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AN INTEGRATED MULTI-OBJECTIVE SUPPLY CHAIN MODEL IN A FUZZY ENVIRONMENT

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ABSTRACT

In today's global marketplace, the success of a supply chain (SC) depends on its managerial ability to integrate and coordinate business relationships among SC members. Ultimately, effectively integrated supply management results in lower costs, higher quality, better customer service, and higher profits for the organization, their suppliers, and their distributors. Recent advances in information technology provide an opportunity to the firms to integrate the planning of the fundamental stages, procurement, production and distribution, of the SCs. This paper provides a multi-objective production-distribution planning model. To provide a more realistic modeling structure by treating the vagueness in the target values of the SC partners' objectives, and to reduce the computational burden, fuzzy modeling approach is used in this paper. The model is implemented using linear programming (LP), goal programming (GP) and fuzzy goal programming (FGP) approaches. The application of these approaches to the integrated model is illustrated by means of a realistic numerical example and the results are compared.

Keywords: Supply chain modeling; Integrated production-distribution models; Fuzzy goal programming

ÖZET

Günümüz piyasalarının yüksek düzeydeki rekabetçi ve global yapısı, bunun yanında tedarik sürelerinin azaltılması yönündeki sürekli baskı sonucu kurumlar, tedarik zinciri yönetimini gelişmeleri için bir anahtar olarak görmektedir. Günümüzde firmalar bireysel olarak tek bir marka ile ve bağımsız bir şekilde rekabet etmektense belli tedarik zincirlerinin bir parçası konumundadırlar. Bu durumda, bir firmanın nihai başarısı tedarik zincirindeki iş ortakları arasındaki ilişki ağını bütünleştirebilme ve koordine edebilme konusundaki yönetimsel becerilerine bağlıdır.

Geleneksel bir dağıtım kanalı, bireysel olarak kârlarını enbüyüklemeye çalışan, birbirinden bağımsız imalatçı, toptancı ve perakendeci firmalardan oluşur. Ancak, bu yapı içerisinde bir bütün olarak sistemin kârı azalmaktadır. Son zamanlarda bünyesinde imalatçı, toptancı ve perakendeci firmaların bütünleşik olarak hareket ettikleri dikey dağıtım sistemleri ortaya çıkmıştır. Aslında tedarik zinciri yönetimi, imalatçı firmaların tedarikçilerini aynı yapı içerisine dahil etmektedir.

Bir tedarik zincirindeki temel işlemler; tedarik, üretim planlama ve kontrol ve dağıtımdır. "Uygun bir tedarik zinciri yapısı" kavramı son yıllarda oldukça yoğun bir şekilde tartışılmaktadır. Örneğin, tedarik zinciri tasarımı için kullanılan yöntem ve modeller konusunda ve tedarik zincirlerinin bulanık mantık ile modellenmesi üzerine çalışmalar yapılmaktadır. Günümüzde, zaman odaklı rekabet ve tam zamanında üretim trendi üretim ve dağıtım kararlarının bütünleşik olarak alınmasını gerektirmektedir.

Tedarik zincirleri birbirleri ile çelişebilen amaçlara sahip organizasyonların meydana getirdiği karmaşık ağlardır. Bu durum, kalitatif ve kantitatif amaçlar arasındaki etkileşimi açıkça dikkate alan bütünleşik tedarik, üretim ve dağıtım planlama kararlarında çok amaçlı bir yapı kullanılmasını gerekli kılmaktadır.

Gerçek hayatta, tedarik zincirleri bir şekilde belirsiz bir çevrede faaliyet göstermektedirler. Bu belirsizlik, amaçlara ait hedef değerlerinde, dış tedarikte, tedarik zinciri boyunca sağlanan tedarikte ve müşteri talebinde ortaya çıkabilmektedir. Bugüne kadar geliştirilen tedarik zinciri modellerinde, birkaç model hariç, bu belirsizlikler dikkate alınmamış veya olasılık yaklaşımı kullanılarak yaklaşık çözümler sunulmuştur. Ancak, standart olasılık metotları, özellikle geçmişe ait verilerin yetersiz olması veya verilerin doğruluğunun kesin olmaması durumunda uygun sonuçlar vermezler. Bu durumda, değerleri kesin olmayan parametreler yöneticilerin deneyimi veya sübjektif değerlendirmeleriyle belirlenebilir. Bulanık küme teorisi (Fuzzy Set Theory), belirsizliklerin ele alınmasında ve tanımlanmasında uygun bir yapı sağlamaktadır. Bu teori, karmaşık gerçek hayat problemlerine daha esnek ve uygun modeller oluşturulabilmesini sağlamaktadır. Son on yılda, çok amaçlı karar verme problemlerinin çözümünde kullanılmak üzere bulanık hedef programlama, interaktif bulanık çok amaçlı karar verme gibi çok sayıda bulanık programlama tekniği geliştirilmiştir.

Tedarik zinciri literatürünün pek de uzun olmayan geçmişi incelendiğinde bulanık küme teorisini kullanan az sayıda çalışma olduğu görülebilir. Bu makalede çok dönemli, çok ürünlü, ve çok üretim merkezli bir üretim-dağıtım modeli geliştirilmiştir. Bu model, kapasite ve stok denge kısıtları altında üretim, dağıtım ve stok tutma maliyetlerini enküçükleyen çok amaçlı bir yapıdadır. Karar vericilerin kesin olmayan hedef değerlerini modele dahil edebilmek amacıyla bulanık hedef programlama yaklaşımları kullanılmıştır. Bulanık modelleme yaklaşımlarının çözüm karmaşıklığı ve modelleme esnekliği açısından üstünlüğünü ortaya koymak amacıyla model, doğrusal programlama, hedef programlama ve bulanık hedef programlama yaklaşımları kullanılarak çözülmüştür.

Oluşturulan modeldeki üretim ve dağıtım sistemleri operasyonel olarak birbirine bağlı ve yakın ilişkilidir. Her birinde on üç adet ön işlem istasyonu ve yedi adet montaj istasyonu olan üç fabrika üretim sistemini oluşturmaktadır. Her bir fabrikada, iki temel proses (ön işlem ve montaj) kullanılarak yirmi farklı tipte ürün üretilmektedir. Fabrikaların üretim kapasitelerinin eşit olduğu varsayılmıştır. Her bir fabrikada toplam 298 işçi olup fabrikalardaki her bir montaj istasyonundaki işçi sayısı dönemsel olarak değişebilmektedir. Üretim sisteminde oluşan maliyetler olan stok tutma maliyetleri ve değişken üretim maliyetleri fabrikalar arasında farklılık göstermektedir. Dağıtım sistemi ise ürünlerin geçici olarak stoklandığı üç depo ve nihai ürünlerin talebinde başlangıç noktası olarak kabul edilen beş perakendeciden oluşmaktadır. Ürünler fabrikalardan depolara ve depolardan perakendecilere kamyonlarla taşınmaktadır. Bir kamyonun taşıma kapasitesi her bir ürün tipi için 1000 birimdir. Fabrikalardan depolara yapılan taşımaların maliyetleri depolama birimlerinin maliyet fonksiyonuna, depolardan perakendecilere yapılan taşımaların maliyeti ise perakendecilerin maliyet fonksiyonlarına dahil edilmiştir. Uygulamada dört aylık bir döneme ait üretim-dağıtım planı oluşturulmuştur. Ele alınan problemdeki fabrikaların tümü aynı firmaya aittir. Depolama birimlerinin tümü fabrikaların sahibi firmadan bağımsız olmak üzere tek bir firmaya aittir. Perakende firmaları ise birbirinden, fabrikaların ve depolama birimlerinin ait olduğu firmalardan bağımsız firmalardır. Tedarik zincirindeki her bir iş ortağı firmanın kendine özgü amaçları ve kısıtları vardır.

Önerilen model, literatürdeki bütünleşik tedarik zinciri modellerinden iki yönüyle farklılık göstermektedir. Birincisi, önerilen model daha gerçekçi bütünleşik bir tedarik zinciri yapısı sağlamaktadır. İkincisi, önerilen modelde kullanılan çözüm yaklaşımlarının farklılığıdır.

Bu çalışmada sunulan uygulama sonuçları göstermektedir ki bulanık hedef programlama yaklaşımları kullanılan diğer yaklaşımlara (doğrusal programlama ve hedef programlama) göre daha kısa sürede çözüm sağlamıştır. Bulanık modelleme ve çözüm yaklaşımlarının daha gerçekçi tedarik zinciri modelleri oluşturulmasında kullanılabileceği ortaya konmuştur.

INTRODUCTION

In the face of today's highly competitive and global markets, and constant pressure to reduce lead times, enterprises consider supply chain management to be the key area for improvement. Today, individual firms no longer compete as independent entities with unique brand names, but rather as integral part of SC links. As such, the ultimate success of a firm will depend on its managerial ability to integrate and coordinate the intricate network of business relationships among SC partners [1].

A supply chain is referred to as an integrated system which synchronizes a series of inter-related business processes in order to: 1) acquire raw materials and parts, 2) transform these raw materials and parts into finished products, 3) distribute these products to either retailers or customers, 4) facilitate information exchange among various business entities (e.g. suppliers, manufacturers, distributors, third-party logistics providers, and retailers). Its main objective is to enhance the operational efficiency, profitability, and competitive position of SC partners [2].

A conventional distribution channel consists of an independent manufacturer, wholesalers, and retailers each of which is a separate business entity seeking to maximize its own profit although this goal is known to eventually reduce profit for the system as a whole. Recently, vertical distribution systems which consist of the manufacturer, wholesalers, and retailers acting as an integrated system have evolved. In fact, supply chain management includes the suppliers of the manufacturer into the same framework [3].

The main processes in a SC are procurement, production planning and control, and distribution and logistics. The production planning and control describes the design and management of entire manufacturing process, such as material handling, scheduling and inventory control. The distribution and logistics process includes the management of inventory retrieval, transportation, and final product delivery [4, 5]. The concept of an appropriate SC is popularly discussed in recent years. For example, we find issues of model construction and methods for SC design [6, 7], fuzzy modeling of a SC [8,9,10], designing the green SC [11] etc. Today, time based competition and just-in-time trend in manufacturing requires integrating production and distribution decision processes. Different aspects of such integrated production-distribution systems are discussed in [5, 6, 7, 12, 13, 14, 15, 16, 17, 18 and 19].

SC is a complex network of organizations with conflicting objectives. This implies that the SC research needs to include multi-objective treatments of joint procurement, production, and distribution planning decisions that can explicitly consider tradeoffs among quantitative and qualitative objectives. Ashayeri and Rongen [20], Min and Melachrinoudis [21], Melachrinoudis and Min [22], and Nozick and Turnquist [23] can be given as some of the important researches in this concern.

In real world, SCs operate in a somehow uncertain environment. Uncertainty may be associated with target values of objectives, external supply, supply deliveries along the SC and customer demand etc. SC models developed so far, except a few ones, either ignored uncertainty or consider it approximately through the use of probability concepts [8]. A probability distribution is usually derived from evidence recorded in the past. However, when there is lack of evidence available or lack of certainty in evidence, the standard probabilistic reasoning methods are not appropriate. In this case, uncertain parameters can be specified based on the experience and managerial subjective judgment. Fuzzy Set Theory (FST) introduced by Zadeh [24], provides an appropriate framework to describe and treat these uncertainties.

FST helps to improve crisp models and provides more robust and flexible models for real-world complex decision problems, especially those involving human aspects. In the last decade, many fuzzy programming techniques such as FGP, interactive fuzzy multi-objective decision making have been developed for solving multi-objective decision making problems.

Scanning the not very long history of the SC literature one may see that there exist limited number of research that use FST. Petrovic et al. [8] developed a fuzzy generative SC model to determine target order-up-to levels of inventories under uncertain demand and external supply of raw materials. This model, however, were confined to a single product problem with no capacity constraint. Petrovic [10] extended this model by incorporating the element of uncertain lead times during the replenishment process into fuzzy model framework. Chen and Tzeng [9] use fuzzy multi-objective approach in order to reduce the computational complexity of their integrated SC model.

In this paper, a multi-period, multi-product and multi-plant production-distribution model is developed. The model is formulated as a multi-objective model which minimizes the costs of production, distribution and inventory holding subject to capacity and inventory balance constraints.

In order to incorporate the decision maker's imprecise aspiration levels for the goals FGP approaches are used. The model is implemented using different approaches such as LP, GP and FGP and the results are compared in order to indicate superiority of the fuzzy approaches in terms of computational burden and modeling flexibility.

The proposed model can be distinguished from the previous models on integrated SC in two ways. First, the proposed model provides more realistic integrated SC structure. Second, the proposed model distinguishes itself from previous models in the solution approaches used.

The paper is further organized as follows: In the next section, basic concepts and the frameworks of fuzzy multi-objective linear programming and FGP are presented. Integrated production-distribution system modeled in this study is described, and then, LP, GP and FGP formulations of the model are presented in the subsequent sections, respectively. Finally, computational results and conclusions are given in the last section.

FUZZY MULTI - OBJECTIVE LINEAR PROGRAMMING

Consider the following linear multi-objective model,

$$\begin{aligned} &\text{opt} \quad Z = CX \\ &\text{s.t.} \quad AX \le b \end{aligned} \qquad (1)$$

where $Z=(z_1, z_2, \ldots, z_k)^I$ is the vector of objectives, C is a K*N matrix of constants, X is an N*1 vector of the decision variables, A is an M*N matrix of constants, and b is an M*1 vector of constants. This model can be applied to solve many real-world problems. Fuzzy set theory can be useful in order to increase the model realism.

The fuzzy programming approach for handling the multi-objective problems was firstly introduced by Zimmermann [25]. Narasimhan [26], Ignizio [27], Wang and Wang [28] and Cadenas and Verdegay [29] investigated and developed the use of FST in solving problems with multiple goals.

Fuzzy version of the model (1) can be adopted according to Zimmermann [25] as follows;

$$\begin{aligned} &CX \succ Z \\ &\text{s.t. } AX \prec b \end{aligned} \qquad (2)$$

Where the symbols " $\prec$ and $\succ$ " denote the fuzzified versions of " $\le$ and $\ge$ " and can be read as "essentially less (greater) than or equal to".

To solve (2), Zimmermann [25] suggested a linear membership function for each goal $\mu_{1k}(C_k X)$, where

$$\mu_{1k}(C_k X) = \begin{cases} 1 & \text{if } C_k X \ge \bar{Z}_k, \\ 1 - \dfrac{(\bar{Z}_k - C_k X)}{d_{1k}} & \text{if } \bar{Z}_k - d_{1k} \le C_k X \le \bar{Z}_k \\ 0 & \text{if } C_k X \le \bar{Z}_k - d_{1k} \end{cases}$$

And another linear membership function $\mu_{2i}(a_i X)$ for the i[th] constraint in the system constraints $AX \le b$, where

$$\mu_{2i}(a_i X) = \begin{cases} 1 & \text{if } a_i X \le b_i \\ 1 - \dfrac{(a_i X - b_i)}{d_{2i}} & \text{if } b_i \le a_i X \le b_i + d_{2i} \\ 0 & \text{if } a_i X \ge b_i + d_{2i} \end{cases}$$

These membership functions are illustrated in Figure 1 and Figure 2 respectively. Where d_{1k} *(k=1,2,...,K)* and d_{2i} *(i=1,2,...,M)* are chosen constants of admissible violations, and a_i is the i^{th} row of matrix A [30]. Thus, to build a fuzzy multi-objective programming model, the decision maker may establish aspiration levels for the values of the objective functions to be minimized and maximized respectively, as well as each of the constraint may be modeled as a fuzzy set by specific membership functions. Hence, the conventional distinction between objectives and constraints no longer applies in the FLP models [31].

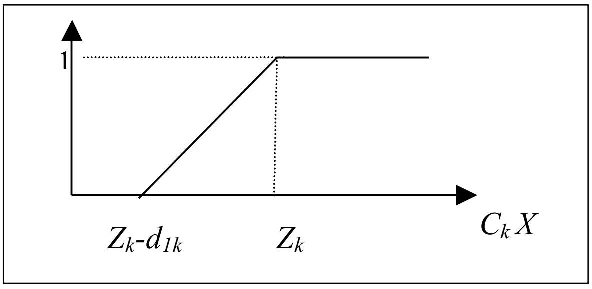


Fig. 1. *Membership Function of Fuzzy Goal*

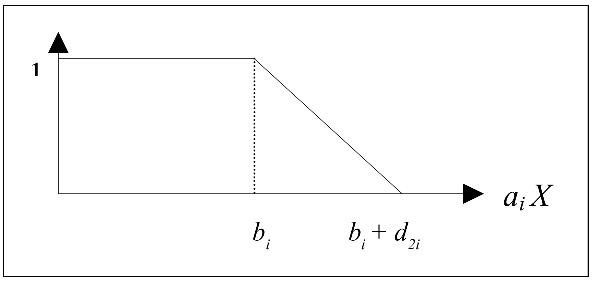


Fig. 2. *Membership Function of Fuzzy Constraints*

$\mu_{1k}(C_k X)$ and $\mu_{2i}(a_i X)$ denote the degree of the membership of goals and constraints respectively. The degree of the membership of goals and constraints express the satisfaction of the decision maker with the solution. So, values of the membership functions must be maximized [28].

In one of the fuzzy set theorems, the membership function of the intersection of any two (or more) sets is the minimum membership function of these sets. After eliciting the linear membership functions and by applying this theorem, objective function of the multi-objective linear programming model, incorporating the fuzzy goals and the fuzzy constraints, can be formulated as follows [32]:

$$\max_x \min(\mu_{11}(C_1 X), ..., \mu_{1k}(C_k X), \mu_{21}(a_1 X), ..., \mu_{2M}(a_M X))$$

By introducing the auxiliary variable λ, this problem can be equivalently transformed as:

$$\begin{array}{lll} \max & \lambda & \\ \text{s.t.} & \mu_{1k}(C_k X) \ge \lambda & k = 1,2,...,K \\ & \mu_{2i}(a_i X) \ge \lambda & i = 1,2,...,M \end{array}$$

According to above descriptions fuzzy linear program can be rewritten as following [30]:

$$\begin{array}{lll} \max & \lambda & \\ \text{s.t.} & \lambda \le 1 - (\overline{Z}_k - C_k X)/d_{1k} & k = 1,2,...,K \\ & \lambda \le 1 - (a_i X - b_i)/d_{2i,} & i = 1,2,...,M \\ & 0 \le \lambda \le 1 \text{ and } X \ge 0 & \end{array}$$

Fuzzy Goal Programming

Goal programming is one of the most powerful multi-objective decision making approaches. In a standard GP formulation, goals and constraints are defined precisely. In fact, very often it is a difficult job for a decision maker to find out what attainments are desired for each objective function [33].

Application of GP to the real life problems may be faced with two important difficulties; expressing the decision maker's vague goals and/or constraints mathematically and optimizing all goals simultaneously. The use of FST can be helpful in such situations [34].

Fuzzy Set Theory in GP was first considered by Narasimhan [26]. Narasimhan [35], Hannan [36] and Tiwari [37]-[38] extended the fuzzy theory to the field of GP. Ramik [33], Rao et al. [39], Wang and Fu [40], Mohamed [30], Ohta and Yamaguchi [41], El-Wahed and Abo-sinna [42], Mohammed [43] have investigated various aspects of decision problems using FGP theoretically.

If there are no priorities and also no relative importance assigned to objectives, formulation of the FGP model is same as in general FLP model. The main difference between FGP and FLP is that FLP uses the definite intervals determined from solutions of the LP models and so the solution does not change from decision maker to decision maker, whereas in FGP, aspiration levels are specified by decision maker and reflect relative flexibility [34].

In FGP, membership function values of each objective are replaced by the deviational variables in GP. This approach depends on the fact that the maximum value of any membership function is 1. Hence, maximizing any of them is equivalent to making it as close as possible to 1 [30].

Since some goals may be more important than others different priority levels are used in FGP formulations frequently. In order to reflect the relative importance of the goals, the weighted average of membership function values were used by Hannan [36]. Tiwari et al. [38] have proposed a weighted additive model that incorporates the weight of each goal into the objective function, i.e., $f(\lambda) = \sum_{k=1}^{K} w_k \lambda_k$, where w_k denotes the weight of the k^{th} fuzzy goal, and $\sum w_k = 1$. Weights in the weighted additive model reveal the relative importance of the fuzzy goals.

The structure of the production-distribution system modeled in this study is described in the following section.

THE INTEGRATED PRODUCTION-DISTRIBUTION PROBLEM

The production-distribution problems in SCs can be constructed in different forms. In this paper, a multi-period, multi-product and multi-plant production-distribution planning problem is dealt with. The production and distribution systems considered are operationally connected and closely related with each other. Three manufacturing plants, each has thirteen pretreatment stations and seven assembly lines, constitute the production system. Two main processes, pretreatment and assembly, are performed in each plant which produces twenty different types of product. Production capacities of the plants are assumed equal. The number of workers in each assembly line is allowed to be changed from period to period, however total number of workers is fixed to 298 in each plant. The costs incurred in the production system such as inventory holding cost and variable production cost vary from plant to plant.

The distribution system contains three warehouses where products are temporarily stored, and five retailers that are assumed the origin of the demand. Products are transported by trucks from plants to warehouses and moved from warehouses to retailers to satisfy their demands. The loading capacity of a vehicle is 1000 units for each type of product. Transportation costs from plants to warehouses and from warehouses to retailers are included in warehouses' and retailers' cost functions, respectively. The production-distribution plan for a four-month period is provided in the application.

It is assumed that all of the manufacturing plants belong to same company while the retailers are independent business entities. Additionally, all of the warehouses belong to same company independent of the other companies mentioned. It is also assumed that each partner involved in the SC has its own objectives and constraints.

MODEL DEVELOPMENT

The integrated production-distribution problem defined in the previous section is modeled using four different approaches: LP, GP, FGP and additive FGP. Through the model developed, it can be decided when and which product, how much of it should be produced at which plant, and should take which route to retailers and store how much of products at which storage points to satisfy the desired goals with in a certain period. Mathematical formulations of the model are presented in the following section.

The LP Model

Total cost of the SC is tried to minimize in the LP model. Production, inventory holding and shortage costs of manufacturing plants, and transportation, inventory holding, and shortage costs of retailers and warehouses are included in the total cost function. In the objective function, total cost of the manufacturing plants and total cost of the warehouses are represented by 'Procost' and 'Warecost', respectively. Additionally, Ret(1)cost, Ret(2)cost, Ret(3)cost, Ret(4)cost, and Ret(5)cost represent the retailers' costs. Mathematical formulations of these cost functions are presented in Table 1. Definition of the sets, the parameters and the decision variables are given as follows.

Sets

I : set of product type
J : set of pretreatment station
M : set of plant
P : set of warehouse
Q : set of retailer
S : set of assembly line
T : set of time period

Parameters:

a_{ij} : unit production time for product i in pretreatment station j

b_{is} : unit production time for product i in assembly line s

$CAPO_{jt}$: overtime capacity of pretreatment station j in period t (min)

$CAPOW_{jt}$: overtime weekend capacity of pretreatment station j in period t (min)

$CAPOA_{smt}$: overtime capacity of assembly line s of plant m in period t (min)

$CAPOAW_{smt}$: overtime weekend capacity of assembly line s of plant m in period t (min)

CP_{imt}: unit variable production cost of product i in plant m in period t

CO_{mt} : overtime cost per minute in plant m in period t

COW_{mt} : overtime weekend cost per minute in plant m in period t

$CTLP_{mpt}$: transportation cost per travel from plant m to warehouse p in period t

$CTPQ_{pqt}$: transportation cost per travel from warehouse p to retailer q in period t

$CTLQ_{pqt}$: transportation cost per travel from plant m to retailer q in period t

D_{iqt} : the quantity of product i demanded by retailer q in period t

$MinW_{sm}$: minimum workforce level that must be assigned in assembly line s of plant m

$MaxW_{sm}$: maximum workforce level that can be assigned in assembly line s of plant m

PR_t : regular time working capacity in man-hours per employee in period t (min)

PO_t : overtime working capacity in man-hours per employee in period t (min)

POW_t : overtime weekend working capacity in man-hours per employee in period t (min)

R_{jt} : available regular time of pretreatment station j in period t (min)

RA_{smt} : available regular time of assembly line s of plant m in period t (min)

SQ_{iqt} : unit holding cost of product i in retailer q in period t

SP_{ipt} : unit holding cost of product i in warehouse p in period t

SPP_{ip} : shortage cost of product i in warehouse p

SQQ_{iq} : shortage cost of product i in retailer q

TA_{mp} : transportation time from plant m to warehouse p

TB_{mq} : transportation time from plant m to retailer q

TC_{pq} : transportation time from warehouse p to retailer q

TBS : loading capacity of a vehicle per travel

TCS_{pt} : the available distribution time of warehouse p in period t

$TCSS_{qt}$: the available distribution time of retailer q in period t

TQ_q : product holding capacity of retailer q

TP_p : product holding capacity of warehouse p

NW: total number of workers to be assigned to assembly lines

Decision variables:

I_{imt} : inventory of product i in plant m at the end of period t

LP_{impt} : amount of product i transported from plant m to warehouse p in period t

LQ_{imqt} : amount of product i transported from plant m to retailer q in period t

O_{jmt} : overtime capacity used in pretreatment station j of plant m in period t

OW_{jmt} : overtime weekend capacity used in pretreatment station j of plant m in period t

OA_{smt} : overtime capacity used in assembly line s of plant m in period t

OAW_{smt} : overtime weekend capacity used in assembly line s of plant m in period t

P_{ipt} : amount of end of period inventory of product i in warehouse p in period t

PL_{imt} : amount of end of period deficit of product i in plant m in period t

PQ_{ipqt} : amount of product i transported from warehouse p to retailer q in period t

Q_{iqt} : amount of end of period inventory of product i in retailer q in period t

QL_{iqt} : amount of end of period deficit of product i at retailer q in period t

TLP_{mpt} : the number of travel needed from plant m to warehouse p in period t

TLQ_{mqt} : the number of travel needed from plant m to retailer q in period t

TPQ_{pqt} : the number of travel needed from warehouse p to retailer q in period t

X_{imt} : production quantity of product i in plant m in period t

W_{smt} : workforce level assigned to assembly line s of plant m in period t (min)

WL_{ipt} : amount of end of period deficit of product i at warehouse p in period t

The mathematical statement of the model is as follows:

$$\begin{aligned}\text{Min}\quad & \text{Procost} + \text{Ret}(1)\text{cost} + \text{Ret}(2)\text{cost} + \text{Ret}(3)\text{cost} \\ & + \text{Ret}(4)\text{cost} + \text{Ret}(5)\text{cost} + \text{Warecost}\end{aligned}$$

s.t.

$$\sum_{i=1}^{20} a_{ij} X_{imt} - R_{jt} - O_{jmt} - OW_{jmt} \le 0 \quad \forall j, m, t \tag{3}$$

$$\sum_{i=1}^{20} b_{is} X_{imt} - RA_{smt} - OA_{smt} - OAW_{smt} \le 0 \quad \forall m, s, t \tag{4}$$

$$X_{imt} + I_{imt-1} - I_{imt} + PL_{imt} = DEM_{imt} \quad \forall i, m, t \tag{5}$$

$$\sum_{m}^{3} DEM_{imt} = DEMAND_{it} \quad \forall i, t \tag{6}$$

$$X_{imt} + I_{imt-1} - I_{imt} = \sum_{p}^{3} LP_{impt} + \sum_{q}^{5} LQ_{imqt} \quad \forall i, m, t \tag{7}$$

$$\begin{aligned} O_{jmt} - CAPO_{jt} \le 0 \quad & \forall j, m, t \\ OW_{jmt} - CAPOW_{jt} \le 0 \quad & \forall j, m, t \end{aligned} \tag{8}$$

$$\begin{aligned} OA_{smt} - CAPOA_{smt} \le 0 \quad & \forall s, m, t \\ OAW_{smt} - CAPOAW_{smt} \le 0 \quad & \forall s, m, t \end{aligned} \tag{9}$$

$$\begin{aligned} RA_{smt} - PR_t\, W_{smt} = 0 \quad & \forall s, m, t \\ CAPOA_{smt} - PO_t\, W_{smt} = 0 \quad & \forall s, m, t \\ CAPOAW_{smt} - POW_t\, W_{smt} = 0 \quad & \forall s, m, t \end{aligned} \tag{10}$$

$$\sum_{s=1}^{7} W_{smt} = NW \quad \forall m,t$$
$$W_{smt} - MinW_{sm} \geq 0 \quad \forall s,m,t \quad (11)$$
$$MaxW_{sm} - W_{smt} \geq 0 \quad \forall s,m,t$$

$$P_{ipt-1} + \sum_{m}^{3} LP_{impt} + WL_{ipt} - P_{ipt} = \sum_{q}^{5} PQ_{ipqt} \quad \forall i,p,t \quad (12)$$

$$P_{ipt-1} + \sum_{m}^{3} LP_{impt} - P_{ipt} = \sum_{q}^{5} PQ_{ipqt} \quad \forall i,p,t \quad (13)$$

$$Q_{iqt-1} + \sum_{p}^{3} PQ_{ipqt} + \sum_{m}^{3} LQ_{imqt} + QL_{iqt} - Q_{iqt} = D_{iqt} \quad \forall i,q,t \quad (14)$$

$$\sum_{i}^{20} Q_{iqt} \leq TQ_q \quad \forall q,t \quad (15)$$

$$\sum_{p}^{3} P_{ipt} \leq TP_p \quad \forall p,t \quad (16)$$

$$\sum_{m}^{3} TA_{mp}\, TLP_{mpt} \leq TCS_{pt} \quad \forall p,t \quad (17)$$

$$\sum_{m}^{3} TB_{mq}\, TLQ_{mqt} + \sum_{p}^{3} TC_{pq}\, TPQ_{pqt} \leq TCSS_{qt} \quad \forall qt \quad (18)$$

$$TLP_{mpt} \geq [(\sum_{i}^{20} LP_{impt}) / TBS] \quad \forall m,p,t \quad (19)$$

$$TLQ_{mqt} \geq [(\sum_{i}^{20} LQ_{imqt}) / TBS] \quad \forall m,q,t \quad (20)$$

$$TPQ_{pqt} \geq [(\sum_{i}^{20} PQ_{ipqt}) / TBS] \quad \forall p,q,t \quad (21)$$

$$X_{imt}, I_{imt}, PL_{imt}, DEM_{imt} \geq 0 \quad \forall i,m,t$$
$$O_{jmt}, OW_{jmt} \geq 0 \quad \forall j,m,t$$
$$OA_{smt}, OAW_{smt}, W_{smt} \geq 0 \quad \forall s,m,t$$
$$P_{ipt}, WL_{ipt} \geq 0 \quad \forall i,p,t$$
$$Q_{iqt}, QL_{iqt} \geq 0 \quad \forall i,q,t$$
$$LP_{impt} \geq 0 \quad \forall i,m,p,t \quad (22)$$
$$LQ_{imqt} \geq 0 \quad \forall i,m,q,t$$
$$PQ_{ipqt} \geq 0 \quad \forall i,p,q,t$$

Total production quantity of each pretreatment station and each assembly line per period is limited by the available production capacity that also includes overtime and overtime-weekend by constraint (3) and (4) respectively. Constraint (5) ensures that the amount of demand met by plant m in period t plus the inventory of that product at the end of the period equals the total supply consisting of the inventory from the previous period or the amount of lost sales plus the production in the current period. Constraint (6) provides the allocation of total demand of each product in period t to plants as their individual demand.

Constraint (7) is the balance equation for the product inventory of the plants in period *t*: the amount of product stored in plant *m* in period *t* is the sum of the amount of product produced in period *t* and the amount of product stored in the previous period and subtract the amount of product transported from the plant to warehouses or retailers. Constraint (8) limits the overtime and overtime weekend capacity of the pretreatment stations to the available plant capacity while (9) is used to limit overtime and overtime weekend capacity of the assembly lines of each plant to the available plant capacity in period *t*.

Constraint (10) is used to determine the available plant capacity corresponding to the changing workforce level. Constraint (11) is used to set the limit of maximum and minimum available workforce level to assign for the assembly lines of each plant in the current period. In addition, constraint (11) ensures that total assigned workforce level must be equal to total available workforce level in the current period in plant *m*. Constraint set (12) is the balance equations for the inventory of the warehouses. Constraint (13) is the balance equation for the warehouse *p*: the amount of products that enter to the warehouse must be equal to the amount of products that leave from and stored at the warehouse. Constraint (14) is the balance equation for the inventory of retailer *q* in period *t*. Constraints (15) and (16) limits the product holding capacity for retailers and warehouses respectively. Constraints (17) and (18) are the distribution time constraints for warehouses and retailers in period *t*. Constraint (19)-(21) determines the number of travel in period *t* to transport the products from plants to warehouses, from plants to retailers, and from warehouses to retailers respectively. Constraint set of (22) enforce the non-negativity restriction on the decision variables.

GP Model

In this model, there are seven main goals that are based on personal opinions or subjective judgments of the decision makers of the SC members. The objective of manufacturing plants is to maximize the total profit while warehouses want to minimize their total costs. Additionally, each retailer involved in the SC has its own objective of minimizing their costs and meeting their demand. Maximizing the profit of the plants has the highest priority among the objectives. Minimization of the cost of retailer 1 and retailer 2 are the objectives with second and third priority respectively while minimization of the total cost of warehouses is the objective with fourth priority. Finally, minimization of the costs of retailer 3, 4 and 5 are the objectives which are given the fifth, sixth and the seventh priorities respectively.

Table 1. *Mathematical Formulations of the Objective Functions*

Objective Function		Mathematical Formulation
Profit		$\sum_{i=1}^{20}\sum_{m=1}^{3}\sum_{t=1}^{4}(X_{imt}PRC_i) - \left[\begin{array}{l}\sum_{i=1}^{20}\sum_{m=1}^{3}\sum_{t=1}^{4}(CP_{im}X_{imt}+CI_{im}I_{imt}+CL_{im}PL_{imt})+\\ \sum_{j=1}^{13}\sum_{m}^{3}\sum_{t}^{4}(CO_m O_{jmt}+COW_m OW_{jmt})+\\ \sum_{s=1}^{7}\sum_{m}^{3}\sum_{t}^{4}(CR_m RA_{smt}+CO_m OA_{smt}+COW_m OAW_{smt})\end{array}\right]$
Production Cost of plants (Procost)		$\sum_{i=1}^{20}\sum_{m=1}^{3}\sum_{t=1}^{4}(CP_{im}X_{imt}+CI_{im}I_{imt}+CL_{im}PL_{imt})+$ $\sum_{j=1}^{13}\sum_{m}^{3}\sum_{t}^{4}(CO_m O_{jmt}+COW_m OW_{jmt})+$ $\sum_{s=1}^{7}\sum_{m}^{3}\sum_{t}^{4}(CR_m RA_{smt}+CO_m OA_{smt}+COW_m OAW_{smt})$
Cost of Retailer q (Ret(1)cost,…,Ret(5)cost)		$\sum_{i}^{20}\sum_{t}^{4}(SQ_{iq}Q_{iqt}+SQQ_{iq}QL_{iqt})+\sum_{m}^{3}\sum_{t}^{4}(TLQ_{mqt}CTLQ_{mq})+\sum_{p}^{3}\sum_{t}^{4}(TPQ_{pqt}CTPQ_{pq})$
Total warehouse cost (Warecost)		$\sum_{i}^{20}\sum_{p}^{3}\sum_{t}^{4}(SP_{ip}P_{ipt}+SPP_{ip}WL_{ipt})+\sum_{m}^{20}\sum_{p}^{3}\sum_{t}^{4}(TLP_{mpt}LPC_{mp})$

Target values of these goals are assigned directly by decision makers. These values are presented in Table 2.

Considering the given priority levels, the GP model can be formulated as follows:

$$\text{Min} \quad P_1(d_1^-)+P_2(d_3^+)+P_3(d_4^+)+P_4(d_2^+)$$
$$+P_5(d_5^+)+P_6(d_6^+)+P_7(d_7^+)$$

s.t.

$$\text{Profit} \quad +d_1^- - d_1^+ = 40.000.000$$
$$\text{Warecost}+d_2^- - d_2^+ = 900.000$$
$$\text{Ret(1)cost}+d_3^- - d_3^+ = 600.000$$
$$\text{Ret(2)cost}+d_4^- - d_4^+ = 200.000$$
$$\text{Ret(3)cost}+d_5^- - d_5^+ = 450.000$$
$$\text{Ret(4)cost}+d_6^- - d_6^+ = 330.000$$
$$\text{Ret(5)cost}+d_7^- - d_7^+ = 450.000$$

and system constraints (3)…(22)

Table 2. *Target Values in the GP Model.*

Objective Function		Target Value
Profit		40000000
Ret1cost		600000
Ret2cost		200000
Ret3cost		450000
Ret4cost		330000
Ret5cost		450000
Warecost		900000

FGP Model

In FGP model, aspiration levels are specified by decision maker and reflect relative flexibility. While the decision maker decides his fuzzy aspiration levels, the LP results are starting points and the intervals are covered by LP solutions. For example, although the target value of the profit maximization objective was 42,000,000 in LP solution, fuzzy aspiration levels assigned to profit objective by the decision maker are expressed as acceptable intervals including flexibility. Then the lower and upper bounds may be determined as 38,000,000 and 42,000,000 respectively.

Aspiration levels $[L_k,U_k]$ for FGP model are determined as in Table 3. After constructing aspiration levels with respect to the linguistic terms of "approximately less than or equal to", "approximately greater than or equal to" and "around", the fuzzy membership functions can be defined for each goal in the same manner.

Table 3. *Aspiration Levels in FGP Model*

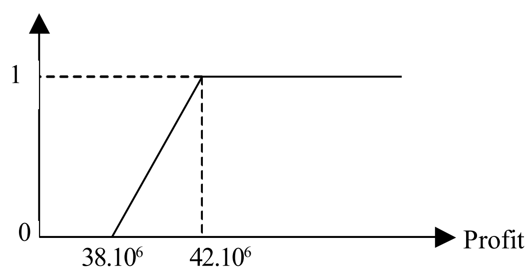
Objective Function			Min (L_k)	Max (U_k)
Z_1	Profit		38000000	42000000
Z_2	Ret1cost		650000	750000
Z_3	Ret2cost		300000	400000
Z_4	Ret3cost		400000	500000
Z_5	Ret4cost		300000	400000
Z_6	Ret5cost		350000	400000
Z_7	Warecost		800000	1100000

Membership functions of 'profit' and 'warecost' objectives are presented below as examples:

$$\mu_1 = \begin{cases} 0 & \text{if } z_1 \le 38000000 \\ \dfrac{z_1 - 38.10^6}{42.10^6 - 38.10^6} & \text{if } 38000000 < z_1 < 42000000 \\ 1 & \text{if } z_1 \ge 42000000 \end{cases}$$

$$\mu_7 = \begin{cases} 1 & \text{if } z_7 \le 800000 \\ \dfrac{1100000 - z_7}{1100000 - 800000} & \text{if } 800000 < z_7 < 1100000 \\ 0 & \text{if } z_7 \ge 1100000 \end{cases}$$

We can illustrate these piecewise linear membership function shapes as follows:



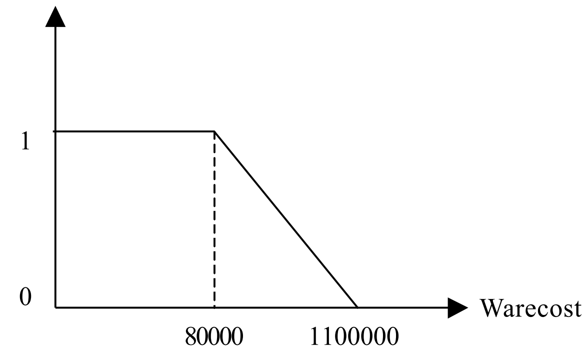


Fig. 3. *Membership Functions of the Objectives*

As mentioned in the previous sections, the membership function of the intersection of any two (or more) sets is the minimum membership function of these sets. After eliciting the linear membership functions and by applying to this theorem, the objective function can be formulated as follows:

$$\max_x \min\begin{pmatrix} \mu_1(Z_1), \mu_2(Z_2), \mu_3(Z_3), \mu_4(Z_4), \\ \mu_5(Z_5), \mu_6(Z_6), \mu_7(Z_7) \end{pmatrix}$$

By introducing the auxiliary variable, λ, this problem can equivalently be transformed as:

$$\begin{aligned} \max \quad & \lambda \\ \text{s.t.} \quad & \mu_1(Z_1) \geq \lambda \\ & \mu_2(Z_2) \geq \lambda \\ & \vdots \quad \vdots \quad \vdots \\ & \mu_7(Z_7) \geq \lambda \\ & 0 \leq \lambda \leq 1 \end{aligned}$$

and system constraints (3)...(22)

Then, FGP model can be written as follows:

max λ

s.t.

$$\lambda \leq \frac{(Z_1 - 38000000)}{4000000}, \ \lambda \leq \frac{(750000 - z_2)}{100000}$$

$$\lambda \leq \frac{(400000 - z_3)}{100000}, \ \lambda \leq \frac{(500000 - z_4)}{100000}$$

$$\lambda \leq \frac{(400000 - z_5)}{100000}, \ \lambda \leq \frac{(400000 - z_6)}{50000}$$

$$\lambda \leq \frac{(1100000 - z_7)}{300000}$$

$0 \leq \lambda \leq 1$ and system constraints (3)...(22)

Additive FGP Model

In this model, weighted additive structure of Tiwari et al. [38] that incorporates weights for each goal into the objective function is used. Using additive FGP approach, weighted sum of the achievement levels are maximized instead of individual achievement levels of SC partners' goals. However, we assumed there are no priorities and also no relative importance assigned to the objectives. Therefore, all weights considered are equal to one. Additive FGP model maximizes the sum of the achievement level of the fuzzy goals. Aspiration levels presented in Table 3 are used at the solution stage to reflect the relative flexibility.

Additive FGP model can be formulated as follows:

$$\max \quad \sum_{k=1}^{7} \lambda_k$$

s.t.

$$\lambda_1 \leq \frac{(Z_1 - 38000000)}{4000000}, \ \lambda_2 \leq \frac{(750000 - z_2)}{100000}$$

$$\lambda_3 \leq \frac{(400000 - z_3)}{100000}, \ \lambda_4 \leq \frac{(500000 - z_4)}{100000}$$

$$\lambda_5 \leq \frac{(400000 - z_5)}{100000}, \ \lambda_6 \leq \frac{(400000 - z_6)}{50000}$$

$$\lambda_7 \leq \frac{(1100000 - z_7)}{300000}$$

$0 \leq \lambda_k \leq 1$

and system constraints (3)...(22)

COMPUTATIONAL RESULTS

The integrated production-distribution model developed in this study is implemented by using four different approaches: LP, GP, FGP and additive FGP. Computational results are presented in Table 4. As can be seen from this table, the highest profit value, 41120500, is obtained by using LP. However, total cost value, 3668698, and the difference of the cost values among retailers' and of warehouse is relatively high. Target levels determined by decision makers for each objective are considered by using GP. Target levels for profit, warehouse cost, and for retailer 3 and 4 costs are exactly satisfied while there are positive deviations in the target levels of retailer 1, 2 and 5. The deviation in the target level of retailer 5 cost is the highest one: $d_5^+ =$ 417601 (92.8 %), because minimization of the retailer 5 cost has the lowest priority among the goals.

Table 4. *Computational Results*

	Solution Approach			
Objective Function	LP	GP	FGP (λ=0,4132)	Additive FGP
Profit	41120500	40000000	39253500	38523860 (λ=0,175)
Ret1cost	898344	684801	708216	684801 (λ=0,652)
Ret2cost	269721	490765	358216	300000 (λ=1,000)
Ret3cost	463789	450000	458216	400000 (λ=1,000)
Ret4cost	331352	330000	358216	317184 (λ=0,828)
Ret5cost	400978	867601	379108	367680 (λ=0,646)
Warecost	1304514	900000	974650	1062686 (λ=0,124)
Total Cost (except production cost of the plants)	3668698	3723167	3236622	3132351

In FGP model, relative flexibility is reflected by decision maker through aspiration levels. FGP approach allows the tradeoff among SC partners' goals and maximizes the minimum auxiliary variable λ by using 'max λ' as the objective function. In this way, all partners' objectives in the SC are considered simultaneously. The results obtained through FGP approach show that cost of retailer 5 is reduced extensively while the cost of retailer 1, 3, and 4 increase in small amounts. As can be seen from the results, if production plants sacrifice a small portion (1.86 %) of their profits, retailer 5's cost can be reduced extensively (56.3 %) compared to the solution of GP. It is obvious that, FGP may provide SC partners to increase their level of satisfaction by considering all of the goals simultaneously. According to FGP solution, the value of λ (global achievement level) is 0.41.

Additive FGP model is used to maximize the total achievement degrees of fuzzy goals. The values of auxiliary variables, λ, obtained by solving additive FGP model are also presented in Table 4. Although the achievement levels, λ, for profit (0.18), and for warehouse cost (0.124) are relatively low, the total cost value (3132351) is minimum compared to the other solutions presented. Here, the goals of all of SC partners are given the same weight.

CONCLUSION

Today, time based competition, JIT, and globalization trends require integrating production and distribution decision processes in SCs. In this paper, an integrated production-distribution system in a SC environment is modeled.

Regarding the benefits of all partners in a SC is crucial to provide the collaboration and effectiveness. Considering this, multi-objective approach is used in the model. To provide a more realistic modeling structure by treating the vagueness in the target values of the SC partners' objectives, and to reduce the computational burden, fuzzy modeling approach is used in this paper. The model is implemented using linear programming (LP), goal programming (GP) and fuzzy goal programming (FGP) approaches. It can be concluded from the results that FGP is an effective approach in providing alternative solutions for integrated SC planning problems. The results support our view that fuzzy modeling approach may generate more realistic and satisfactory solutions with relatively less computational burden for integrated SC models.

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