in such a way as to attain optimal answers, or ranges of answers, as opposed to an optimum answer to 10-decimal place precision (Sisti & Farr, 2005).

In this chapter the authors present, first, a novel fuzzy compromise linear programming (CLPFR) model to solve a product mix problem under theory of constraint (TOC). The problem contains multiple constraint resources. The developed CLPFR model helps in finding a robust solution with better profit and product mix solution. Later, the authors simulate the level of satisfaction of the decision maker (DM) as well as the degree of fuzziness of the solution found using the CLPFR model. Simulations have been carried out with MATLAB® v. 7.04 R.14 SP.2 software. A thorough interpretation and discussion of the outcome of the product mix decision using the CLPFR model has also been presented in this chapter.

Earlier Susanto, Bhattacharya, Vasant, and Suryadi (2006) introduced the CLPFR model to optimize product mix of a chocolate manufacturing firm. Susanto, Vasant, Bhattacharya, and Kahraman (2006) reported a "compromise linear programming having fuzzy objective function coefficients" (CLPFOFC) with fuzzy sensitivity. Their work was also applied to solve a chocolate manufacturing firm's product mix decision using the CLPFOFC model.

In reality, the capacity available for some resources are not always precise, since, for example the company manager can ask workers to work overtime or add more materials from suppliers. Therefore, some tolerances should be allowed on some constraints. This situation reflects the fuzziness in the availability of resources. This problem is called as fuzzy compromise linear programming (CLPFR) having fuzzy resources.

The TOC Problem

Enormous volume of works exists in the arena of product mix decision under TOC heuristic using linear as well as integer programming models. Luebbe & Finch (1992) compared the TOC and linear programming using the five-step improvement process in TOC. They categorized the TOC as a manufacturing philosophy and linear programming (LP) as a specific mathematical optimization technique. It was stated that the algorithm could optimize the product mix as integer LP (ILP) (Luebbe & Finch, 1992).

Balakrishnan and Cheng (2000) reported that LP was a useful tool in the TOC analysis. They (Balakrishnan & Cheng, 2000) showed that some of Luebbe and Finch's (1992) conclusions were not generalizable. Finch and Luebbe's (2000) argued that Balakrishnan and Cheng (2000) did not compare LP with TOC. Finch and Luebbe (2000) commented that Balakrishnan & Cheng's (2000) work was a comparison of LP with one of many techniques sometimes incorporated in TOC.

Hsu and Chung (1998) presented an algorithm using dominance rule classifying non-critically constrained resources into three levels for solving the TOC product mix problem.

Plenert (1993) discussed an example having multiple constrained resources in order to delineate that the TOC heuristic didn't provide an optimal feasible solution. Lee and Plenert (1993) demonstrated that TOC was inefficient when new product was introduced. Lee and Plenert (1993) observed that the solution from TOC during introduction of new product produced a non-optimal product mix. They (Lee & Plenert, 1993; Plenert, 1993) used an ILP formulation that identified a product mix. The product mix fully utilized the bottleneck. Their conclusion was that ILP solution was more efficient than the TOC heuristic. Mayday (1994) and Posnack (1994) criticized Lee and Plenert (1993) and Plenert (1993).

Coman and Ronen (2000) formulated a production outsourcing problem as a LP problem and identified an analytical solution. Coman and Ronen (2000) argued that the TOC solution was inferior to the LP-enhanced solution since it computed the throughput relative to a no-production alternative while the LP solution computed the throughput based on the contractor's mark-up.

Onwubolu (2001) compared the performance of the Tabu search-based approach to both the original TOC heuristic, the ILP solution and the revised TOC algorithm. Further, large-scale difficult problems were generated randomly and solved by Onwubolu (2001). The research work of Boyd and Cox (2002) was focused to compare the TOC solution to the product mix problem with an optimal solution given by LP or ILP.

Bhattacharya and Vasant (2006) developed and subsequently used fuzzy-LP with smooth S-curve membership function (MF) in making product mix decisions under TOC heuristic more explicit. Bhattacharya, Vasant, Sarkar, and Mukherjee (2006) introduced a fully fuzzified and intelligent TOC product mix decision. In order to avoid linearity in the real life application problems, especially in product mix decision problems, a non-linear function such as modified MF was used in the above works. This MF was used when the problems and its solutions were independent (Vasant, 2003; Bhattacharya & Vasant, 2006; Bhattacharya, Vasant, Sarkar, & Mukherjee, 2006).

Now, let us discuss the product mix problem when multiple constrained resources exist. The effectiveness of the CLPFR model will be delineated in solving the said product mix problem under TOC. Hsu and Chung (1998) and Onwubolu and Mutingi (2001) illustrated the said product mix problem as shown in Figure 1. The same problem of Hsu and Chung (1998) is solved in this chapter in order to compare the developed CLPFR model with that of the earlier proposed methodologies.

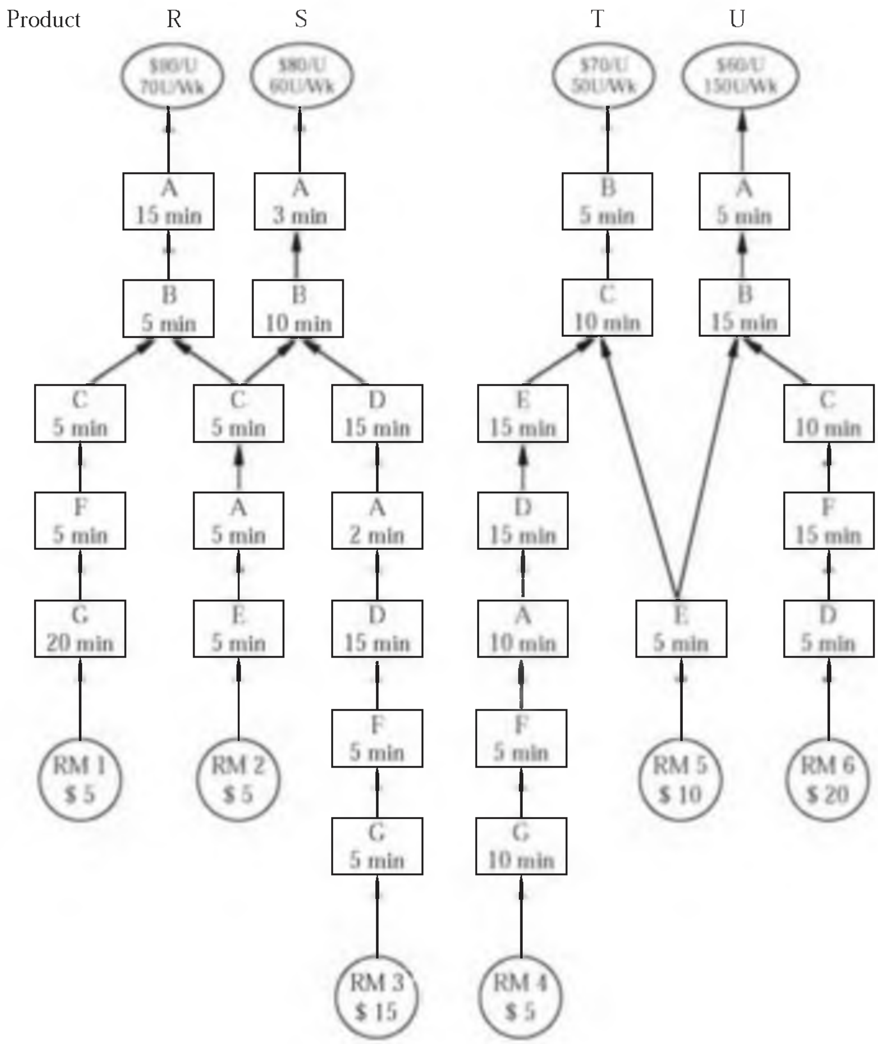
The problem of Hsu and Chung (1998) can be modelled as a dual simplex LP problem with a view to maximize the throughput when multiple resource constraints exist. In their (Hsu & Chung 1998) problem, four different types of products, namely, R, S, T & U, are to be produced wherein seven different resources, A to G, exists. Each resource has a capacity of 2,400 minutes. Table 1 illustrates loads required for producing one unit of each of the products R, S, T and U.

Table 2 shows loads on each of the resources. It is seen from Table 2 that only resource G is underutilized and resource E runs in its full capacity, while resources A-D and F are overloaded. Resource B is the capacity constraint resource (CCR) as it is the most overloaded and the said CCR is indicated in Table 2 using a vertical upward arrow. Now, throughput per constraint resource minute needs to be calculated for finding out the required number of products to be produced within the available capacity of each resource per week.

Table 1. Loads required for producing four products

Products	Weekly market potential (units)	Unit selling price (US$ / unit)	Processing time per unit (min)							Raw material cost per unit (US$ / unit)	Throughput per unit (US$ /unit)
			A	B	C	D	E	F	G		
R	70	90	20	5	10	--	5	5	20	10	80
S	60	80	10	10	5	30	5	5	5	20	60
T	50	70	10	5	10	15	20	5	10	20	50
U	150	50	5	15	10	5	5	15	--	30	30

Figure 1. Modified product mix problem of Hsu and Chung (1998)



The total throughput is (70 x 80 + 60 x 60 + 50 x 50 + 80 x 30) = 14100. *Table 3* formalizes capacity utilization for each of the resources. From *Table 3* it is identified that the CCR is still there with resources A and D, as these two resources exceed the available maximum capacity of 2,400 minutes. Thus, it appears that product mix solution under TOC heuristic [particularly the problem of Hsu & Chung (1998)] is infeasible when multiple constraint resources exist.

In the spirit to maintain the Hsu and Chung's (1998) mathematical formulation, some inconsistencies have been found in their paper. The inconsistencies are as follows:

Table 2. Load calculations and constrained resources

Products	Weekly market potential (units)	Capacity per unit for resources (min)						
		A	B	C	D	E	F	G
R	70	1400	350	700	--	350	350	1400
S	60	600	600	300	1800	300	300	300
T	50	500	250	500	750	1000	250	500
U	150	750	2250	1500	750	750	2250	--
Total load (min)		3250	3450	3000	3300	2400	3150	2200
Available capacity (min)		2400	2400	2400	2400	2400	2400	2400
Overload (min)		850	1050	600	900	0	750	-200
Capacity utilization (%)		131.42	143.75	125	137.50	100	131.25	91.67

Table 3. Load calculation after removing CCR at B

Products	Weekly market potential (units)	Capacity per unit for resources (min)						
		A	B	C	D	E	F	G
R	70	1400	350	700	--	350	350	1400
S	60	600	600	300	1800	300	300	300
T	50	500	250	500	750	1000	250	500
U	80	400	1200	800	400	400	1200	--
Total load (min)		2900	2400	2300	2950	2050	2100	2200
Available capacity (min)		2400	2400	2400	2400	2400	2400	2400
Overload (min)		500	0	-100	550	-350	-300	-200
Capacity utilization (%)		120.83	0	95.83	122.92	85.42	87.5	91.67

1. There should be an arrow connecting node E to C for product T, since it more complies with the resource E usage per unit of product T;
2. The resource C usage per unit of product U, should be changed from 15 min to 10 min. so it complies with resource C constraint [see Figure 1 of Hsu & Chung (1998), more specifically the resource C usage for product U (15 minutes), with the corresponding values in Table 1 and Table 2 of their paper, which is 10 minutes]; and
3. The price per unit of RM6, should be changed from US$10 to US$20, so that it complies with the objective function coefficient of U in the objective function (equation 1 of Hsu & Chung, 1998),that is, US$30. To maintain the Hsu and Chung's (1998)

mathematical formulation, a modification to the price of per unit RM6 from the existing US$10 to US$20, is suggested in *Figure 1*.

Extensive published literatures depict that TOC heuristic is implicit for solving product mix decision problem when multiple constrained resources exist. The same was also reported by Onwubolu and Mutingi (2001). Moreover, TOC-based product mix decisions can never be better than a correctly formulated LP approach (Souren et al., 2005).

In the next sections a detailed computational analysis with the developed CLPFR model will be illustrated. The CLPFR model makes the TOC heuristic more explicit in making product mix decision when multiple constrained resources exist.

"CLPFR" Algorithm

The development of compromise linear programming having fuzzy resources (CLPFR) algorithm passes through the following steps:

Step 1: Formulating the crisp linear programming problem

Step 2: Determining the resources whose availability are to be fuzzified and subsequent determination of their tolerances

Step 3: Defining the membership functions representing the fuzziness of the i^{th} resource, $i = 1, 2, ..., m$, m being the number of resource whose availability are to be fuzzified

Step 4: Solving the following crisp LP:

$$\max \mathbf{cx}$$
subject to
$$(A\mathbf{x})_i \leq b_i$$
$$\mathbf{x} \geq \mathbf{0}$$
$$i = 1, 2, ..., m$$

Step 5: Solving the following LP with the i^{th} constraint tolerances:

$$\max \mathbf{cx}$$
subject to

$(A\mathbf{x})_i \leq b_i + t_i$

$t_i \geq 0$

$\mathbf{x} \geq \mathbf{0}$

$i = 1, 2, ..., m$

Step 6: Defining the membership function representing the degree of the optimality of the solution

Step 7: Defining the following linear programming problem:

$$\max_{\mathbf{x} \geq \mathbf{0}} \min\{\mu_0(\mathbf{x}), \mu_1(\mathbf{x}), ..., \mu_m(\mathbf{x})\}$$

Step 8: Converting the LP of Step 7 into the following equivalent compromise linear programming problem:

$\max \alpha$

subject to

$\mu_0(\mathbf{x}) \geq \alpha$

$\mu_i(\mathbf{x}) \geq \alpha$

$\alpha \in [0,1]$

$\mathbf{x} \geq \mathbf{0}$

$i = 1, 2, ..., m$

Step 9: Obtaining an equivalent compromise solution to Step 8 by using the following equivalent compromise linear programming problem:

$\max \alpha$

subject to

$\mathbf{cx} \geq z^1 - (1 - \alpha)(z^1 - z^0)$

$(\mathbf{Ax})_i \leq b_i + (1 - \alpha)t_i,$

$\alpha \in [0,1]$

$\mathbf{x} \geq \mathbf{0}$

$i = 1, 2, ..., m$

TOC Product Mix Problem Formulation Using "CLPFR"

This chapter improves the solution of the problem reported earlier by Hsu and Chung (1998) fuzzifying the availability of resources A to G. For illustration purpose, the fuzzification is carried out introducing following tolerances $t_1 = 120$ minutes, $t_2 = 240$ minutes, $t_3 = 180$ minutes, $t_4 = 120$ minutes, $t_5 = 320$ minutes, $t_6 = 240$ minutes and $t_7 = 180$ minutes to resource A, B, C, D, E, F and G, respectively.

As a first step of the proposed CLPFR model, the crisp LP model is to be converted into an equivalent CLPFR using the following identified decision variables:

x_1 = the number of product R to be produced (units)
x_2 = the number of product S to be produced (units)
x_3 = the number of product T to be produced (units)
x_4 = the number of product U to be produced (units)

According to the developed CLPFR algorithm, the following steps have been computed for the product mix problem under TOC adopted from Hsu and Chung (1998):

Step 1: The crisp linear programming problem is formulated as follows:

The objective function for the crisp LP is:

maximize profit $z = 80x_1 + 60x_2 + 50x_3 + 30x_4$

subject to the following constraints

Constraint-1 (for resource A): $20x_1 + 10x_2 + 10x_3 + 5x_4 \leq 2400$

Constraint-2 (for resource B): $5x_1 + 10x_2 + 5x_3 + 15x_4 \leq 2400$

Constraint-3 (for resource C): $10x_1 + 5x_2 + 10x_3 + 10x_4 \leq 2400$

Constraint-4 (for resource D): $0x_1 + 30x_2 + 15x_3 + 5x_4 \leq 2400$

Constraint-5 (for resource E): $5x_1 + 5x_2 + 20x_3 + 5x_4 \leq 2400$

Constraint-6 (for resource F): $5x_1 + 5x_2 + 5x_3 + 15x_4 \le 2400$

Constraint-7 (for resource G): $20x_1 + 5x_2 + 10x_3 + 0x_4 \le 2400$

Constraint-8 (demand for product R): $x_1 \le 70$

Constraint-9 (demand for product S): $x_2 \le 70$

Constraint-10 (demand for product T): $x_3 \le 70$

Constraint-11 (demand for product U): $x_4 \le 70$. and

non-negativity constraints: $x_1, x_2, x_3, x_4 \ge 0$

Step 2: The constraints to be fuzzified are constraint numbers (1) to (7). The tolerances for each of the resources are as follows:

- t_1 = 120 minutes for the availability of resource A (resource-1).
- t_2 = 240 minutes for the availability of resource B (resource-2).
- t_3 = 180 minutes for the availability of resource C (resource-3).
- t_4 = 120 minutes for the availability of resource D (resource-4).
- t_5 = 320 minutes for the availability of resource E (resource-5).
- t_6 = 240 minutes for the availability of resource F (resource-6), and
- t_7 = 180 minutes for the availability of resource G (resource-7).

Step 3: The membership functions representing the fuzziness of the i^{th} resource (constraint) are defined in the following fashion as illustrated.

Let t_i be the tolerance of the availability of the i^{th} resource. The fuzziness of this resource is defined by the fuzzification of the i^{th} constraint, $(A\mathbf{x})_i \le b_i$, through the fuzzy set i with membership function having triangular fuzzy number:

$$\mu_i(\mathbf{x}) = \begin{cases} 1, & \text{if } (A\mathbf{x})_i \le b_i \\ 1 - \dfrac{(A\mathbf{x})_i - b_i}{t_i}, & \text{if } b_i \le (A\mathbf{x})_i \le b_i + t_i \\ 0, & \text{if } (A\mathbf{x})_i > b_i + t_i \end{cases}$$

This triangular membership function represents the degree of satisfaction for the i^{th} constraint.

In the case discussed, the following membership functions represent the fuzziness of constraints (1) to (7) respectively:

$$\mu_1(\mathbf{x}) = \begin{cases} 1, & \text{if } (20x_1 + 10x_2 + 10x_3 + 5x_4) \le 2400 \\ 1 - \dfrac{(20x_1+10x_2+10x_3+5x_4)-2400}{120}, & \text{if } 2400 \le (20x_1 + 10x_2 + 10x_3 + 5x_4) \le 2520 \\ 0, & \text{if } (20x_1 + 10x_2 + 10x_3 + 5x_4) > 2520 \end{cases}$$

$$\mu_2(\mathbf{x}) = \begin{cases} 1, & \text{if } (5x_1 + 10x_2 + 5x_3 + 15x_4) \le 2400 \\ 1 - \dfrac{(5x_1+10x_2+5x_3+15x_4)-2400}{240}, & \text{if } 2400 \le (5x_1 + 10x_2 + 5x_3 + 15x_4) \le 2640 \\ 0, & \text{if } (5x_1 + 10x_2 + 5x_3 + 15x_4) > 2640 \end{cases}$$

$$\mu_3(\mathbf{x}) = \begin{cases} 1, & \text{if } (10x_1 + 5x_2 + 10x_3 + 10x_4) \le 2400 \\ 1 - \dfrac{(10x_1+5x_2+10x_3+10x_4)-2400}{180}, & \text{if } 2400 \le (10x_1 + 5x_2 + 10x_3 + 10x_4) \le 2580 \\ 0, & \text{if } (10x_1 + 5x_2 + 10x_3 + 10x_4) > 2580 \end{cases}$$

$$\mu_4(\mathbf{x}) = \begin{cases} 1, & \text{if } (30x_2 + 15x_3 + 5x_4) \le 2400 \\ 1 - \dfrac{(30x_2+15x_3+5x_4)-2400}{120}, & \text{if } 2400 \le (30x_2 + 15x_3 + 5x_4) \le 2520 \\ 0, & \text{if } (30x_2 + 15x_3 + 5x_4) > 2520 \end{cases}$$

$$\mu_6(\mathbf{x}) = \begin{cases} 1, & \text{if } (5x_1 + 5x_2 + 20x_3 + 5x_4) \le 2400 \\ 1 - \dfrac{(5x_1+5x_2+20x_3+5x_4)-2400}{320}, & \text{if } 2400 \le (5x_1 + 5x_2 + 20x_3 + 5x_4) \le 2720 \\ 0, & \text{if } (5x_1 + 5x_2 + 20x_3 + 5x_4) > 2720 \end{cases}$$

$$\mu_6(\mathbf{x}) = \begin{cases} 1, & \text{if } (5x_1 + 5x_2 + 5x_3 + 15x_4) \le 2400 \\ 1 - \dfrac{(5x_1+5x_2+5x_3+15x_4)-2400}{240}, & \text{if } 2400 \le (5x_1 + 5x_2 + 5x_3 + 15x_4) \le 2640 \\ 0, & \text{if } (5x_1 + 5x_2 + 5x_3 + 15x_4) > 2640 \end{cases}$$

$$\mu_7(\mathbf{x}) = \begin{cases} 1, & \text{if } (20x_1 + 5x_2 + 10x_3) \le 2400 \\ 1 - \dfrac{(20x_1+5x_2+10x_3)-2400}{180}, & \text{if } 2400 \le (20x_1 + 5x_2 + 10x_3) \le 2580 \\ 0, & \text{if } (20x_1 + 5x_2 + 10x_3) > 2580 \end{cases}$$

Step 4: The solution to the following crisp LP is carried out:

max $\mathbf{cx}$
subject to

$(A\mathbf{x})_i \leq b_i$

$\mathbf{x} \geq \mathbf{0}$

i = 1, 2, ... 7

Let $\mathbf{x}^0$ be the solution and $z^0 = \mathbf{cx}^0$ be the optimal value.
Therefore, the solution to the crisp LP problem of *Step 1* is as follows:

$\mathbf{x}^0 = (50.667 \quad 38.1667 \quad 50 \quad 101)$.

the optimal value is $z^0 = 11\,873.33$

Step 5: The following crisp LP is solved with the constraint tolerances

max $\mathbf{cx}$
subject to

$(A\mathbf{x})_i \leq b_i + t_i$

$t_i \geq 0$

$\mathbf{x} \geq \mathbf{0}$

i = 1, 2, ... 7

Let $\mathbf{x}^1$ be the solution and $z^1 = \mathbf{cx}^1$ be the optimal value.
The formulation of the crisp LP with the constraint tolerances will be as follows:

Objective function: maximize profit $z = 80x_1 + 60x_2 + 50x_3 + 30x_4$

subject to the constraints

Constraint-1" (for resource A): $20x_1 + 10x_2 + 10x_3 + 5x_4 \leq 2520$

Constraint-2" (for resource B): $5x_1 + 10x_2 + 5x_3 + 15x_4 \leq 2640$

Constraint-3" (for resource C): $10x_1 + 5x_2 + 10x_3 + 10x_4 \leq 2580$

Constraint-4" (for resource D): $0x_1 + 30x_2 + 15x_3 + 5x_4 \leq 2520$

Constraint-5" (for resource E): $5x_1 + 5x_2 + 20x_3 + 5x_4 \leq 2720$

Constraint-6" (for resource F): $5x_1 + 5x_2 + 5x_3 + 15x_4 \leq 2640$

Constraint-7" (for resource G): $20x_1 + 5x_2 + 10x_3 + 0x_4 \leq 2580$

Constraint-8 (demand for product R): $x_1 \leq 70$

Constraint-9 (demand for product S): $x_2 \leq 70$

Constraint-10 (demand for product T): $x_3 \leq 70$

Constraint-11 (demand for product U): $x_4 \leq 70$, and

Non-negativity constraints: $x_1, x_2, x_3, x_4 \geq 0$

The solution is:

$$\mathbf{x}^1 = \begin{pmatrix} 52.2667 & 39.7667 & 50 & 115.4 \end{pmatrix}$$

and the optimal value is: $z^1 = 12\ 529.33$

Note that the LP constraints in *Step 4* are contained in the LP constraints in *Step 5*, thus it is clear that the following relation is trivial:

$z^1 = \mathbf{cx}^1 \geq z^0 = \mathbf{cx}^0$

Step 6: The following membership function is defined to represent the degree of optimality of the solution:

$$\mu_0(\mathbf{x}) = \begin{cases} 1, & \text{if } \mathbf{cx} > z^1 \\ 1 - \dfrac{z^1 - \mathbf{cx}}{z^1 - z^0}, & \text{if } z^0 \leq \mathbf{cx} \leq z^1 \\ 0, & \text{if } \mathbf{cx} < z^0 \end{cases}$$

As discussed above, the membership function representing the degree of the optimality of the solution is as follows:

$$\mu_0(\mathbf{x}) = \begin{cases} 1, & \text{if } (80x_1 + 60x_2 + 50x_3 + 30x_4) > 12\,529.33 \\ 1 - \dfrac{12\,529.33 - (80x_1 + 60x_2 + 50x_3 + 30x_4)}{656}, & \text{if } 11873.33 \leq (80x_1 + 60x_2 + 50x_3 + 30x_4) \leq 12\,529.33 \\ 0, & \text{if } (80x_1 + 60x_2 + 50x_3 + 30x_4) < 11\,873.33 \end{cases}$$

Steps 7 & 8: So far we have introduced 8 (eight) membership functions as follows:

- $\mu_0(\mathbf{x})$ represents the degree of optimality of the solution
- $\mu_1(\mathbf{x})$ ... $\mu_7(\mathbf{x})$, each represents the degree of satisfaction for constraints (1) to (7)

The main aim is to maximize the value of all of these membership functions. In reality, since such aim is never possible to be achieved, a compromise is required. Since all of these membership functions are non-dimensional, one can apply the *max-min* method for the compromise.

Thus the problem is formulated as follows:

$$\max_{x > 0} \min \{\mu_0(\mathbf{x}), \mu_1(\mathbf{x}), ..., \mu_7(\mathbf{x})\}$$

or, equivalently the *compromise linear programming problem*

max α

subject to

$\mu_0(\mathbf{x}) \geq \alpha$

$\mu_i(\mathbf{x}) \geq \alpha$, i = 1,2, ...,7

$\alpha \in [0,1]$

$\mathbf{x} \geq \mathbf{0}$

Step 9: The solution to the equivalent compromise linear programming problem results in some algebraic manipulations.

$$\max \alpha$$

subject to

$$\mathbf{cx} \geq z^1 - (1-\alpha)(z^1 - z^0)$$

$$(\mathbf{Ax})_i \geq b_i + (1-\alpha)t_i,\ i = 1, 2, ..., 7$$

$$\alpha \in [0,1]$$

$$\mathbf{x} \geq \mathbf{0}$$

After some algebraic manipulation, we get the following linear programming problem:

$\max \alpha$

subject to

$80x_1 + 60x_2 + 50x_3 + 30x_4 \geq 12529.33 - 656(1-\alpha)$ or $80x_1 + 60x_2 + 50x_3 + 30x_4 - 656\alpha \geq 11873.33$

$20x_1 + 10x_2 + 10x_3 + 5x_4 \leq 2400 + (1-\alpha)t_1$ or $20x_1 + 10x_2 + 10x_3 + 5x_4 + 120\alpha \leq 2520$

$5x_1 + 10x_2 + 5x_3 + 15x_4 \leq 2400 + (1-\alpha)t_2$ or $5x_1 + 10x_2 + 5x_3 + 15x_4 + 240\alpha \leq 2640$

$10x_1 + 5x_2 + 10x_3 + 10x_4 \leq 2400 + (1-\alpha)t_3$ or $10x_1 + 5x_2 + 10x_3 + 10x_4 + 180\alpha \leq 2580$

$0x_1 + 30x_2 + 15x_3 + 5x_4 \leq 2400 + (1-\alpha)t_4$ or $0x_1 + 30x_2 + 15x_3 + 5x_4 + 120\alpha \leq 2520$

$5x_1 + 5x_2 + 20x_3 + 5x_4 \leq 2400 + (1-\alpha)t_5$ or $5x_1 + 5x_2 + 20x_3 + 5x_4 + 320\alpha \leq 2720$

$5x_1 + 5x_2 + 5x_3 + 15x_4 \leq 2400 + (1-\alpha)t_6$ or $5x_1 + 5x_2 + 5x_3 + 15x_4 + 240\alpha \leq 2640$

$20x_1 + 5x_2 + 10x_3 + 0x_4 \leq 2400 + (1-\alpha)t_7$ or $20x_1 + 5x_2 + 10x_3 + 0x_4 + 180\alpha \leq 2580$

$x_1 \leq 70$

$x_2 \leq 70$

$x_3 \leq 70$

$x_4 \leq 70$, and

the non-negativity constraints: $x_1, x_2, x_3, x_4 \geq 0$

The Product Mix Solution and Discussions

The results of TOC problem using CLPFR model, obtained with the aid of the WinQSB® software, are tabulated in *Table 4*.

Table 4 is converted into *Table 5* showing optimal combination of products to be produced.

From the definitions of μ_0, μ_1, ..., μ_7 for the optimal solution, the following values are obtained:

$$\mu_0(\mathbf{x}) = \mu_0(51.4667, 38.9667, 50, 108.2000) = 0.5000$$
$$\mu_1(\mathbf{x}) = \mu_1(51.4667, 38.9667, 50, 108.2000) = 0.5000$$
$$\mu_2(\mathbf{x}) = \mu_2(51.4667, 38.9667, 50, 108.2000) = 0.5000$$
$$\mu_3(\mathbf{x}) = \mu_3(51.4667, 38.9667, 50, 108.2000) = 1$$
$$\mu_4(\mathbf{x}) = \mu_4(51.4667, 38.9667, 50, 108.2000) = 0.5000$$
$$\mu_5(\mathbf{x}) = \mu_5(51.4667, 38.9667, 50, 108.2000) = 1$$
$$\mu_6(\mathbf{x}) = \mu_6(51.4667, 38.9667, 50, 108.2000) = 1$$
$$\mu_7(\mathbf{x}) = \mu_7(51.4667, 38.9667, 50, 108.2000) = 1$$

Let us now examine and discuss on each of the value for μ_0, μ_1, ..., μ_7 and α.

Discussions on μ_0

The value of the optimal solution with no tolerance in constraints is $z^0 = 11873.33$. From the definition of μ_0, the value of $z^0 = 11873.33$ corresponds to the value 0. The value of the optimal solution using maximum tolerance in each of the first seven constraints is $z^1 = 12529.33$. From the definition of μ_0, the value of $z^1 = 12529.33$ corresponds to the value 1. Thus, the optimal value of the TOC objective function is:

$$80(51.4667) + 60(38.9667) + 50(50) + 30(108.2000) = 12\,201.34$$

By linear interpolation, this optimal value corresponds to the degree of optimality of the solution, μ_0, which is equal to 0.5000.

Discussions on μ_1

When the usage of resource A is less than, or equal to the current capacity, that is, 2,400 hours, no tolerance for resource A is required. This situation corresponds to $\mu_1 = 1$. This

Table 4. Solutions from WinQSB® software

	Decision variables	Solution values
1	x_1	51.4667
2	x_2	38.9667
3	x_3	50.0000
4	x_4	108.2000
5	α	0.5000

Table 5. The optimal combination of products

Products	Quantity to be produced
R	51.4667
S	38.9667
T	50
U	108.2000

implies that there is no violation of the boundary situations for the original constraint of availability of resource A.

Let us discuss another case when the usage of resource A is greater than, or equal to the capacity having maximum tolerance, that is, 2,520 hours. This situation corresponds to $\mu_1 = 0$ indicating maximum violation of the boundary situations for the original constraint of availability of resource A.

The optimal solution for the usage level of resource A is:

$$20x_1 + 10x_2 + 10x_3 + 5x_4 = 2460.00.$$

By linear interpolation this value corresponds to the degree of satisfaction of the constraint for resource A.

Discussions on μ_2

When the usage of resource B is less than, or equal to the current capacity, that is, 2,400 hours, no tolerance for this resource is warranted. This situation corresponds to $\mu_2 = 1$. This indicates no violation of the boundary conditions for the original constraint of availability of resource B.

When the usage of resource B is greater than, or equal to the capacity having maximum tolerance, that is, 2,640 hours, the situation corresponds to $\mu_2 = 0$. This situation indicates maximum violation of the boundary conditions for the original constraint of availability of resource B.

Since the optimal solution for the usage level of resource B is:

$$5x_1 + 10x_2 + 5x_3 + 15x_4 = 2520.00.$$

then, by linear interpolation, it is found that this value corresponds to the degree of satisfaction of the constraint for resource B, $\mu_2 = 0.5000$.

Discussions on μ_3

Let us discuss on the first boundary condition. The usage of resource C is less than, or equal to the current capacity, that is, 2,400 hours. It indicates that no tolerance for resource C is warranted and the situation corresponds to $\mu_3 = 1$. It is to be noted that for this condition no violation of the boundary conditions for the original constraint of availability of resource C is present.

For the second boundary condition, the usage of resource C is greater than, or equal to the capacity having maximum tolerance, that is, 2,580 hours. This situation corresponds to $\mu_3 = 0$. This is an indication of maximum violation of the boundary conditions for the original constraint of availability of resource C.

The usage level of resource C in the optimal solution is:

$$10x_1 + 5x_2 + 10x_3 + 10x_4 = 2291.50.$$

Therefore, from the definition of μ_3, we get $\mu_3 = 1$, that is, no violation in the usage level of resource C.

Discussions on μ_4

The first boundary condition for the usage of resource D is less than, or equal to the current capacity, that is, 2,400 hours. This condition indicates that no tolerance for resource D is warranted. This situation corresponds to $\mu_4 = 1$, which implies no violation of the boundary conditions for the original constraint of availability of resource D.

The second boundary condition teaches that the usage of resource D is greater than, or equal to the capacity having maximum tolerance, that is, 2,520 hours. Simulating within this boundary values, $\mu_4 = 0$ is obtained. The resulted value indicates maximum violation of the boundary conditions for the original constraint of availability of resource D.

The usage level of resource D in the optimal solution is:

$$0x_1 + 30x_2 + 15x_3 + 5x_4 = 2460.00$$

Using linear interpolation technique it is found that this value corresponds to the degree of satisfaction of the constraint for resource D as $\mu_4 = 0.5000$

Discussions on μ_5

If the usage of resource E is less than, or equal to the current capacity, that is, 2,400 hours, then no tolerance for resource E is required. This situation corresponds to $\mu_5 = 1$. The value of μ_5 indicates no violation of the boundary conditions for the original constraint of availability of resource E.

If the usage of resource E is greater than, or equal to the capacity having maximum tolerance, that is, 2,720 hours, then this situation corresponds to $\mu_5 = 0$. This value of μ_5 implies maximum violation of the boundary conditions for the original constraint of availability of resource E.

The usage level of resource E in the optimal solution is:

$$5x_1 + 5x_2 + 20x_3 + 5x_4 = 1993.167.$$

From the definition of μ_5, we get $\mu_5 = 1$, that is, no violation of the boundary conditions in the usage constraint of resource E.

Discussions on μ_6

For the usage constraint of resource F, if the same is less than, or equal to the current capacity, that is, 2,400 hours, then no tolerance for this resource warranted. The corresponding value for μ_6 under this situation is equal to 1. This value restricts any violation of the boundary conditions for the original constraint of availability of resource F.

If the usage constraint of resource F is greater than, or equal to the capacity having maximum tolerance, that is, 2,720 hours, then this situation corresponds to the value $\mu_6 = 0$. This validates the situation of maximum violation of the boundary conditions for the original constraint of availability of resource F.

The usage level of resource F in the optimal solution is:

$$5x_1 + 5x_2 + 5x_3 + 15x_4 = 2325.167.$$

Therefore, from the definition of μ_6, we get $\mu_6 = 1$, that is, no violation of the boundary conditions in the usage constraint of resource F.

Discussions on μ_7

The first boundary condition binds the usage of resource G within less than, or equal to the current capacity, that is, 2,400 hours. This implies that no tolerance for resource G is required. This situation corresponds to $\mu_7 = 1$, indicating no violation of the boundary conditions for the original constraint of availability of resource G.

The second boundary condition for the usage of resource G is greater than, or equal to the capacity with maximum tolerance, that is, 2,580 hours. This condition corresponds to $\mu_7 = 0$. This value of μ_7 indicates maximum violation of the boundary conditions for the original constraint of availability of resource G.

It is to be noted that the usage level of resource G in the optimal solution is:

$$20x_1 + 5x_2 + 10x_3 + 0x_4 = 1724.168.$$

Using the definition of μ_7, one gets $\mu_7 = 1$, that is, no violation of the boundary conditions in the usage constraint of resource G.

Discussions on α

For the TOC problem having fuzzy constraints, the chief aim is to achieve the following two goals:

- to achieve the maximum throughput, if necessary, by exploiting the use of all the constraints tolerance available; and at the same time
- to maintain to the level of resource usage such that no single constraint is violated.

Such an aim is not achievable often, and therefore, a compromise is required to achieve these two goals. This compromise is made with the application of *max-min* principle to the following two parameters:

- the degree of optimality of the solution, represented by the membership function μ_0, and
- the degree of satisfaction of constraints for resources A to G, represented by the membership functions $\mu_1, \mu_2, \ldots, \mu_7$ respectively.

In *Step 7* of the algorithm, the problem formulated is to maximize the value of $\alpha = \min\{\mu_0, \mu_1, ..., \mu_7\}$. From the previous discussions on the values of $\mu_0, \mu_1, \mu_2, ..., \mu_7$, it is clear why one obtains $\alpha = 0.5000$ in the optimal solution. The value of α indicates that the values of the degree of optimality of the solution, and the degree of satisfaction of the constraints for resources A to G will not be less than 0.5000.

Simulations Using MATLAB®

Another simulation phase of the algorithm with MATLAB® software is described under this heading. This simulation is carried out with an aim to sense the degree of fuzziness of the solution and the level-of-satisfaction of the decision maker (DM). Degree of fuzziness gets induced in the set of solutions due to imprecision of the tolerance values of the CLPRF algorithm. Induction of fuzziness in the solution will affect the level-of-satisfaction of the DM. This level-of-satisfaction is one kind of human "emotion" of the decision makers, which is guided by many factors while making a decision. Moreover, the degree of fuzziness and the level-of-satisfaction of the DM are not tangible quantities. Therefore, sensitivity simulation using a suitable and flexible membership function is the only solution to grab the emotion of DM as well as the degree of fuzziness present in the solution of CLPFR algorithm. Let us now begin with formulating a suitable membership function so as to simulate the sensitiveness of the solution found using the CLPFR algorithm.

In order to solve the issue of degeneration, in fuzzy problems, Leberling (1981) employed a non-linear logistic function, for example a tangent hyperbola that has asymptotes at 1 and 0. The logistic membership function has similar shape as that of tangent hyperbolic function employed by Leberling (1981) but it is more flexible than that of the tangent hyperbola of Leberling (1981). It should be emphasized that some non-linear MFs such as *S*-curve MFs are desirable for use in real life product mix decision problems than that of linear MFs (Vasant, 2004).

The generalised logistic function (Leberling, 1981) is given by:

$$f(x) = \frac{B}{1 + Ce^{gx}}$$

where B and C are scalar constants and γ, $0 < \gamma < \infty$, is a fuzzy parameter measuring the degree of vagueness, wherein $\gamma = 0$ indicates crisp.

The generalized logistic MF (Bhattacharya & Vasant, 2006; Vasant, 2004) is defined as:

$$f(x) = \begin{cases} 1 & x < x_L \\ \dfrac{B}{1 + Ce^{gx}} & x_L < x < x_U \\ 0 & x > x_U \end{cases}$$

The *S*-curve MF is a particular case of the logistic function. The said *S*-curve MF has got specific values of *B*, *C* and γ. The logistic MF is re-defined as $0.001 \le \mu(x) \le 0.999$. In real-life problems, the physical capacity requirement cannot be 100%. Thus, the range $0.001 \le \mu(x) \le 0.999$ is selected. At the same time, the capacity requirement cannot be 0% (Bhattacharya & Vasant, 2006; Vasant, 2004; Bitran, 1980).

$$\mu(x) = \begin{cases} 1 & x < x^a \\ 0.999 & x = x^a \\ \dfrac{B}{1+Ce^{gx}} & x^a < x < x^b \\ 0.001 & x = x^b \\ 0 & x > x^b \end{cases}$$

In this simulation procedure the relationship between the degree of possibility, μ, and the level-of-satisfaction, φ, is $\mu = (1 - \varphi)$. Rule-based codes have been generated using MATLAB®'s M-file for simulating the sensitiveness of the solution found using the CLPFR algorithm. These codes help a decision maker to vary the values of the coefficient α in the interval (0,1). Thus, the DM is able to have the optimal throughput (Z) for a particular value of level-of-satisfaction (φ) and degree of fuzziness (γ). *Table 6* illustrates throughput (Z) simulation data at disparate degree of fuzziness (γ) and level-of-satisfaction (φ) of the DM. It is observed from *Table 6* that the characteristics plot simulating a relationship among all these three parameters will behave as a monotonically increasing function.

In the first row, second column of *Table 6*, there are two inputs and one output data. The inputs are $\gamma = 3$ and $\mu = 0.10$ and the corresponding output is Z = US$11908. As the μ increases the Z values decrease for any particular γ value. This indicates that decrease in level-of-satisfaction (φ) results in decrease in the profits. The first row indicates that the fuzziness dominates for a very poor level-of-satisfaction of the decision maker because at poor level of satisfaction, higher degree of fuzziness gets associated with the output itself.

Figure 2 is a surface and contour simulation illustrating the behavioural patterns of Z-values with respect to the degree of possibility (μ) at disparate degree of fussiness (γ). It is to be noted that the higher the level of satisfaction values (φ), the lesser will be the dominance of the degree of vagueness (γ). Thus higher level of outcome of decision variable for a particular level-of-satisfaction point results in a lesser degree of fuzziness inherent in the said decision variable.

Figure 3 depicts a 2-D contour simulation illustrating relationship between level-of-satisfaction (μ) and degree of fuzziness (γ). Lower μ values indicate higher level-of-satisfaction (φ) of the decision made and the corresponding degree of fuzziness (γ) will be low. This is because of the relationship $\mu = (1 - \varphi)$.

Figure 4 illustrates a 2-D contour simulation depicting characteristics showing the relationship between the throughput (Z) and the degree of possibility (μ). *Figure 5* simulates relationship between the throughput (Z) and the degree of fuzziness (γ). From all these simulations it is evident that the decision with the proposed CLPFR methodology is to be made with higher level-of-satisfaction with lesser degree of fuzziness. The characteristic simulations guide a DM in deciding his/her level-of-satisfaction with an allowable degree of fuzziness of the decision made.

Conclusion

It has been found from the CLPFR model that the throughput of the product mix problem under TOC is US$12,201.34. Hsu & Chung (1998) used dominance rule technique and their throughput was US$11,873 whereas Onwubolu and Mutingi (2001) tackled the same problem with a throughput of US$11,860. The TOC heuristic results in a throughput of US$14,100. TOC solution is not free from bottleneck and multiple constraint resources exist. Therefore, the previous solutions to the product mix problem of Hsu and Chung (1998) were not optimal. Bhattacharya and Vasant (2006), and Bhattacharya, Vasant, Sarkar, and Mukherjee (2006) tried to solve Hsu and Chung's (1998) product mix problem using a modified S-curve MF, which resulted in a robust solution. But their throughput was comparatively less than the solution presented in this chapter. *Table 7* elucidates a thorough comparison among all the solutions of the Hsu and Chung's (1998) product mix problem.

The proposed CLPFR model finds out a robust optimal solution to the Hsu and Chung's (1998) product mix problem. The fuzzy plots simulate DM's preferences in selecting his/her choice of level-of-satisfaction as per a predetermined degree of fuzziness while making the product mix decision. Further extension of the CLPFR model simulating with a suitably designed smooth logistic membership function (which is of course a more realistic assumption) may increase throughput trading off suitably among decision variables and other constraints.

Table 6. Throughput (Z) simulation at disparate fuzziness (γ) and level-of-satisfaction (ϕ) of the DM

Z / γ	$\mu = 1 - \phi$								
	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
3.0	11908	11889	11883	11880	11877	11876	11875	11874	11874
3.4	11918	11894	11886	11882	11879	11877	11876	11875	11874
3.8	11931	11901	11890	11884	11881	11878	11877	11875	11874
4.2	11946	1.1910	1.1912	0.0596	0.0403	0.0271	0.0176	0.0103	0.0046
4.6	0.3675	0.1923	0.1198	0.0798	0.0544	0.0368	0.0239	0.0140	0.0062
5.0	0.4498	0.2469	0.1575	0.1064	0.0732	0.0499	0.0326	0.0192	0.0086
5.4	0.5391	0.3118	0.2046	0.1408	0.0982	0.0675	0.0444	0.0264	0.0118
5.8	0.6323	0.3859	0.2617	0.1843	0.1306	0.0910	0.0605	0.0362	0.0164
6.2	0.7264	0.4671	0.3283	0.2373	0.1717	0.1217	0.0820	0.0496	0.0227
6.6	0.8186	0.5529	0.4027	0.2995	0.2220	0.1606	0.1102	0.0678	0.0314
7.0	0.9073	0.6403	0.4826	0.3697	0.2813	0.2084	0.1462	0.0918	0.0434
7.4	0.9912	0.7269	0.5655	0.4458	0.3485	0.2651	0.1908	0.1230	0.0596
7.8	1.0697	0.8110	0.6489	0.5253	0.4216	0.3294	0.2440	0.1621	0.0813
8.2	1.1427	0.8912	0.7307	0.6057	0.4982	0.3997	0.3049	0.2096	0.1095
8.6	1.2103	0.9670	0.8096	0.6851	0.5760	0.4736	0.3718	0.2649	0.1452
9.0	1.2729	1.0380	0.8848	0.7622	0.6532	0.5490	0.4427	0.3268	0.1887
9.4	1.3308	1.1043	0.9557	0.8358	0.7282	0.6239	0.5154	0.3935	0.2398
9.8	1.3843	1.1660	1.0222	0.9056	0.8002	0.6970	0.5882	0.4628	0.2973
10.2	1.4339	1.2235	1.0845	0.9714	0.8687	0.7674	0.6594	0.5329	0.3595
10.6	1.4799	1.2770	1.1428	1.0332	0.9334	0.8345	0.7283	0.6022	0.4246
11.0	1.5226	1.3269	1.1972	1.0911	0.9943	0.8980	0.7942	0.6698	0.4908
11.4	1.5625	1.3734	1.2480	1.1454	1.0515	0.9580	0.8568	0.7348	0.5566
11.8	1.5996	1.4169	1.2956	1.1963	1.1053	1.0145	0.9161	0.7969	0.6210
12.2	1.6344	1.4576	1.3401	1.2439	1.1558	1.0677	0.9721	0.8559	0.6833
12.6	1.6670	1.4957	1.3820	1.2887	1.2032	1.1178	1.0249	0.9119	0.7430
13.0	1.6976	1.5316	1.4212	1.3308	1.2479	1.1650	1.0747	0.9648	0.8000
13.4	1.7263	1.5653	1.4582	1.3705	1.2900	1.2095	1.1218	1.0149	0.8543
13.8	1.7534	1.5970	1.4931	1.4078	1.3296	1.2514	1.1662	1.0622	0.9058
14.2	1.7790	1.6270	1.5259	1.4431	1.3671	1.2910	1.2082	1.1070	0.9547
14.6	1.8032	1.6553	1.5571	1.4765	1.4025	1.3285	1.2479	1.1495	1.0011
15.0	1.8261	1.6822	1.5865	1.5081	1.4361	1.3641	1.2855	1.1897	1.0452
15.4	1.8478	1.7076	1.6144	1.5380	1.4679	1.3977	1.3213	1.2279	1.0870
15.8	1.8684	1.7318	1.6409	1.5665	1.4981	1.4297	1.3552	1.2641	1.1268
16.2	1.8880	1.7547	1.6661	1.5935	1.5268	1.4601	1.3874	1.2986	1.1646
16.6	1.9066	1.7766	1.6901	1.6192	1.5542	1.4891	1.4181	1.3314	1.2006
17.0	1.9244	1.7974	1.7130	1.6438	1.5802	1.5167	1.4474	1.3627	1.2350
17.4	1.9414	1.8173	1.7348	1.6672	1.6051	1.5430	1.4753	1.3926	1.2678
17.8	1.9576	1.8363	1.7556	1.6895	1.6288	1.5681	1.5019	1.4211	1.2991
18.2	1.9730	1.8544	1.7756	1.7109	1.6515	1.5922	1.5274	1.4484	1.3290
18.6	1.9878	1.8718	1.7946	1.7313	1.6733	1.6152	1.5518	1.4745	1.3577
19.0	2.0020	1.8884	1.8129	1.7509	1.6941	1.6372	1.5752	1.4995	1.3851
19.4	2.0156	1.9044	1.8304	1.7697	1.7140	1.6583	1.5976	1.5234	1.4115

Table 6. continued

Z / γ	$\mu = 1 - \phi$								
	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
19.8	2.0287	1.9197	1.8472	1.7877	1.7332	1.6786	1.6191	1.5464	1.4367
20.2	2.0412	1.9344	1.8633	1.8050	1.7516	1.6981	1.6397	1.5685	1.4610
20.6	2.0533	1.9485	1.8788	1.8217	1.7693	1.7168	1.6596	1.5897	1.4843
21.0	2.0649	1.9621	1.8937	1.8377	1.7863	1.7348	1.6787	1.6102	1.5067
21.4	2.0760	1.9751	1.9081	1.8531	1.8026	1.7521	1.6971	1.6298	1.5283
21.8	2.0868	1.9877	1.9219	1.8679	1.8184	1.7688	1.7148	1.6487	1.5491
22.2	2.0971	1.9999	1.9352	1.8822	1.8336	1.7849	1.7318	1.6670	1.5692
22.6	2.1071	2.0116	1.9481	1.8960	1.8482	1.8004	1.7483	1.6846	1.5885
23.0	2.1168	2.0229	1.9605	1.9094	1.8624	1.8154	1.7642	1.7016	1.6072
23.4	2.1261	2.0338	1.9725	1.9222	1.8761	1.8299	1.7795	1.7180	1.6252
23.8	2.1351	2.0444	1.9841	1.9346	1.8893	1.8439	1.7943	1.7339	1.6426
24.2	2.1438	2.0546	1.9953	1.9467	1.9020	1.8574	1.8087	1.7492	1.6595
24.6	2.1522	2.0645	2.0061	1.9583	1.9144	1.8705	1.8226	1.7641	1.6758
25.0	2.1604	2.0740	2.0166	1.9696	1.9263	1.8831	1.8360	1.7784	1.6915
25.4	2.1683	2.0833	2.0268	1.9805	1.9379	1.8954	1.8490	1.7923	1.7068
25.8	2.1759	2.0923	2.0366	1.9910	1.9492	1.9073	1.8616	1.8058	1.7216
26.2	2.1834	2.1010	2.0462	2.0013	1.9600	1.9188	1.8738	1.8189	1.7360
26.6	2.1906	2.1094	2.0554	2.0112	1.9706	1.9300	1.8857	1.8316	1.7499
27.0	2.1975	2.1176	2.0644	2.0208	1.9808	1.9408	1.8972	1.8439	1.7634
27.4	2.2043	2.1255	2.0731	2.0302	1.9908	1.9513	1.9083	1.8558	1.7765
27.8	2.2109	2.1332	2.0816	2.0393	2.0004	1.9616	1.9192	1.8674	1.7893
28.2	2.2173	2.1407	2.0898	2.0481	2.0098	1.9715	1.9297	1.8787	1.8016
28.6	2.2235	2.1480	2.0978	2.0567	2.0189	1.9811	1.9399	1.8896	1.8137
29.0	2.2296	2.1551	2.1056	2.0650	2.0278	1.9905	1.9499	1.9003	1.8254
29.4	2.2354	2.1620	2.1132	2.0732	2.0364	1.9997	1.9596	1.9106	1.8368
29.8	2.2412	2.1687	2.1205	2.0811	2.0448	2.0086	1.9690	1.9207	1.8478
30.2	2.2467	2.1752	2.1277	2.0888	2.0530	2.0172	1.9782	1.9305	1.8586
30.6	2.2522	2.1816	2.1347	2.0962	2.0609	2.0256	1.9871	1.9401	1.8691
31.0	2.2574	2.1878	2.1415	2.1035	2.0687	2.0338	1.9958	1.9494	1.8793
31.4	2.2626	2.1938	2.1481	2.1107	2.0763	2.0418	2.0043	1.9585	1.8893
31.8	2.2676	2.1997	2.1546	2.1176	2.0836	2.0496	2.0126	1.9673	1.8990
32.2	2.2725	2.2055	2.1609	2.1244	2.0908	2.0572	2.0207	1.9760	1.9085
32.6	2.2773	2.2111	2.1670	2.1309	2.0978	2.0647	2.0285	1.9844	1.9177
33.0	2.2820	2.2165	2.1730	2.1374	2.1046	2.0719	2.0362	1.9926	1.9268
33.4	2.2865	2.2219	2.1789	2.1437	2.1113	2.0790	2.0437	2.0006	1.9356
33.8	2.2909	2.2271	2.1846	2.1498	2.1178	2.0859	2.0510	2.0084	1.9442
34.2	2.2953	2.2322	2.1902	2.1558	2.1242	2.0926	2.0581	2.0161	1.9526
34.6	2.2995	2.2371	2.1956	2.1616	2.1304	2.0992	2.0651	2.0235	1.9608
35.0	2.3037	2.2420	2.2010	2.1673	2.1365	2.1056	2.0719	2.0308	1.9688

Figure 2. A surface and contour plot simulating the behavioural patterns of Z-values (using S-curve MF) with respect to the degree of possibility (μ) at disparate fussiness (γ)

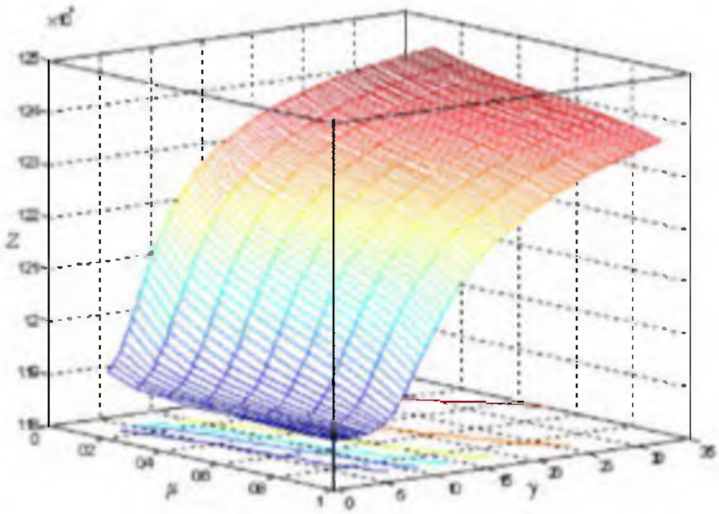


Figure 3. A 2-D contour simulation depicting relationship between the level-of-satisfaction (μ) and the degree of fuzziness (γ) of the decision made

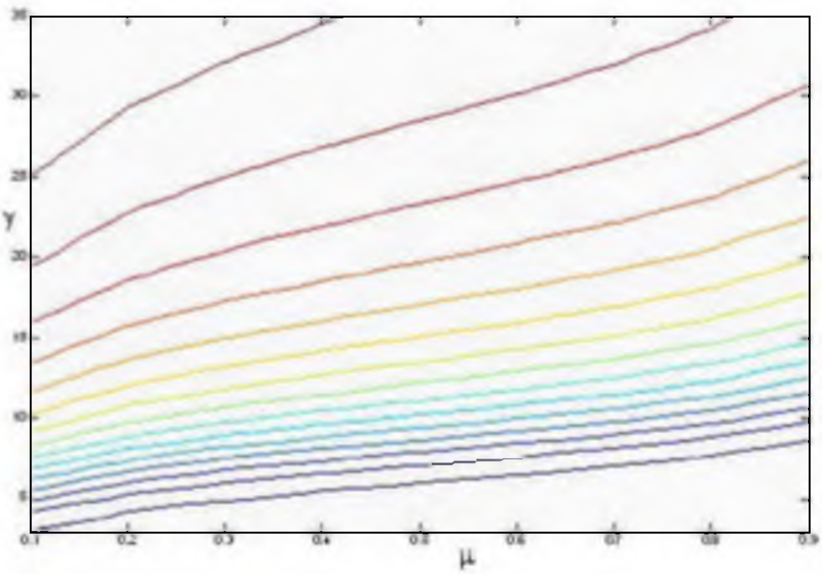


Figure 4. A 2-D contour characteristics simulation depicting relationship between the throughput (Z) and the degree of possibility (μ)

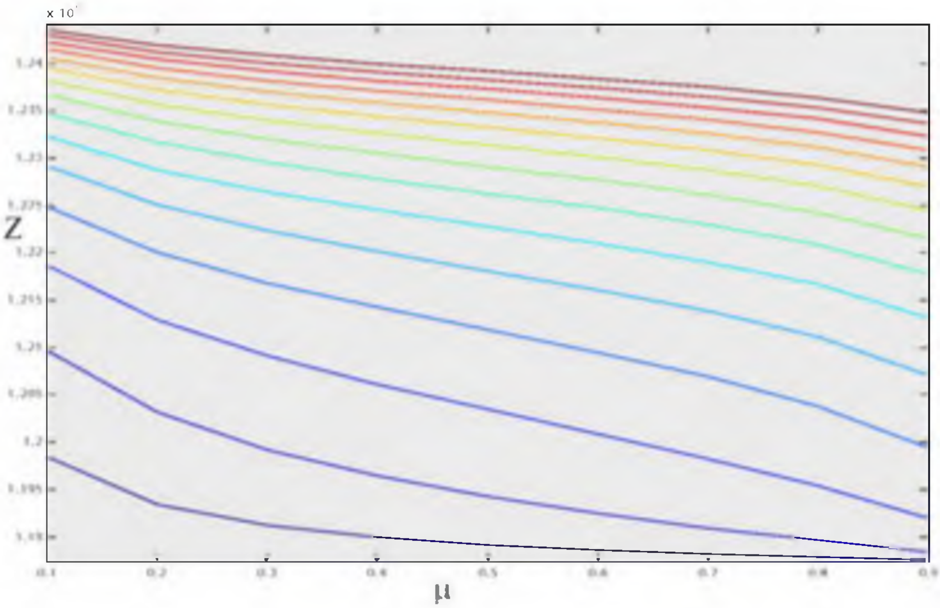


Figure 5. A 2-D contour characteristics simulation showing relationship between the throughput (Z) and the degree of fuzziness (γ)

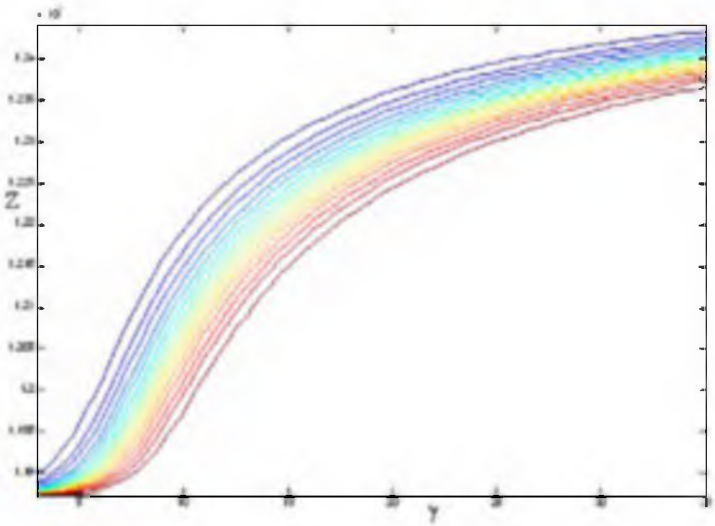


Table 7. Throughput comparison for the product-mix problem

Problem	No. of Resources	TOC solution	LP solution	Dominance rule solution (Hsu & Chung, 1998)	GA solution (Onwubolu & Mutingi, 2001)	FLP solution (Bhattacharya & Vasant, 2006)	CLPFR solution
Hsu & Chung (1998)	7	14100	----	11873	11860	11873	12201.34

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