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A novel mathematical model to design an agile supply chain for perishable products

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ABSTRACT

This paper proposes a novel multi-objective mathematical model to design a multi-product agile supply chain (ASC) in which one of the most useful utilities in the field of no waste system is considered. The proposed ASC network include different levels of plants, warehouse facilities, distribution facilities, customers in the forward logistics flow, and collection, repair, recycling and disposal facilities for the reverse logistics flow. The objective functions are to minimize the total cost, minimization of lead time, minimization of risk and maximization of flexibility. As the model is multi-objective, the fuzzy goal programming (FGP) method is then applied to deal with the multi-objectiveness of the model. To validate the proposed model, the GAMS software and CPLEX solver is used to solve several test problem instances in different sizes. These problems are then analysed under different conditions using sensitivity analyses. It is revealed that the proposed model has the appropriate performance to obtain efficient optimal solutions.

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1. Introduction

One of the most important factors for improving the financial and operational performance of organizations is applying an agile structure in the supply chain of the organization. In general, the agility of the supply chain is flexible while considering two factors of the timely and cost-effective meeting of customer demands and considering an unpredictable environment for product supply [1]. On the other hand, considering the conditions of supply chain should be of concern. Therefore, one of the most important aspects of the global management is supply chain management, and more importantly, risk management of the supply chain in the organization. Moreover, benefiting from the learning phenomenon is one of

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the most effective factors that improve agility. Organizations perform some tasks continuously in order to make organizational improvements and minimize the range of sudden change while taking steps toward enhancement and learning [2]. Marchi et al. [3] and Mukherjee et al. [4] confirmed a decrease in costs, an increase in the pace of production process, an increase in product quality, and a decrease in malfunction and rework following the implementation of a mathematical model and presenting an algorithm. Willis et al. [5] evaluated the function of learning, integration, and flexibility to determine the important role of integration in a supply chain. According to the results, learning increased flexibility in the supply chain. In another study, Mahmoodi [6] introduced a four-level, three-objective model assuming several types of raw materials and different types of products from a supply chain network. The main objectives of the mentioned study were to minimize costs, reduce risks and increase flexibility in the supply chain. According to Khorasani [7], agile supply chain systems increased the company's ability to survive in an unpredictable business environment. This scholar proposed new indexes for the optimization of an agile and flexible supply chain by using modeling techniques.

Conceptual models are often presented to study agile supply chains. Therefore, the present study aimed to determine the effect of flexibility and lead time on the agility of the organization and implement it in the form of a mathematical model. Supply chains have become more vulnerable to disruption due to changes in logistic systems and supply chains in the past few decades, such as globalization, reduced inventories, and an increased tendency toward outsourcing. In order to prevent possible threats that may be caused by the mentioned phenomena, managers use the concept of supply chain risk management, which seeks to coordinate supply chain components in the use of risk management tools and deal with uncertainties occurred by logistics-related activities [8]. Moradi et al. proposed an integrated approach of pricing and network design for an agile supply chain. In this research, uncertainty in demand was considered in fuzzy form, and three objectives of reducing costs, decreasing lead time, and increasing flexibility were optimized [9]. Piya et al. [10] evaluated the relationship between agility and supply chain network design. The foregoing study was specifically carried out in the field of oil and gas, and the most important factors of an agile supply chain in the oil and gas industry were assessed through field studies. Moreover, Kalaboukas et al. [11] assessed the implementation of an agile supply chain, for which an operational mathematical model was proposed. In another research, Ahmad & Huma [12] evaluated supply chain risk strategies in a detailed study. These researchers assessed a lean and agile supply chain and 140 supply chains at a professional level [13]. According to their results, approaches such as robust improvement and resilience were the most important improvement strategies for a lean and agile supply chain [14-15].

In the present study, the proposed model is a multi-objective, multiproduct, multilayer, and multi-period supply chain network, studied by using the learning phenomenon. A literature review revealed that this was the first time that the topic of risk management and learning is presented in the form of a mathematical model along with two important agility indexes (i.e., flexibility and lead time). In general, the innovations of the model are as follows [16-17]:

- Considering an increase in the flexibility index along with a function with the objective of lead time minimization as a factor to increase supply chain agility
- Applying the learning phenomenon in the production process, which leads to the reduction of production costs and increase of production at equal or shorter periods.
- Considering a function with the objective of maximization of flexibility while minimizing the risk of supply chain

The proposed model is solved by fuzzy goal programming and Torabi and Hassini (TH) methods [9], which are the suitable methods for the multi-objective problems.

2. Materials and Methods

2.1 Mathematical Modelling of Problem

The present study considers a four-objective, three-layer, multi-period, and multiproduct supply chain network problem. In this model, the first-fourth objective functions seek to minimize costs, minimize the lead time, increase flexibility and decrease risk levels, respectively. In addition, attempts are made to reduce production costs by directing the system toward an even-learning one. On the other hand, it is aimed to reduce the system's vulnerability through continuous risk assessment due to emphasis on flexibility and dealing with sudden changes and associated consequences.

Indexes:

p	Index of Producers
m	Index of Raw Material
t	Index of Time Periods
c	Index of Customers
i	Index of Products
l	Index of Transportation Systems
d	Index of Distributers
s	Index of Suppliers

Parameters:

fos_{st}	Fixed cost of opening s-th supply section in t-th period
fop_{pt}	Fixed cost of opening p-th plant in t-th period
fod_{dt}	Fixed cost of opening d-th distribution center in t-th period
de'_{ict}	Demand of c-th customer for i-th product in t-th period based on demand forecast
p1	Probability obtained by forecasting demand
de_{ict}	Demand of c-th customer for i-th product in t-th period
pc_{ict}	Production cost of each i-th product unit in p-th plant in t-th period
hcd_{idt}	Cost of storage of each i-th product unit in d-th distribution system in t-th period
stp_{splt}	Time of transportation from s-th supplier to p-th plant by l-th transportation system in t-th period
stc_{dclt}	Transportation time from the d-th distribution system to the c-th customer by l-th transportation system in t-th period
$Trc2_{ipdlt}$	Cost of transportation of each i-th product unit from the p-th plant to the d-th distribution system by l-th transportation system in t-th period
$dis1_{spl}$	Distance from s-th supplier to p-th plant by the transportation system
$dis3_{dcl}$	Distance from d-th distribution system to c-th customer by l-th transportation system
rp_{ipt}	Risk of production of i-th product from p-th producer in t-th period
srf_{ist}	Consequence (financial loss) of supply chain risk from s-th supplier in t-th period
drf_{idt}	Consequence (financial loss) of risk of i-th product distribution by d-th distributor in t-th period
crp_{ipt}	Cost of reducing the production risk of i-th product from p-th producer in t-th period
mr_{it}	The highest acceptable risk for i-th product in t-th period
lcs	Low limit of supplier capacity
lcp	Low limit of plant capacity
lcd	Low limit of distribution system capacity
θ	Total time available for production in each period
Φ^{min}_{ip}	The shortest production time of each i-th product unit
λ_{ip}	Learning rate per production of each i-th product unit
fus_{st}	Fixed cost of using s-th supply sector in t-th period
fup_{pt}	Fixed cost of using p-th plant in t-th period
fus_{dt}	Fixed cost of using d-th distribution center in t-th period
de''_{ict}	Demand of c-th customer for i-th product in t-th period based on market study
p1	Probability obtained through market study
N	Big number
Hcp_{ipt}	Cost of maintaining each i-th product unit in p-th plant in t-th period
mi_{id}	Minimum inventory of i-th product in d-th distribution system
std_{pdlt}	Time of transportation from p-th plant to d-th distribution system by l-th transportation system in t-th period
$Trc1_{msplt}$	Transportation cost of each m-th raw material unit from s-th supplier to p-th plant by l-th transportation system in t-th period
$Trc3_{idclt}$	Transportation cost of each i-th product unit from d-th distribution system to c-th customer by l-th transportation system in t-th period
$dis2_{sdl}$	Distance from p-th plant to d-th distribution system by l-th transportation system
rs_{ist}	Risk of supplying i-th product from s-th supplier in t-th period
rd_{idt}	Risk of i-th product from d-th supplier in t-th period
prf_{ipt}	Consequence (financial loss) of risk production of i-th product from p-th producer in t-th period
crs_{ist}	Cost of reducing the risk of i-th product supply from s-th supplier in t-th period
crd_{idt}	Cost of reducing the risk of i-th product distribution from d-th distributor in t-th period
ucs	High limit of supplier capacity
usp	High limit of plant capacity
Usd	High limit of distribution system capacity
α	Percentage of using m-th raw material in i-th product
φ^{max}_{ip}	Longest production time of each i-th product unit
k	Fixed coefficient 0<k<1

Decision Variables:

$SHR1_{msplt}$	The amount of m-th raw material shipped from s-th supplier to p-th plant by l-th transportation system in t-th period
$SHI3_{idclt}$	The amount of i-th product shipped from d-th distributor system to c-th customer by l-th transportation system in t-th period
PI_{ipt}	i-th product inventory in p-th plant in t-th period
DI_{idt}	i-th product inventory in d-th distribution system in t-th period
XK_{mst}	The amount of m-th raw material purchased from s-th supplier in t-th period
AP_{pt}	1, if p-th plant produces a product in th-period; otherwise, 0.
CAS_{st}	S-th supplier capacity in t-th period
CAD_{dt}	d-th distribution system capacity
CEP_{pt}	Increased capacity of p-th plant in t-th period
SF_t	S-th supplier flexibility

DCF_t	d-th distributor system flexibility
η_{ipt}	The level of production knowledge of the production in the beginning of t-th period
$Learn_{ipt}$	The level of learning for production of each i-th product unit in p-th plant in t-th period
PFL_{pt}	Determined variable for linearization of the non-linear section $CAP_{pt} \times AP_{pt}$
φXPL_{ipt}	Determined variable for linearization of non-linear section obtained from multiplying the variables of $XP_{ipt} \times \varphi_{ipt}$
$SHI2_{ipdlt}$	The amount of i-th product shipped from p-th plant to d-th distribution system by l-th transportation system in t-th period
SI_{mst}	Inventory of m-th raw material at the supplier and in t-th period
SI_{mst}	Inventory of m-th raw material at the s-th supplier in t-th period
XP_{ipt}	The amount of i-th product produced in p-th plant in t-th period
AS_{st}	1, if s-th supplier produces a product in t-th period; otherwise, 0.
AD_{dt}	1, if d-th distributor distributes a product in t-th period; otherwise, 0.
CAP_{pt}	Capacity of p-th plant in t-th period
CES_{St}	Level of increase in capacity of s-th supplier in t-th period
CED_{dt}	Level of increase in the capacity of d-th distribution system in t-th period
PF_t	Flexibility of p-th plant
DVF_t	Overall flexibility of i-th product supply chain
φ_{ipt}	Duration of producing each i-th product unit in p-th plant in t-th period
SLF_{st}	Variable determined for linearization of the non-linear section obtained from multiplying the variables of $CAS_{st} \times AS_{st}$
DEL_{dt}	Variable determined for linearization of the non-linear section obtained from multiplying the variables of $CAD_{dt} \times AD_{dt}$

Model Definition:

$$\begin{aligned} Z1: \text{Min cost} = & \sum_s \sum_t (fost_{st} \times AS_{st}) \sum_p \sum_t (fop_{pt} \times AP_{pt}) \\ & + \sum_d \sum_t (fod_{dt} \times AD_{dt}) \sum_s \sum_t (fus_{st} \times CAS_{st}) + \sum_p \sum_t (fup_{pt} \times CAP_{pt}) \\ & + \sum_d \sum_t (fud_{dt} \times CAD_{dt}) \sum_i \sum_p \sum_t (hcp_{ipt} \times PI_{ipt}) + \sum_p \sum_t (hcd_{idt} \times DI_{idt}) \\ & + \sum_i \sum_p \sum_t (\varphi XPL_{ipt} \times pc_{ipt}) \\ & + \sum_m \sum_s \sum_p \sum_l \sum_t (SHR1_{msplt} \times trc1_{msplt}) \\ & + \sum_i \sum_p \sum_d \sum_l \sum_t (SHI2_{ipdlt} \times trc2_{ipdlt}) \\ & + \sum_i \sum_d \sum_c \sum_l \sum_t (SHI3_{idclt} \times trc3_{idclt}) + \sum_i \sum_s \sum_t (crs_{ist} \times rs_{ist} \times AS_{st}) \\ & + \sum_i \sum_p \sum_t (crp_{ipt} \times rp_{ipt} \times AP_{pt}) + \sum_i \sum_d \sum_t (crd_{idt} \times rd_{idt} \times AD_{dt}) \end{aligned} \quad (1)$$

$$\begin{aligned} & Z2: \text{Min leadtim} = \\ & \sum_m \sum_s \sum_p \sum_l \sum_t (SHR1_{msplt} \times stp_{splt} \times dis1_{spl}) \\ & + \sum_i \sum_p \sum_d \sum_l \sum_t (SHI2_{ipdlt} \times std_{pdlt} \times dis2_{pdl}) \\ & + \sum_i \sum_d \sum_c \sum_l \sum_t (SHI3_{idclt} \times stc_{cdlt} \times dis3_{dcl}) \end{aligned} \quad (2)$$

$$Z3: \text{Max flexibility} = \frac{\sum_t (DVF_t)}{|T|} \quad (3)$$

$$\begin{aligned} Z4: \text{Min Risk} = & \sum_i \sum_s \sum_t (rs_{ist} \times AS_{st}) \\ & + \sum_i \sum_p \sum_t (rp_{ipt} \times AP_{pt}) + \sum_i \sum_d \sum_t (rd_{idt} \times AD_{dt}) \end{aligned} \quad (4)$$

$$\sum_m \sum_p \sum_l SHR1_{msplt} \le CAS_{st} \quad \forall s, t \quad (5)$$

$$CAS_{st} = CAS_{s(t-1)} + CES_{st} \quad \forall s, t \quad (6)$$

$$CAS_{st} \le ucs \times AS_{st} \quad \forall s, t \quad (7)$$

$$CAS_{st} \le lcs \times AS_{st} \quad \forall s, t \quad (8)$$

$$\sum_i \sum_d \sum_l SHI2_{ipdlt} \le CAP_{pt} \quad \forall p, t \quad (9)$$

$$\sum_i PI_{ipt} \le CAP_{pt} \quad \forall p, t \quad (10)$$

$$CAP_{pt} = CAP_{p(t-1)} + CEP_{pt} \quad \forall p, t \quad (11)$$

$$CAP_{pt} = usp \times AP_{pt} \quad \forall p, t \quad (12)$$

$$CAP_{pt} \ge lcp \times AP_{pt} \quad \forall p, t \quad (13)$$

$$\sum_i \sum_c \sum_l SHI3_{idclt} \le CAD_{dt} \quad \forall d, t \quad (14)$$

$$CAD_{dt} = CAD_{d(t-1)} \times CED_{dt} \quad \forall d, t \quad (15)$$

$$CAD_{dt} \le ucd \times AD_{dt} \quad \forall d, t \quad (16)$$

$$CAD_{dt} \ge lcd \times AD_{dt} \quad \forall d, t \quad (17)$$

$$\sum_i DI_{idt} \le CAD_{dt} \quad \forall d, t \quad (18)$$

$$\sum_d \sum_l SHI3_{idclt} \le de_{ict} \quad \forall i, t, c \quad (19)$$

$$\begin{aligned} & SI_{mst} \\ & = SI_{ms(t-1)} + XK_{mst} \\ & - \sum_l \sum_p SHR1_{msplt} \quad \forall m, s, t \end{aligned} \quad (20)$$

$$\begin{aligned} PI_{ipt} = & PI_{ip(t-1)} + XP_{ipt} \\ & - \sum_l \sum_d SHI2_{ipdlt} \quad \forall i, p, t \end{aligned} \quad (21)$$

$$\begin{aligned} & DI_{idt} \\ & = DI_{id(t-1)} \\ & + \sum_p \sum_l SHI2_{ipdlt} \\ & - \sum_i \sum_c SHI3_{idclt} \quad \forall i, d, t \end{aligned} \quad (22)$$

$$SF_t - \sum_i \sum_s (SEL_{st} \times de_{ict}) \quad \forall c, t \quad (23)$$

$$0 \le SFL_{st} \le CAS_{st} \quad \forall s, t \quad (24)$$

$$CAS_{st} - N \times (1 - AS_{st}) \le SEL_{st} \quad \forall s, t \quad (25)$$

$$SFL_{st} \le N \times AS_{st} \quad \forall s, t \quad (26)$$

$$PF_t = \sum_i \sum_p (PFL_{pt} \times de_{ict}) \quad \forall c, t \quad (27)$$

$$0 \le PFL_{pt} \le CAP_{pt} \quad \forall p,t \tag{28}$$

$$CAP_{pt} - N \times (1 - AP_{pt}) \le PEL_{pt} \quad \forall p,t \tag{29}$$

$$PFL_{pt} \le N \times AP_{pt} \quad \forall p,t \tag{30}$$

$$DCF_t = \sum_d \sum_i (DFL_{dt} \times de_{ict}) \quad \forall c,t \tag{31}$$

$$0 \le DFL_{pt} \le CAD_{dt} \quad \forall d,t \tag{32}$$

$$CAD_{dt} - N \times (1 - AD_{dt}) \le DEL_{dt} \quad \forall d,t \tag{33}$$

$$DFL_{dt} \le N \times AD_{dt} \quad \forall d,t \tag{34}$$

$$DVF_t = \min(SF_t, PF_t, DCF_t) \quad \forall t \tag{35}$$

$$\sum_i XP_{ipt} = \alpha \sum_m \sum_s \sum_l SHR1_{msplt} \quad \forall p,t \tag{36}$$

$$DI_{idt} \ge mi_{id} \times AD_{dt} \quad \forall i,d,t \tag{37}$$

$$\sum_{\forall s} rs_{ist} \times AS_{st} \le mr_{it} \quad \forall i,t \tag{38}$$

$$\sum_{\forall p} rp_{ipt} \times AP_{pt} \le AD_{dt} \quad \forall i,d,t \tag{39}$$

$$\sum_{\forall d} rd_{idt} \times AD_{dt} \le mr_{it} \quad \forall i,t \tag{40}$$

$$learn_{ipt} = \frac{k(uf_{ip} - ls_{ip})}{usp} \times XP_{ipt} \quad \forall i,p,t \tag{41}$$

$$\eta_{ipt} = \eta_{ip(t-1)} + learn_{ip(t-1)} \ge 1 \quad \forall i,p,t \tag{42}$$

$$\varphi_{ipt} = \varphi^{max}{}_{ip} - \frac{\eta_{ipt}\left(\varphi^{max}{}_{ip} - \varphi^{min}{}_{ip}\right)}{uf_{ip}} \quad \forall i,p,t \tag{43}$$

$$\varphi^{max}{}_{ip} - \frac{\frac{k(uf_{ip} - ls_{ip})}{usp}\sum_{t'=1}^{t'=t-1} XP_{ipt}}{uf_{ip}}\left(\varphi^{max}{}_{ip} - \varphi^{min}{}_{ip}\right) \times XP_{ipt} \le \theta \quad \forall i,p,t \tag{44}$$

$$\varphi XPL_{ipt} \ge (\varphi_{ipt} \times 1500) + \left(\varphi^{max}{}_{ip} \times XP_{ipt}\right) - \left(\varphi^{max}{}_{ip} \times 1500\right) \quad \forall i,p,t \tag{45}$$

$$\varphi XPL_{ipt} \ge (\varphi_{ipt} \times 0) + \left(\varphi^{min}{}_{ip} \times XP_{ipt}\right) - \left(\varphi^{min}{}_{ip} \times 0\right) \quad \forall i,p,t \tag{46}$$

$$\varphi XPL_{ipt} \le (\varphi_{ipt} \times 1500) + \left(\varphi^{min}{}_{ip} \times XP_{ipt}\right) - \left(\varphi^{min}{}_{ip} \times 1500\right) \quad \forall i,p,t \tag{47}$$

$$\varphi XPL_{ipt} \ge (\varphi_{ipt} \times 0) + \left(\varphi^{max}{}_{ip} \times XP_{ipt}\right) - \left(\varphi^{max}{}_{ip} \times 0\right) \quad \forall i,p,t \tag{48}$$

$$SHR1_{msplt}, SHI2_{ipdlt}, SHI3_{idclt}, SI_{mst}, PI_{ipt}, DI_{idt}, XP_{ipt}, XK_{mst}, CAS_{st}, CAP_{pt}, CAD_{dt}, CES_{st}, CEP_{pt}, CED_{dt}, SFL_{st}, PFL_{pt}, DCFL_{dt}, SF_t, PF_t, DCF_t, DVF_t, \eta_{ipt}, \varphi_{ipt}, Learn_{ipt}, \varphi XPL_{ipt} \ge 0 \quad \forall m,s,p,l,t,i,d,c \tag{49}$$

$$AS_{st}, AP_{pt}, AD_{dt} \in \{0,1\} \quad \forall s,p,t,d \tag{50}$$

Eq. (1) is the first objective of the mathematical model, which seeks to minimize the total costs. Eq. (2), is the second objective of the model, and it minimize to reduce the lead time in the supply chain. In Eq. (3), the third objective is to maximize the flexibility of the entire supply chain. In addition, Eq. (4) is the fourth objective function and is presented to reduce total risks of the supply chain. Eqs. (5)-(19) are related to the constraints that limit the capacity of each facility in the supply chain. Moreover, Eqs. (20)-(22) are related to the level of inventory at each of these levels and it formulated based on the balance of inventory in each facility. Meanwhile, Eqs. (23)-(31) express the level of flexibility. The flexibility is the difference of available capacity and total inventory. Eqs. (24)-(26) are designed for linearization of Eq. (23). Furthermore, Eqs. (28)-(30) are developed for linearization of Eq. (27), and Eqs. (32)-(34) are designed for linearization of Eq. (31). Eq. (35) expresses that the level of flexibility of the entire system equates to the minimum level of flexibility at each level and in each period. Eq. (36) demonstrates that a specific coefficient of raw material is used in the production of each product. Moreover, Eq. (37) shows that shortage in the system is not allowed, and Eqs. (38)-(40) are constraints related to the risk of each level. Eq. (41) indicates how learning is calculated, whereas Eq. (42) shows that the estimated level of learning is added to the information level of the production system in the next period. Eq. (43) shows that the time required for production in the first period of production with the least level of information is equal to $\varphi^{max}{}_{ip}$ and productivity increases during different production periods based on learning of the production system. Finally, Eq. (44) is applied to control the production time in each period, whereas Eqs. (45)-(48) are presented for linear approximation of the nonlinear part of the first objective function.

3. Results and Discussion

In this research, we use a mixed integer quadratic programming (MIQP), and optimal values of each objective function is obtained by solving through the fuzzy ideal programming method based on [18] (Table 1). Moreover, the structure of implementing the research and providing the numerical results are inspired from [19-21].

According to Figure 1, increasing the problem size has a great impact on the first objective function. Meanwhile, increasing the problem dimensions has the lowest impact on the third and fourth objectives.

Table 1. Optimal amounts of each objective function by problem solving with the FGP method

Row	Problem Sizes	First Objective Function Value (Z1)	Second Objective Function Value (Z2)	Third Objective Function Value (Z3)	Fourth Objective Function Value (Z4)
1	Small	106739820.00	467965.42	49.96	2.87
2	Medium	318875354.00	227548385.00	84.24	8.15
3	Large	106739820.00	443580219.00	9.13	9.50

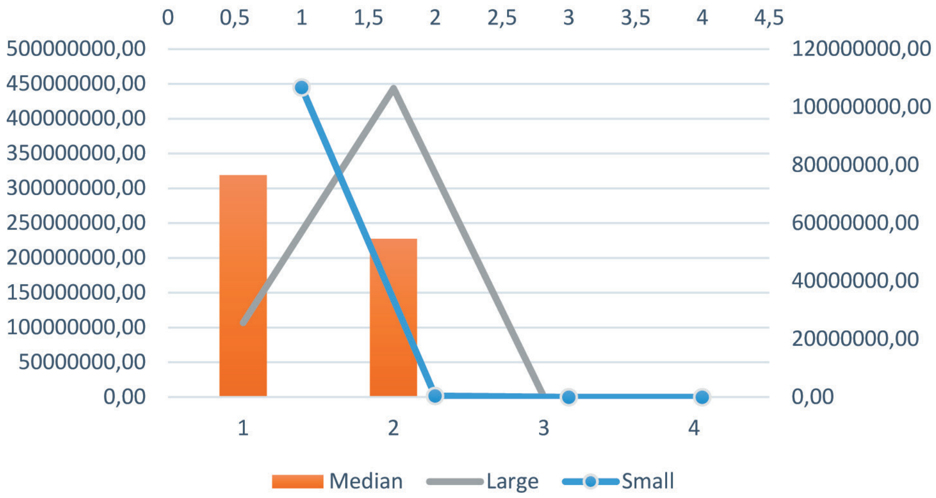

Figure 1. Comparison of amounts of objective functions at different dimensions

Table (2) presents the amount of production in each period.

Table (3) shows the calculated learning values according to the amount of production, which were added to the production system information level in each period. Table (4) presents the uptrend of values related to the level of information in the production system.

Table (5) shows the downward trend of the time spent to produce the product during different periods based on the learnability of the system. Figure 2 shows the trend of production duration values in different periods.

According to Figure 2, there is an upward trend for production time. Meanwhile, in some periods (e.g., period two), attempts are made to increase the

Table 2. Values related to the amount of i-th product production by p-th producer in t-th period by the FGP method

XP_{ipt}	t=1	t=2	t=3	t=4	t=5
i=1,p=1	0	585.20396	492.999504	441.134	0
i=1,p=4	381.307	0	65.714478	0	381.307
i=5,p=1	616.733	313.896912	0	116.587	504.061
i=5,p=4	251.842	467.871624	789.299838	143.639	161.376

Table 3. Values related to the level of learning for production of each product unit in each period in the FGP method

$Learn_{ipt}$	t=1	t=2	t=3	t=4	t=5
i=1,p=1	0	1.50634	1.26936	0	0
i=1,p=4	0.96432	0	0.16646	0	0.96432
i=5,p=1	1.62278	0.82574	0	0.30668	1.32594
i=5,p=4	0.55104	1.02418	1.72856	0.31488	0.35342

Table 4. Values related to the level of production system information in the beginning of each period in the FGP method

η_{ipt}	t=1	t=2	t=3	t=4	t=5
i=1,p=1	2.69	2.69	4.20	5.47	5.47
i=1,p=4	2.79	3.75	3.75	3.92	3.92
i=5,p=1	2.57	4.19	5.02	5.02	5.33
i=5,p=4	3.51	4.07	5.09	6.82	7.13

Table 5. Production period in the FGP method

φ_{ipt}	t=1	t=2	t=3	t=4	t=5
i=1,p=1	0.51	0.40	0.34	0.28	0.28
i=1,p=4	0.52	0.36	0.36	0.20	0.35
i=5,p=1	0.44	0.30	0.27	0.27	0.26
i=5,p=4	0.56	0.37	0.32	0.23	0.22

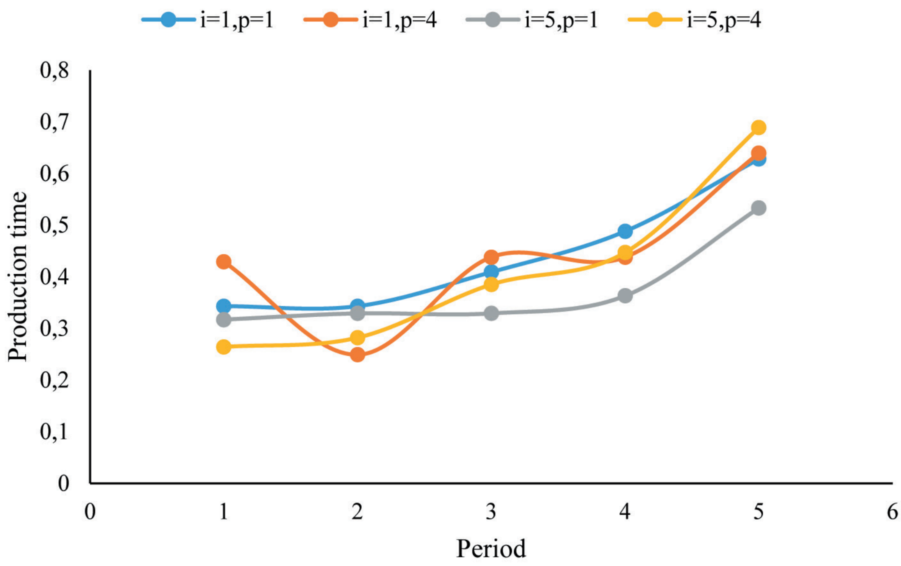

Figure 2. Diagram of trend of production time values in optimal mode

system's operation speed by relatively reducing the production time. In the following part, weighting method is implemented to estimate Pareto fronts for the proposed model. Comparison of each pair of objective functions shows how all functions are in conflict of each other. Table 6 shows the value of each objective function in each test problem.

In order to evaluate the behavior of the objective functions relative to each other, comparing diagrams are drawn for each pair of objective functions, which demonstrates that the behaviors of pairs of the first and second, first and third, third and fourth, second and third, second and fourth, and first and fourth objective functions contradict each other. The corresponding results are presented in figures 3, 4 and 5.

According to figures 3, 4, and 5, since the objectives of the mathematical model are in complete conflict with each other, the best value of the other objectives cannot be achieved by optimizing one of them. Accordingly, using a multi-objective mathematical model in the present study seems appropriate and rational. Some of the important outputs are reported below. This type of problem is selected based on Table (6) because of the lowest maximum deviation and least total deviation, where the problem is weighted W2=0.5 and W1=0.5. Table 7 shows the optimal values of each objective function by solution via the TH approach. Moreover, Table (8) shows the amount of production in each period.

Tables (9) and (10) show the upward trend of changes in the level of information and the downward trend of the time spent to produce the product during different periods and based on the weighting method, respectively.

Table 6. Pareto fronts in the weighting method

Test Problem	w1	w2	z1	z2	z3	z4	Mean deviation (A)	Maximum deviation (B)	A+B
1	0	1	2934746695.0	29685469.0	1098.1	106.2	0.0944	0.0975	0.1919
2	0.1	0.9	4158951218.0	29652832.9	1098.6	106.2	0.0938	0.0975	0.1913
3	0.2	0.8	4160699494.0	29685279.0	1098.1	106.2	0.0944	0.0975	0.1919
4	0.3	0.7	4166489279.0	29454907.5	1096.3	106.2	0.0926	0.0987	0.1913
5	0.4	0.6	4185421784.0	29786313.7	1090.3	105.9	0.0858	0.1011	0.1870
6	0.5	0.5	4185423010.0	29786319.8	1090.3	105.9	0.0858	0.1011	0.1870
7	0.6	0.4	4185415654.0	29786289.1	1090.3	105.9	0.0858	0.1011	0.1870
8	0.7	0.3	4236066618.0	29465310.1	1074.3	105.7	0.0821	0.1085	0.1906
9	0.8	0.2	4550436925.0	27601060.6	1132.0	105.5	0.0650	0.1551	0.2201
10	0.9	0.1	4848531469.0	27601060.6	1283.1	105.5	0.0582	0.1992	0.2575
11	1	0	4902976290.0	27568467.4	1302.4	105.5	0.0576	0.2072	0.2685

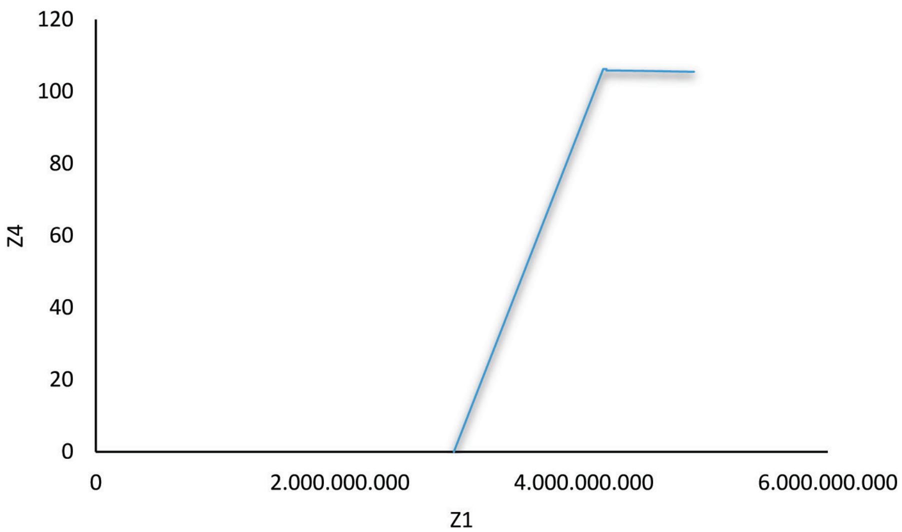

Figure 3. Evaluation of the first and fourth objective functions in the Pareto front

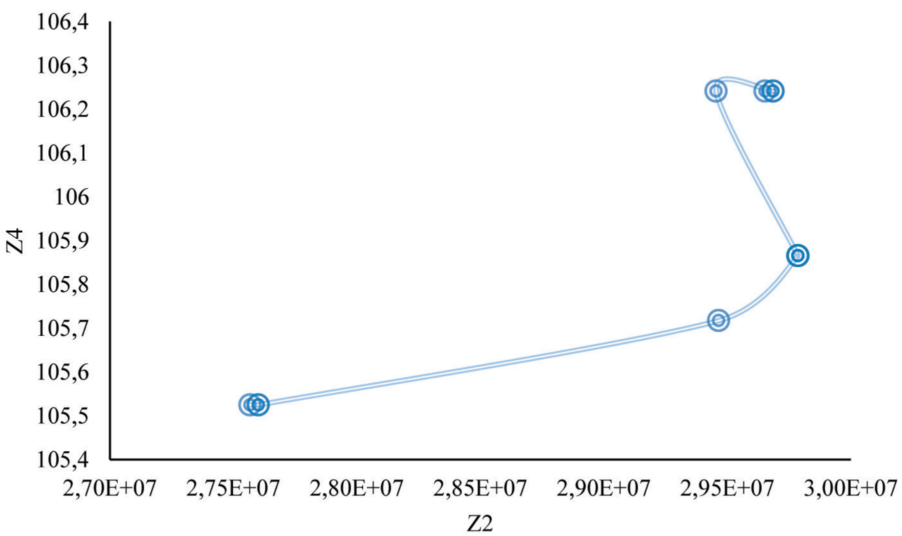

Figure 4. Evaluation of the second and fourth objective functions in the Pareto front

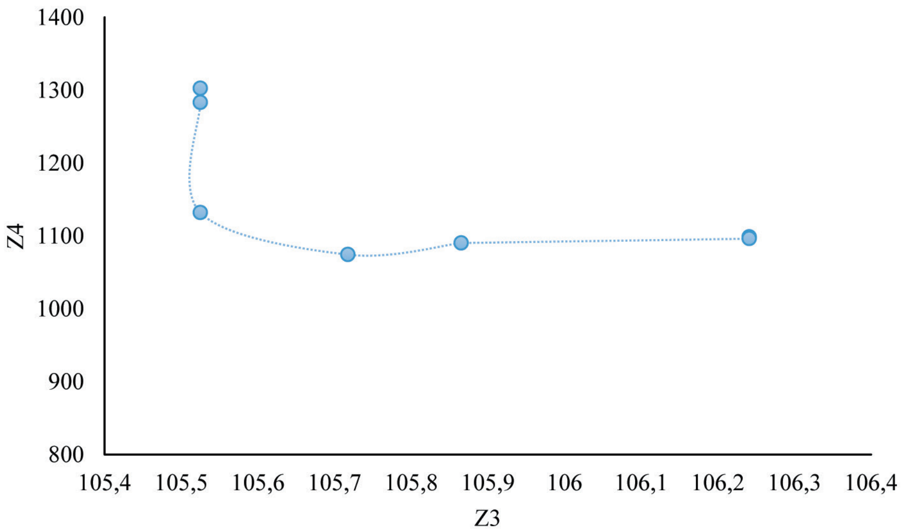

Figure 5. Evaluation of the third and fourth objective function in the Pareto front

Table 7. Optimal values of each objective function by problem solving with the TH method

Test problem	Problem Size	z1 Objective Function Value	z2 Objective Function Value	z3 Objective Function Value	z4 objective function value
1	Small	108991731.0	451036.8	49.96	2.87
2	Medium	320905190.0	2283779.8	83.60	8.12
3	Large	596472300.0	4380256.2	12.05	9.50

Table 8. Values related to the level of i-th product production by p-th producer in t-th period in the weighting method

XP_{ipt}	t=1	t=2	t=3	t=4	t=5
i=1,p=2	0.00	637.75	0.00	0.00	244.28
i=2,p=1	587.72	582.63	0.00	610.19	0.00
i=4,p=3	787.73	628.89	660.35	0.00	399.54
i=5,p=3	220.98	356.57	325.12	0.00	691.76

Table 9. Values related to the level of production system information in the beginning of the weighting method

η_{ipt}	t=1	t=2	t=3	t=4	t=5
P4.PRO1	3.47	3.47	4.57	4.57	4.57
P4.PRO4	2.85	4.00	5.14	5.14	6.33
P5.PRO1	2.57	4.19	5.49	6.85	6.85
P5.PRO4	3.51	3.89	4.50	5.06	5.06

Table 10. Values related to the production period of each product unit in each period in the weighting method

φ_{ipt}	t=1	t=2	t=3	t=4	t=5
P4.PRO1	0.46	0.34	0.30	0.30	0.30
P4.PRO4	0.56	0.37	0.31	0.31	0.26
P5.PRO1	0.44	0.30	0.29	0.21	0.21
P5.PRO4	0.56	0.45	0.34	0.32	0.32

Table 11. Values related to the level of learning for the production of each product unit in each period in the weighting method

$Learn_{ipt}$	t=1	t=2	t=3	t=4	t=5
P4.PRO1	0.00	1.10	0.00	0.00	0.42
P4.PRO4	1.15	1.14	0.00	1.19	0.00
P5.PRO1	1.62	1.30	1.36	0.00	0.82
P5.PRO4	0.38	0.61	0.56	0.00	1.19

Table 11 shows the amount of learning in each specific period based on the TH method, which is added to the level of information of each producer in each period.

4. Conclusion

According to the results of the present study, the solution proposed for using the learning phenomenon in a supply chain system has a significant impact on the level of agility. In addition, it considerably contributes to the minimization of costs, especially in the production section. Based on the two solution methods, flexibility in a supply chain system is one of the most important indexes of agility, and taking the risk management process into account is one of the most effective solutions to control the situation. In addition, the level of information in the production system will increase over time due to the learnability of the production system, which will lead to the decrease of production time of each product unit over time. According to the results, reduced production time leads to the decrease of costs in the first objective function. Moreover, the supply chain system takes step toward the increase of flexibility while taking demand and capacity of each level into account in order to respond to demand fluctuations. The results also demonstrate that an improvement in the flexibility of the system reduces the emergence of some disruptions. Therefore, the fourth objective function, which is developed to control the level of risk in the supply chain, will have a downward trend over time and with the increase of flexibility. This system is always growing due to the learning phenomenon in the production process. This is mainly due to the fact that the implementation of the learning process in an organization simplifies the management and implementation of forecasting and planning processes, resource provision, logistics and support, management services and many sub-processes of the chain. Moreover, learning enables organizations to invest in manufacturing and operating processes instead of losing money and spending too much on software systems. It is hoped that the present study can take a step toward the improvement of supply chain systems and the current logistic conditions in the industry. However, it is recommended that the following issues be taken into account in future studies:

1. Using heuristic and metaheuristic approaches and comparing the results with proposed accurate solution methods
2. Considering uncertainties in the model and solution with relevant methods
3. Considering another objective function to increase the production quality of products
4. Regulating a variable for instantaneous control and measurement of agility changes
5. Changing the form of the function of learning rate and its implementation in the model.

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