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A fuzzy multi-objective optimization model for designing a sustainable supply chain forward network: A case study

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Abstract

Global warming in the industry sector has forced political leaders to seek sustainable supply chains. The ceramic tile industry (CTI) is a highly competitive industry which has a major impact on the environment. The aim of the current paper is to present a sustainable supply chain in CTI in order to minimize costs, minimize adverse environmental effects as well as increase social benefits. To do so, a multi-period, multi-product, multi-supplier, multi-objective supply chain has been designed. Quality issue with different technologies and capacity limitations for plants, warehouses and distribution centres are considered. The framework of the proposed supply chain network involves a forward network from suppliers offering different raw materials and ends by delivering produced items to end users. The objectives are minimizing the total cost (e.g. variable and fixed costs), minimizing environmental hazards (e.g. industrial dusts and carbon dioxide emission), and maximizing social benefits (e.g. job opportunities).The problem is mathematically formulated by a mixed integer non-linear programming model. This model is solved using a fuzzy goal programming approach. Using a numerical experiment, the proposed model is evaluated in CTI sustainable supply chain model. The results are reported fuzzily and provide three values for each decision variable for a period of two months. In addition, a sensitivity analysis is done on some parameters to appraise the validity and feasibility of the model. The results demonstrate that there should be a balance among the three pillars of sustainability in order to reap economic benefits in addition to considering environmental health.
Keywords: Sustainable supply chain management, mathematical modelling, ceramic tile industry.

1- Introduction

In today's challenging conditions, almost all organizations try to satisfy clients' demands and expectations in order to survive in the growing competitive environment. Hence, supply chain management (abbreviated here as SCM) has become an important concept amongst researchers and industrial experts (Ramezani et al., 2014). It can be said that SCM is a vital tool for businessmen seeking competitive advantages (Wang et al., 2011). SCM is a process which starts by supplying raw materials, continues by producing products during manufacture and ends with delivering the products to customers (Rad and Nahavandi, 2018). The growing volume of operations along the supply chain has

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environmental and social consequences. The related activities are the main source of air pollution which is harmful for human health. Above all, they are the main cause of global warming. In this regard, governments, in developing and developed countries, have published different policies in order to protect the environment and respect human rights (Wang et al., 2011). In fact, there is an increasing attention from academia, policy makers and organizations to consider the relationship between the supply chain and the environment in different industries (Kivimaa and Mickwitz, 2011, López-Gamero et al., 2010, Taddeo et al., 2012, Weber and Rohracher, 2012, Zeng et al., 2010). Organizations are pressured to reduce the negative environmental impacts of their operations (Zailani et al., 2012) including carbon dioxide emissions, energy consumption, solid waste, water consumption and dust particles (Ahi and Searcy, 2015). Also, they need to consider human rights, workforce issues, the environment, proper working conditions, customer care, and social development in order to be morally responsible (ISO26000, 2010). Hence, they need to implement sustainability initiatives. Sustainability is defined as an achievement of organizational, environmental, social and economic goals in order to obtain long term benefits in the organization and along the supply chain (Carter and Rogers, 2008) which enables sustainable supply chain management. In various industries, there is a trade-off between various potential criteria in order to reduce costs, increase quality while taking sustainable issues into account (Soleimani et al., 2017). The ceramic tile industry is a high energy consumption industry with substantial carbon dioxide emissions (Koroneos and Dompros, 2007). Also, CTI uses natural raw materials and produces different types of waste during the production process (Menezes et al., 2008). Gabaldón-Estevan et al. (2014) focused on CTI in Spain in order to understand the influence of European environmental regulations on CTI performance in this country; they also studied the impact of the innovation system and socioeconomic effects of the industry. The results showed that the industry had a significant effect on the environment which was more important than its socioeconomic wellbeing. In addition, Gabaldón-Estevan et al. (2016) focused on energy consumption in European CTI as an intensive energy consumer . They showed that it needed to be committed to resource efficiency, and to the green and competitive low carbon economy which is outlined in the 7th Environmental Action Programme. Redemann and Specht (2017) proposed a mathematical model in CTI in order to decrease heat losses and increase the efficiency of the firing process. The present study aims to provide a sustainable supply chain management model (abbreviated here as SSCMM) in the ceramic tile industry with regards to all three pillars of sustainability. Soleimani et al. (2013) confirmed that designing a SSCMM needs a reliable approach in order to provide a sufficient solution especially for problems with real dimensions. In this regard, we scrutinised different approaches to provide a reliable, environment-friendly solution in CTI committed to the society which would also have economic benefits with precise and imprecise amount of parameters. Hence a multi-objective, multi-period, multi-raw material and multi-product non-linear SSCMM is modelled using the fuzzy logic approach and is solved using the goal programming technique. The components which have been considered in this study are suppliers, manufacture centres, warehouses, distribution centres and end users. The innovation of the current study is that the results are reported fuzzily in order to reflect the practicality of the results. The kind of technology in the production process which is effective in limiting air pollution and the quality of those productions which have economic benefits has been considered. Also, the kind of transportation which is effective on the well-being of the environment has been taken into consideration. On the one hand, we considered carbon dioxide emissions and dust particles as a sign of air pollution. On the other, we considered the work conditions of the employees as a sign of social commitment. The rest of the paper is as follows: a literature overview is given in Section Two. The problem is described and formulated in Section Three. The approach to solving the problem is discussed in Section Four. The obtained solution and sensitivity analysis are discussed in Section Five and a conclusion is given in Section Six.

2- Literature foundation overview

Modelling supply chains and planning problems is the best way of finding a sustainable supply chain management model based on a company's competitive advantages, strategies and long-term goals (Chopra and Meindl, 2016). SSCMM consists of a set of different decision tactics such as determining the number, capacity and location of the entities, transportation modes, flow of raw materials to the establishments for production, as well as the flow of the final products to the end users to satisfy their needs (Govindan et al., 2015). Researchers are mostly trying to design the network in a way as to pursue profits (Chaabane et al., 2012). In other words, they provide trade-offs between the service level aimed at meeting customer demands appropriately and the supply chain costs e.g. the fixed and variable costs of production, transportation etc. (Simchi-Levi et al., 2008). However, researchers are under considerable pressure from stakeholders, NGOs and governmental institutions to consider environmental and social indicators in SSCMM in order to uphold human rights (Tang and Zhou, 2012, Wu and Pagell, 2011, Varsei et al., 2014). The fact is that SSCMM has received great attention since 2008 (Eskandarpour et al., 2015). Decision makers have integrated environmental and social considerations into decision making about production planning, inventory amounts and transportation modes to design SSCMM (Govindan et al., 2015). SSCMM has been designed with regards to different pillars of sustainability and significant growth has occurred regarding environmental issues (Mota et al., 2018). Eskandarpour et al. (2015) focused and reviewed optimization problems and stated that environmental impact assessment appeared in the literatures in two ways: partial assessment of environmental factors and Life-Cycle Assessment (LCA) based models. Partial assessment of environmental factors focuses on some important aspects of environmental issues like carbon dioxide emissions, industrial dusts, wastes and energy use in accordance with the given industry or case-study. It is used when including the entire supply chain in the model is impossible or obtaining environmental data is challenging. In turn, LSA is an approach, introduced by the European Commission, which provides a framework to assess all the potential environmental effects of production or the providing of services such as emissions, resource consumptions, resource depletion and the impact of products and services on health (Rebitzer et al., 2004). Studying social responsibility is still in its early stages (Mota et al., 2018). The social issue is a dimension which considers the impact of organizational operations on society. It can be claimed that companies should incorporate social performance indictors in their strategies in order to meet stakeholder needs, decrease risk and increase profit to gain financial benefit. The social indicators are presented by the Global Reporting Initiative (GRI) which focuses on the social as well as the environmental and economic dimensions (Initiative, 2013). In spite of the necessity of considering social benefit in designing SSCMM, some researchers have considered the social dimension or the three aspects of sustainability simultaneously (Eskandarpour et al., 2015). The most important thing to know about designing a supply chain is that the researchers may know the precise value of some parameters while they may not be sure about the value of some others. In other words, they are uncertain about what reflects the reality of the market (Govindan et al., 2015). Some researchers meet such uncertainty using the fuzzy logic approach (Soleimani et al., 2017). The last but not least issue in designing SSCMM, is determining the flow of products. In this regard, there are three types of supply chains: forward, reverse and closed-loop supply chains. The forward supply chain is a network consisting of the supplier, manufacture centre, distributer and customer. The aim of the forward supply chain is satisfying client demands (Govindan et al., 2015). Reverse logistic is defined as "the logistics activities all the way from used products no longer required by the user to products again usable in a market" (Fleischmann et al., 1997). Meanwhile the concept of the closed-loop supply chain considers both flows, i.e. forward and reverse, simultaneously (Daniel et al., 2002). A summary of previous study and the proposed model is provided in table 1.

Table 1. A summary of studies and the proposed model

Author	Network	Model	Objective Function	Problem definition
(Li et al., 2020)	OL	MINLP	MO	Mode selection and inventory positioning
(Yolmeh and Saif, 2020)	CL	MINLP	SO	Mode selection
(Mogale et al., 2019)	OL	MILP	SO	supply chain network costs and determining number and location of procurement centres
(Guo et al., 2019)	OL	MILP	MO	Multi production, transportation, supplier, plant, environmental design

Author	Network	Model	Objective Function	Problem definition
(Shabani et al., 2018)	CL	MILP	SO	Multi production, supplier, plant
(Emamian et al., 2018)	CL	INLP	MO	Multi production, environmental design
(Yaghin, 2018)	OL	INLP	MO	Multi production, supplier and plants
(Liu and Papageorgiou, 2018)	OL	ILP	SO	Multi production, transportation and plant, environmental design
(Mota et al., 2018)	CL	ILP	MO	Multi production, transportation and plant, environmental design
(Kadziński et al., 2017)	OL	ILP	MO	Multi transportation, environmental design
(Varsei and Polyakovskiy, 2017)	OL	ILP	MO	Multi plant and transportation, environmental design
(Ghaithan et al., 2017)	OL	ILP	MO	Multi plant
(Nurjanni et al., 2017)	CL	ILP	MO	Environmental design
(Özceylan et al., 2017)	CL	ILP	MO	Environmental design
(Kisomi et al., 2016)	CL	ILP	MO	Multi plant and transportation
(Kisomi et al., 2016)	CL	ILP	SO	Multi production
(Fahimnia et al., 2015)	OL	INLP	MO	Multi production, supplier and transportation, environmental design
(Validi et al., 2015)	OL	ILP	MO	Multi transportation and environmental design
(Karimi et al., 2015)	CL	LP	SO	Multi production, supplier, plant, transportation
(Amin and Zhang, 2012)	CL	ILP	MO	Multi production, supplier and plant
(Masud and Hwang, 1980)	OL	LP	MO	Multi production, period aggregate production planning
Proposal model	OL	INLP	MO	Multi production, supplier, transportation and plants, environmental design, Social consideration

***Note*:** OL= open loop; CL= close loop; INLP= Integer Nonlinear Programming; ILP= Integer Linear Programming; MO=Multi Objective; SO= Single Objective

3- Problem description

3-1- Problem formulation

The current model is a multi-layer model comprised of five layers: multiple suppliers, multi-plants, warehouses, distribution centres and end-users. In this section, a multi-objective non-linear model for designing a multi-period, multi-product SSCMM is proposed. As figure 1 shows, the supply chain begins by supplying the raw materials, continues at the plants by producing the final product and delivering it to the warehouses and consequently to the distribution centres and finishes by delivering it to the end-users. Hence, it is a forward supply chain. In fact, the suppliers (indexed by s) offer raw materials (p) at different times (indexed by t). The raw materials are transported to the plants by various transportation modes (indexed by g) which affect the environment. Three products are manufactured in the plants with a set of potential locations (indexed by i). In the production process, different technologies are used (indexed by m) which have profound effects on social and environmental issues. The products are then shipped to the warehouses with a set of potential locations (indexed by r). Consequently, they are sent to the distribution centres with different sets of locations (j) and finally, to the end-users, also with sets of potential locations (indexed by c).

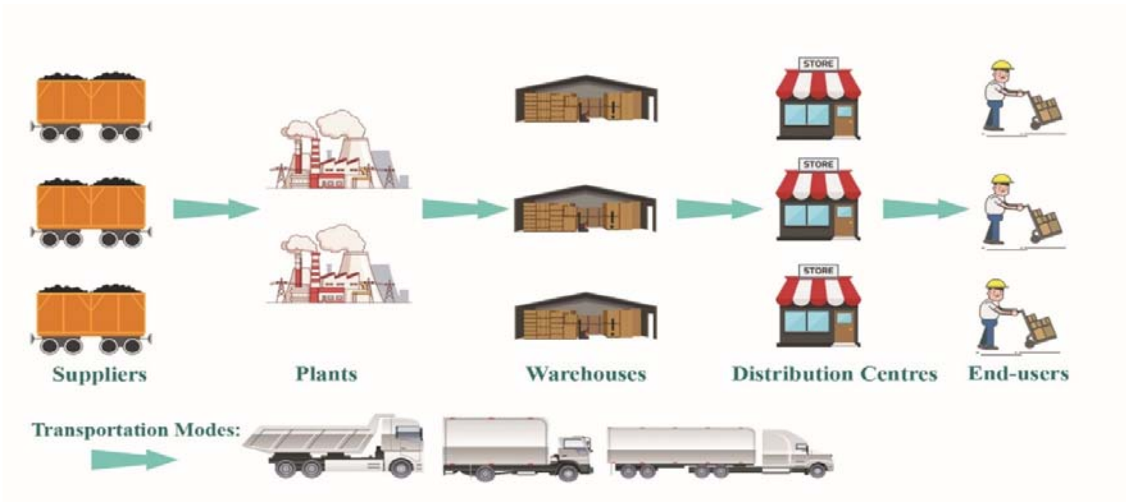

Fig 1. Supply chain network in ceramic tile industry

The following assumptions have to be considered in formulating the problem:

- The current model is a multi-product, multi-period and multi-echelon non-linear SSCMM.
- Fuzzy logic is used in order to show uncertainty.
- A triangular pattern is used to demonstrate the possibility of distribution in order to present uncertain parameters in the objective functions and constraints.
- The capacity of the facilities, including supplying raw materials, the amount of production in the plants, storing products in the warehouses and distribution centres and transportation modes, is considered finite and uncertain.
- It is a mixed integer quadratic programming (MIQP).
- The number and location of the suppliers, plants, warehouses, distribution centres and end-users are fixed and defined.
- The problem solution plan is for a two-month period.
- Three kinds of raw materials are considered.
- Three suppliers for raw materials, two plants, and three warehouses are considered. It is assumed that two of the warehouses are in two of the plants separately and the last warehouse is located outside the plants.
- Three kinds of technology are considered in the production stage. The output of the first technology is a simple tile with low quality; the output of the second technology is a patterned tile with medium quality; and the output of the third technology is a patterned tile with high quality.
- The kind of technology is effective as regards social and environmental issues in terms of benefits.
- The kind and the number of transportation vehicles and the distance between the supply chain parts are effective as regards environmental issues through carbon dioxide emission.
- Three kinds of transportation are considered for the supply of raw materials and distribution of the final products.
- Three national distribution centres are considered.

- The end users are mostly construction companies.

In order to design the SSCMM, the first objective is related to minimization of the total costs which is related to the economic aspect. The second and third objectives are related to environmental issues, and the fourth concerns maximization of social benefits. We are trying to provide a reasonable trade-off between maximization of economic gains, social responsibility and being environment-friendly. The parameters and variables are defined in Appendix A. Above all, the parameters which are uncertain are shown by ~ and are considered in the model formulation. The formulation of the objective functions and the model constraints are defined separately at the end.

3-1-1- Formulation of objective functions

The first objective function aimed at maximizing the economical factor in terms of reducing the total cost of SSCMM (see equation 1). It is comprised of seven parts of fixed and variable costs. The first part is related to the variable costs of purchasing and transmitting raw materials from the suppliers to the plants. The second and third parts are related to the fixed costs of setting up warehouses and distribution centres. The next part relates to the cost of producing and transporting the final products to the warehouses. The fifth part concerns the cost of storing the final products in the warehouses. The sixth part is related to the cost of transporting the final products from warehouses to the distribution centres and storing them there. And the final part is related to the cost of storing in the distribution centres.

$$\begin{aligned} Min(w_1) = {} & \sum_{g}^{G}\sum_{p}^{P}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left((\tilde{b}_{psit} \times \chi_{psit}) + (\tilde{\delta}_{psit} \times \tilde{cap4}_{g} \times XV_{gsit}) \right) + \sum_{r}^{R}\sum_{t}^{T}\left(\tilde{V}_{rt} \times W1_{rt} \right) \\ & + \sum_{j}^{J}\sum_{t}^{T}\left(\tilde{G1}_{jt} \times Y_{jt} \right) + \sum_{g}^{G}\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left((\tilde{P1}_{mit} \times Q_{mirt}) + (\tilde{C1}_{irt} \times \tilde{cap4}_{g} \times YV_{girt}) \right) \\ & + \sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left(\tilde{M1}_{rt} \times Q_{mirt} \right) + \sum_{g}^{G}\sum_{m}^{M}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\left((\tilde{P2}_{mrjt} \times L_{mrjt}) + (\tilde{C2}_{rjt} \times \tilde{cap4}_{g} \times ZV_{grjt}) \right) \\ & + \sum_{m}^{M}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\left(\tilde{M2}_{jt} \times L_{mrjt} \right). \end{aligned} \tag{1}$$

The second and third objective functions are defined in order to minimize environmental hazards. The second objective function aims at reducing the amount of industrial dusts. It has two parts: the first part focuses on the amount of industrial dusts during the breaking and crushing of the raw materials including stones which come from supplier s to manufacturer i during period t. The second part relates to the number of hazards resulting from products which are produced by manufacturer i with technology m during period t (see equation 2). Also, carbon dioxide emissions (see equation 3) which are caused when transporting the raw materials to the plants and the final products to the warehouses, distribution centres and end users are considered. The emission depends on the transportation modes, number of vehicles, amount of gasoil consumption and geographical distances between various centres.

$$Min(w_2) = \sum_{p}^{P}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left(\tilde{gh}_{it} \times \chi_{psit} \right) + \left[\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left(\tilde{S1}_{mit} \times Q_{mirt} \right) \right] \tag{2}$$

$$\begin{aligned} Min w_3 = {} & \sum_{g}^{G}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left(\tilde{CE} \times d1_{si} \times XV_{gsit} \right) + \sum_{g}^{G}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left(\tilde{CE} \times d2_{ir} \times YV_{girt} \right) \\ & + \sum_{g}^{G}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\left(\tilde{CE} \times d3_{rj} \times ZV_{grjt} \right) + \sum_{g}^{G}\sum_{j}^{J}\sum_{c}^{C}\sum_{t}^{T}\left(\tilde{CE} \times d4_{jc} \times MV_{gjct} \right) \end{aligned} \tag{3}$$

The fourth objective function is related to maximizing social benefits (see equation 4). In this regard, it contains four terms. The first, second and third terms relate to the number of job opportunities provided which depends on the production technologies in the plants, warehouses and distribution centres per unit of production in the plants and the stored products in the warehouses and distribution centres. The fourth term is related to the number of lost workdays due to hazards in the workplace which depends on the production technology per unit of production.

$$Max w_4 = \left[\sum_m^M \sum_i^I \sum_t^T \left(\tilde{O1}_{mit} \times X_{mit}\right) + \sum_r^R \sum_t^T \left(\tilde{O2}_{rt} \times W1_{rt}\right) + \sum_j^J \sum_t^T \left(\tilde{O3}_{jt} \times Y_{jt}\right)\right] - \left[\sum_m^M \sum_i^I \sum_t^T \left(\tilde{I1}_{mit} \times X_{mit}\right)\right] \quad (4)$$

3-1-2- Model Constraints

3-1-2-1- Capacity Constraint

The following constraints demonstrate the maximum capacity of different parts of the SSCMM. Equation (5) demonstrates the limitation on supplying (s) raw materials (p) for plants (i) during a time period (t).

$$\sum_i^I \chi_{psit} \le \tilde{\omega}_{pst} \qquad \forall_{p,s,t} \quad (5)$$

Also, equations 6-8 show the maximum capacity of producing the final products in the plants, the maximum capacity for storing the final products in the warehouses and in the distribution centres, respectively.

$$\sum_m^M (Q4_{mit}) \le \tilde{cap1}_{it} \qquad \forall_{i,t} \quad (6)$$

$$\sum_m^M \sum_j^J (L_{mrjt}) \le \tilde{cap2}_{rt} \qquad \forall_{r,t} \quad (7)$$

$$\sum_m^M \sum_c^C (H3_{mjct}) \le \tilde{cap3}_{jt} \qquad \forall_{j,t} \quad (8)$$

In addition, equations 9-12 demonstrate the maximum capacity of the transportation modes (g) for transporting raw materials from the suppliers to the plants, transporting products from the plants to the warehouses, from the warehouses to the distribution centres and to the end users.

$$\sum_g^G (\tilde{cap4}_g \times XV_{gsit}) \ge \chi_{psit} \qquad \forall_{p,s,i,t} \quad (9)$$

$$\sum_g^G (\tilde{cap4}_g \times YV_{girt}) \ge Q_{mirt} \qquad \forall_{m,i,r,t} \quad (10)$$

$$\sum_g^G (\tilde{cap4}_g \times ZV_{grjt}) \ge L_{mrjt} \qquad \forall_{m,r,j,t} \quad (11)$$

$$\sum_{g}^{G}(\tilde{cap}4_{g}\times MV_{gjct})\geq H3_{mjct} \qquad \forall_{m,j,c,t} \tag{12}$$

3-1-2-2- Balance constraints

The production system in the ceramic tile industry is mass production and the supply of raw materials is in mass also. Hence, there is no need to consider a balance in the inventory of raw materials. Thus, the following constraints (equations 13-14) guarantee the balance of the final products in the warehouses and distribution centres such that there will be no shortage of final products in these locations.

$$Q_{mirt}=Q1_{mir,t-1}-L_{mirt} \qquad \forall_{m,i,r,t} \tag{13}$$

$$L_{mrjt}=L1_{mrj,t-1}-H3_{mjct} \qquad \forall_{m,r,j,c,t} \tag{14}$$

3-1-2-3- Customer demand constraint

The customer demand constraints (equation 15-17) show the minimum demands of the warehouses from the plants, the minimum demand of the distribution centres from the warehouses and the minimum demand of the end users from the distribution centres, respectively. They show that all the delivered products should be greater than, or equal to, customer demands at every echelon. In fact, the amount of final products should satisfy such demands.

$$\sum_{m}^{M}\sum_{i}^{I}Q_{mirt}\geq \tilde{D}4_{rt} \qquad \forall_{r,t} \tag{15}$$

$$\sum_{m}^{M}\sum_{r}^{R}L_{mrjt}\geq \tilde{D}6_{jt} \qquad \forall_{j,t} \tag{16}$$

$$\sum_{m}^{M}\sum_{j}^{J}H3_{mjct}\geq \tilde{D}_{Ct} \qquad \forall_{c,t} \tag{17}$$

3-1-2-4- Environmental constraints

The three major sources of pollution in CTI are industrial dusts, which pollute the environment during the crushing of stones; hazardous by products, which are produced during the production process and the emission of carbon dioxide which occurs during the transportation of the raw materials and final products (Gabaldón-Estevan et al., 2014, Gabaldón-Estevan et al., 2016). Hence, in order to be environment-friendly, we considered the maximum amount of allowable industrial dust emitted during the crushing of every ton of stone (see equation 18), the maximum amount of hazardous by products produced during the production process in plant i over time t (see equation 19), and finally, the maximum allowable quantity of carbon dioxide emission which occurs during the transportation of raw materials and final products (see equation 20).

$$\sum_{p}^{P}\sum_{s}^{S}g\tilde{h}_{it}\times\chi_{psit}\leq W\tilde{H}_{it} \qquad \forall_{i,t} \tag{18}$$

$$\sum_{m}^{M} \tilde{S}1_{mit} \times Q4_{mit} \le \tilde{HM}_{it} \qquad \forall_{i,t} \tag{19}$$

$$\sum_{g}^{G}\sum_{s}^{S}(\tilde{CE} \times d1_{si} \times XV_{gsit}) + \sum_{g}^{G}\sum_{r}^{R}(\tilde{CE} \times d2_{ir} \times YV_{girt}) + \sum_{g}^{G}\sum_{j}^{J}(\tilde{CE} \times d3_{rj} \times ZV_{grjt}) + \sum_{g}^{G}\sum_{c}^{C}(\tilde{CE} \times d4_{jc} \times MV_{gjct}) \le \tilde{HE}_{jt} \qquad \forall_{i,t} \tag{20}$$

3-1-2-5- Human resource constraints

These are related to the constraints on the mean number of human resources in the plants, warehouses and distribution centres which should be lower than, or equal to, the required number of workforces (see equations 21 to 23).

$$\sum_{m}^{M} (\tilde{ub}_{it} \times Q4_{mit}) = \tilde{B}1_{it} \qquad \forall_{i,t} \tag{21}$$

$$\sum_{m}^{M}\sum_{i}^{I} (\tilde{uo}_{rt} \times Q_{mirt}) = \tilde{O}2_{rt} \qquad \forall_{r,t} \tag{22}$$

$$\sum_{m}^{M}\sum_{r}^{R} (\tilde{ur}_{jt} \times L_{mrjt}) = \tilde{O}3_{jt} \qquad \forall_{j,t} \tag{23}$$

3-1-2-6- Transportation constraint

The following constraints demonstrate the maximum costs of transporting the raw materials from the suppliers to the plants and the maximum costs of transporting the final products to the warehouses and distribution centres (see equations 24 to 26).

$$ke_{gsit} \times \tilde{cap}4_{g} \times XV_{gsit} \le \tilde{\delta}_{psit} \qquad \forall_{g,p,s,i,t} \tag{24}$$

$$ke1_{girt} \times \tilde{cap}4_{g} \times YV_{girt} \le \tilde{C}1_{irt} \qquad \forall_{g,i,r,t} \tag{25}$$

$$ke2_{grjt} \times \tilde{cap}4_{g} \times ZV_{grjt} \le \tilde{C}2_{rjt} \qquad \forall_{g,r,j,t} \tag{26}$$

3-1-2-7- Decision variables constraints

Equation 27 demonstrates that the decision variables are all positive.

$$\chi_{psit}, XV_{gsit}, Q4_{mit}, Q_{mirt}, YV_{girt}, L_{mrjt}, ZV_{grjt}, H3_{mjct}, MV_{gjct}, Q1_{mir,t-1}, L1_{mrj,t-1} \ge 0 \tag{27}$$

Also, some decision variables are just zero or one:

$$W1_{rt} \begin{cases} 1 & \text{if warehouse establish in potential location r in time period t} \\ 0 & \text{othewise} \end{cases}$$

$$Y_{jt} \begin{cases} 1 & \text{if distribution centre establish in potential location j in time period t} \\ 0 & \text{otherwise} \end{cases}$$

X_{mit} $\begin{cases} 1 & \text{if the technology m used in plant i is used in time period t} \\ 0 & \text{otherwise} \end{cases}$

4- Problem solution approach

There is a wide variety of solution methods which can be employed for solving multi-objective SSCMM including the weighted sum of objectives, epsilon-constraint, goal programming and fuzzy multi-objective programming (Eskandarpour et al., 2015). In some cases, hybrid approaches such as goal programming and fuzzy multi-objective programming have been used (Eskandarpour et al., 2015). In the current paper, the hybrid approach of fuzzy-goal programming is used to solve the SSCMM problem. Goal Programming is one of the most common techniques for solving optimization problems which was introduced by Charnes and Cooper (1961). In GP, we try to minimize the total deviations of each objective value from its aspiration level, which is determined in advance as a goal. The aspiration level doesn't have a precise value in reality due to uncertainty. Hence, combining fuzzy sets with GP, which was developed by Bohner and Minner (2017) and Arıkan and Güngör (2001) can be a good solution. As regards the constraints, some have imprecise values which need to be considered fuzzily and others have precise values and should be considered as hard constraints such as zero-one constraints or balance constraints. Hence, the following steps should be taken:

1) The possibility distribution is defined as the degree of occurrence of events with ambiguous data (Zadeh, 1978) adopting the triangular possibility distribution for all imprecise numbers (Lai and Hwang, 1992). For instance, in order to establish the triangular possibility distribution of the imprecise number$\widetilde{C_{ij}}$, three prominent data items should be given as follows:

1.(a): pessimistic value (c_{ij}^{l}) which has a very low likelihood to the set to which it belongs.

1.(b): possible value (c_{ij}^{r}) which has definite likelihood in the set to which it belongs.

1.(c): optimistic value (c_{ij}^{u})which has a very low likelihood in the set to which it belongs.

2) In order to solve the imprecise objective functions, a triangular possibility distribution will be designed using the three points $(w_1^u.0)$, $(w_1^r.1)$ and $(w_1^l.0)$ based on Lai and Hwang (1992). The method minimizes w_1^r, maximizes $(w_1^r - w_1^u)$ and minimizes $(w_1^l - w_1^r)$ for the ***minimization objective function***:

2.(a): $\min w1 = (C_i^r) = \sum_{i=1}^{n} (C_i^r) X_i$

2.(b): $\max w2 = (C_i^r - C_i^l) = \sum_{i=1}^{n} (C_i^r - C_i^l) X_i$

2.(c): $\min w3 = (C_i^u - C_i^r) = \sum_{i=1}^{n} (C_i^u - C_i^r) X_i$

3) in ***maximization objective functions***:

3.(a): $\max w4 = (C_i^r) = \sum_{i=1}^{n} (C_i^r) X_i$

3.(b): $\min w5 = (C_i^r - C_i^l) = \sum_{i=1}^{n} (C_i^r - C_i^l) X_i$

3.(c): $\max w6 = (C_i^u - C_i^r) = \sum_{i=1}^{n} (C_i^u - C_i^r) X_i$

4) The constraints which have imprecise values are defined using the following triangular possibility distribution and the ***fuzzy constraints*** are designed:

4.(a): $A_j^l = \sum_{j=1}^{k} a_{j\beta}^l X_j \le b_{j\beta}^l$

4.(b): $A_j^r = \sum_{j=1}^{k} a_{j\beta}^r X_j \le b_{j\beta}^r$

4.(c): $A_j^u = \sum_{j=1}^{k} a_{j\beta}^u X_j \le b_{j\beta}^u$

5) All the fuzzy objective functions are converted to the ***fuzzy-GP constraints*** under the following condition and are added to the ***hard constraints*** which have precise values.

5.(a): $(C_i^r) = \sum_{i=1}^{n} (C_i^r) X_i - d_i^+ r + d_r^- r = Goal_i r$

5.(b): $(C_i^r - C_i^l) = \sum_{i=1}^{n} (C_i^r - C_i^l) X_i - d_i^+ l + d_i^- l = Goal_i l$

5.(c): $(C_i^u - C_i^r) = \sum_{i=1}^{n} (C_i^u - C_i^r) X_i - d_i^+ u + d_i^- u = Goal_i u$

The d_i^- and d_i^+ are, respectively, the negative and positive deviations from/toward the aspired value $Goal_i$

6) Each of the multi-objective fuzzy functions will be a ***fuzzy-GP single-objective function*** which is a minimization objective function and aimed at minimizing the deviation from the goal value. This function can be expressed as:

6.(a): $MinWl = \min \sum_{i=1}^{k} (d_i^- l / Goal_i l + d_i^+ l / Goal_i l)$

6.(b): $MinWr = \min \sum_{i=1}^{k} (d_i^- r / Goal_i r + d_i^+ r / Goal_i r)$

6.(c): $MinWu = \min \sum_{i=1}^{k} (d_i^- u / Goal_i u + d_i^+ u / Goal_i u)$

All d_i^- and d_i^+ deviation are divided to their $Goal_i$ in order to be normalized. Hence, the triangular final single objective function of the model with aim of minimizing the deviation with the goals, with the hard and fuzzy constraints and fuzzy-GP constraints are provided in Appendix B.

5- Problem solution

In order to solve the mixed integer quadratic programming in the SSCMM problem, the Branch and Bound (B&B) algorithm in LINGO software is used. The software is run three times in order to estimate the lower, median and upper values of the objective functions and the optimum amount for the decision variables. The value of the final objective is (0, 0.33, and 0.3311474). In order to estimate the value of the objectives, first, their goals need to be estimated. To do so, every objective function is run separately without considering the rest to find its goal values. These values are given in table 2.

Table2. The goal value of fuzzy-goal programming objective functions

Objective Function	*Goall*	*Goalr*	*Goalu*
W1(Toomans)	32,970,440,000	125,486,000,000	4,662,788,000,000
W2(milligram per cubic meters)	7.151089	19.82946	57.47024
W3(milligram per cubic meters)	14921.16	152774.8	453676
W4 (number)	69	72	912

Subsequently, the triangular values of the positive and negative deviations of each objective function from its goals are estimated (see table 3).

Table 3. the triangular values of positive and negative deviations of each objective function

Objective Function	d^{+l}	d^{+r}	d^{+u}	d^{-l}	d^{-r}	d^{-u}
W1(Toomans)	10,468,410,000	41,410,390,000	0	0	0	1,542,423,000,000
W2(milligram per cubic meters)	0.8471529	0	0	0	0.2946	0.0201402
W3(milligram per cubic meters)	6596.780	0	0	0	35378.9	3.4
W4 (number)	0	0	0	0	0	0

The value of each objective function with regards to its deviations are given in table 4. For instance, the first objective function concerns minimizing costs. As can be seen, the lower and median value of the objective function are higher than the lower and median value of the goal but its upper value is lower than the upper value of the goal. It can be concluded that the plants' costs are increasing.

Table 4. The triangular values of objective functions

Objective Function	***Objectives values with regards to their deviation from the goals***
(w1l,w1r,w1u)(Toomans)	(43,438,850,000, 866,896,390,000, 3,120,365,000,000)
(W2l,w2r,w2u)(milligram per cubic meters)	(7.9982419, 19.8, 57.2688378)
(W3l,w3r,w3u)(milligram per cubic meters)	(21517.94, 117386.9, 453672.6)
(W4l,w4r,w4u)(number)	(69, 72, 912)

The optimum values of the decision variables are then estimated some of which have been reported. In table 5, the optimum amounts for supplying different raw materials (tons) from different suppliers for different manufacture centres during different time periods (months) are shown. The first column shows the three kinds of raw materials, the second column shows the three groups of suppliers, the third column shows the manufacture centres and the last two columns are time periods. For instance, manufacture centre 1 must provide the triangular amount of raw material kinds 1, 2, and 3 from suppliers

1, 2, and 3 during time periods 1, and 2. For example, the fuzzy amount of raw material kind 1 from supplier 3 for manufacture centre 1 is (12.15, 33.51, 37.65) tones (red row). It can be said that the optimum amount of raw material should be within this range which means that the mentioned amounts of raw materials are reported fuzzily and the manufacturers can select these amounts from the given range. Also, this manufacturer centre must provide the rest of the raw materials from other suppliers based on the suggested fuzzy amounts in the table for time period 1 or 2.

Table 5. The optimum amount of raw materials *p* which supply from supplier *s* to manufacture centre *i* in time period *t*

χ_{psit} (tones)

Raw materials (p)	Supplier (s)	Manufacture centre (i)	Time periods (t)	
			1	2
1	1	1	(12.85, 36.40, 44.68)	(12.15, 36.29, 47)
1	1	2	(11.28, 36.40, 65.31)	(12.89, 36.29, 47)
1	2	1	(12.63, 36.15, 37.65)	(11.01, 33.89, 46.66)
1	2	2	(13.11, 33.51, 42.34)	(13.85, 33.47, 37.74)
1	3	1	(12.15, 33.51, 37.65)	(14.62, 33.47, 46.33)
1	3	2	(15.34, 38.79, 42.24)	(12.86, 38.85, 40.12)
2	1	1	(12.79, 38.79, 40)	(12.33, 38.85, 47)
2	1	2	(11.39, 40.65, 56)	(12.80, 40.78, 47)
2	2	1	(13.93, 40.65, 46)	(12.22, 40.78, 46.66)
2	2	2	(14.71, 42.07, 47)	(15.42, 42.10, 47.74)
2	3	1	(10.85, 42.07, 47.12)	(12.90, 42.10, 47)
2	3	2	(13.41, 38.75, 40)	(11.34, 38.85, 47)
3	1	1	(13, 38.79, 56)	(12.42, 38.85, 47)
3	1	2	(11.65, 39.18, 40)	(13.08, 39.32, 46.66)
3	2	1	(12.74, 39.18, 47)	(11.33, 39.32, 47.66)
3	2	2	(13.47, 38.40, 40)	(14.11, 38.42, 46)
3	3	1	(11.05, 38.40, 47)	(13.03, 38.42, 40.42)
3	3	2	(13.69, 39.15, 47)	(11.64, 39.20, 48)

In addition, the optimum amount of production resulting from a particular technology can be seen in table 6. The first column demonstrates the kind of technology, the second column is the kind of manufacture centre and the last two columns show time periods. For instance, the optimum triangular amount of production with technology 2 in manufacture centre 1 for one month is (120, 310, 330) tones. It can be said that the optimum amount of production should be within the given range with the related technology. This means that the stated quantities of production are reported fuzzily and the manufacturers can select the amount of production from the given range. Also, this manufacture centre must choose the amount of production with other technologies based on the suggested fuzzy amounts in Table 5 during time period 1 or 2. In other words, the optimum amount of production with technology 2, should be within the given range in order to reach the goals of minimizing costs and maximizing employment opportunities.

Table 6. The optimum amount of production with technology m in manufacture centre i in time

$Q4_{mit}$ ***(squared-meter)***

Technology (m)	**Manufacture centre (i)**	**Time periods (t)**	
		1	2
1	1	(120, 300, 330)	(120, 300, 330)
1	2	(120, 310, 330)	(124, 310, 330)
2	1	(120, 310, 330)	(140, 310, 330)
2	2	(150, 300, 330)	(124.86, 300, 330)
3	1	(102, 310, 330)	(105, 310, 330)
3	2	(120, 310, 330)	(120, 310, 310)

Another optimum value, is the number of vehicles g used for transportation from distribution centre j to end user c during time t (see table 7). For instance, the number of vehicles in mode 1 from distribution centre 3 to end user 2 during time t, is (0, 2, and 4). This means that the optimum number of vehicles in mode 1 can be chosen from the given range but this number should be no less than the lowest, and no more than the highest quantity in order to be at optimum level. The modes of transportation, the kind of distribution centre, the kind of end user and time periods are all effective in relation to the number of transportation vehicles. Also, it can be said that the optimum number for vehicle kind 2 used for transporting products from distributor centre 1 to end user 1 is in the range of (1, 3, 8).

Table 7. The optimum number of transportation for transporting from distribution centres to the end users MV_{gjct} (Number of transportation)

Transportation mode (g)	**Distribution centres (j)**	**End users (c)**	**Time period (t)**	
			1	2
1	1	1	(2,4,6)	(2,4,6)
1	1	2	(2,4,6)	(2,4,6)
1	1	3	(2,4,6)	(2,4,6)
1	2	1	(0,2,3)	(0,2,3)
1	2	2	(0,2,3)	(0,2,3)
1	2	3	(0,2,3)	(0,2,3)
1	3	1	(0,2,4)	(0,2,4)
1	3	2	(0,2,4)	(0,2,4)
1	3	3	(2,4,5)	(2,4,5)
2	1	1	(1,3,8)	(1,3,8)
2	1	2	(1,3,8)	(1,3,8)
2	1	3	(1,3,8)	(1,3,8)
2	2	1	(0,3,3)	(0,3,3)
2	2	2	(0,3,3)	(0,3,3)
2	2	3	(0,3,3)	(0,3,3)
2	3	1	(0,1,3)	(0,1,3)
2	3	2	(0,1,3)	(0,1,3)
2	3	3	(0,1,3)	(0,1,3)
3	1	1	(2,4,6)	(2,4,6)
3	1	2	(2,4,6)	(2,4,6)
3	1	3	(2,4,6)	(2,4,6)
3	2	1	(0,2,4)	(0,2,4)
3	2	2	(0,2,4)	(0,2,4)
3	2	3	(0,2,4)	(0,2,4)
3	3	1	(0,2,4)	(0,2,4)
3	3	2	(0,2,4)	(0,2,4)
3	3	3	(0,2,4)	(0,2,4)

5-2- Sensitivity analysis

In this section, a set of sensitivity analyses on different parameters of the model is carried out in order to validate the proposed model. This is done to explore potential trade off solutions. We have observed the effect of changes in the minimum demand of distribution centre j during time period t ($\bar{D}6_{jt}$) on the objective functions (tables 7-10). So, we increase the amount of the mentioned parameter 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% and report the effects on the objective functions. The increase in the amount of the demand causes steady increase in costs (W1). It can be said that the increase in demand increases the variable costs including purchasing and transporting raw materials from the suppliers to the plants, producing and transporting the final products to the warehouses, the cost of storing the final products in the warehouses and the cost of transporting the final products from the warehouses to the distribution centres and storing them there
(table 8).

Table8. The effect of demand of distribution centre parameter on the first objective function

	w1		
$\bar{D}6_{jt}$	L	R	U
10%	43548460000	86749310000	3120366000000
20%	43548460000	86719310000	3120368000000
30%	43568140000	86749300000	3120379000000
40%	52521940000	86759310000	3120380000000
50%	52534910000	86769610000	3120381000000
60%	52564900000	86769800000	3120381000000
70%	53179580000	86938441000	3120383000000
80%	53579590000	86939590000	3120384000000
90%	53579620000	86941800000	3124385000000
100%	54502840000	87117200000	3321240000000

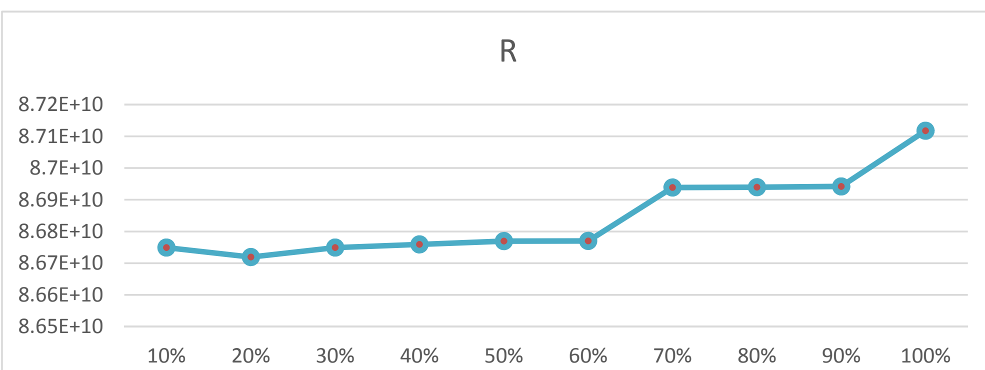

Fig 2. The effect of demand of distribution centre parameter on R based on w1

Also, the increase of demand causes increase in air pollution and industrial dusts (tables 9 and 10). It can be said that the increase in demand causes increase in the amount of production and the amount of distribution. Hence, the amount of air pollution created during the transportation process and the amount of industrial dust which is increased during the production process will increase.

Table 9. The effect of demand of distribution centre parameter on the second objective function

	w2		
$\tilde{D}6_{jt}$	L	M	U
10%	19.79954	24.74560	57.27884
20%	19.89954	24.74560	57.27884
30%	19.98904	27.74573	57.28124
40%	21.16479	24.74590	57.28884
50%	21.16480	24.74596	57.28884
60%	21.16484	24.74697	57.28884
70%	21.16486	24.77460	57.28995
80%	21.16489	24.77590	57.29887
90%	21.16491	24.79300	57.33204
100%	21.51421	24.91400	57.49320

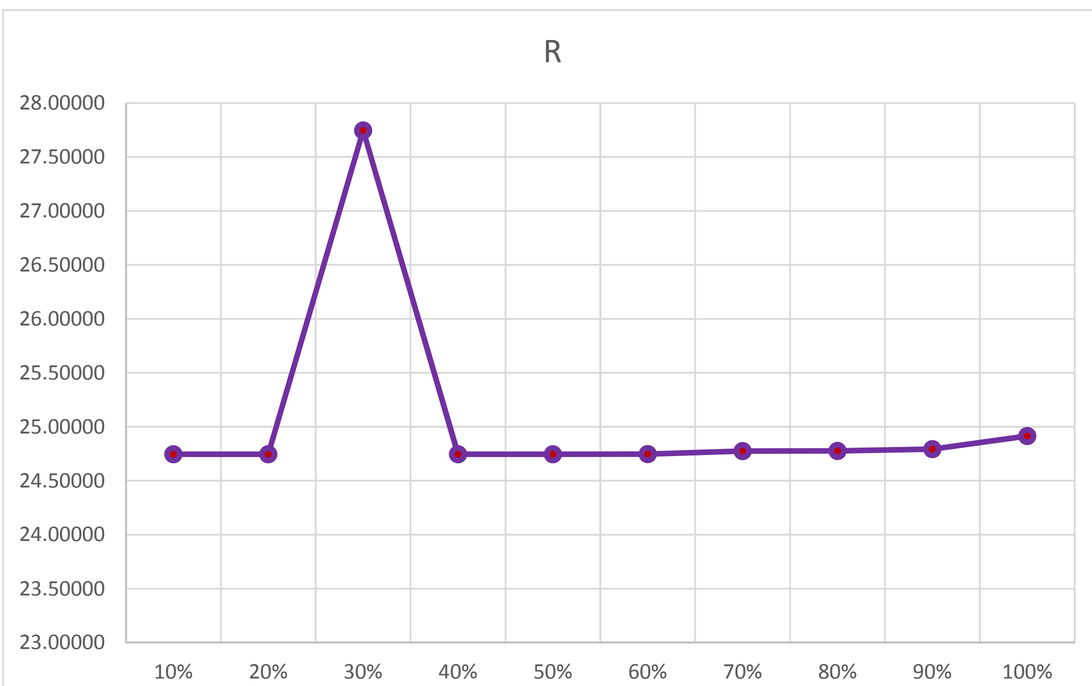

Fig 3. The effect of demand of distribution centre parameter on R based on w2

Table 10. The effect of demand of distribution centre parameter on the third objective function

w3

$\tilde{D}6_{jt}$	L	R	U
10%	33953.50000	278144.20000	453675.60000
20%	33954.90000	278153.60000	453784.00000
30%	33954.30000	278165.00000	453676.00000
40%	33995.80000	278184.80000	453676.60000
50%	33995.90000	278189.20000	453670.60000
60%	33996.00000	278189.40000	453672.90000
70%	33996.06000	278288.90000	453674.80000
80%	33996.10000	278348.00000	453674.80000
90%	33998.20000	278940.00000	453678.60000
100%	34115.00000	279982.00000	455421.90000

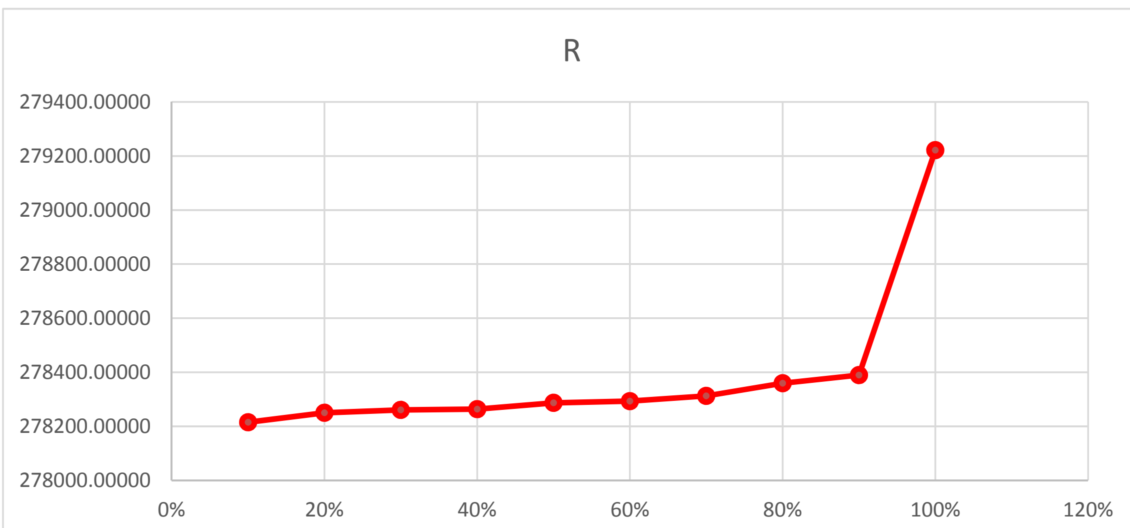

Fig 4. The effect of demand of distribution centre parameter on R based on w3

What is surprising is that the amount of demand does not affect the social objective function. This is because of the kind of decision variables. They are related to job opportunities which are not under the influence of the number of demands (table 11).

Table11. The effect of demand of distribution centre parameter on the fourth objective function

	w4		
$\tilde{D6}_{jt}$	L	R	U
10%	69	72	912
20%	69	72	912
30%	69	72	912
40%	69	72	912
50%	69	72	912
60%	69	72	912
70%	69	72	912
80%	69	72	912
90%	69	72	912
100%	69	72	912

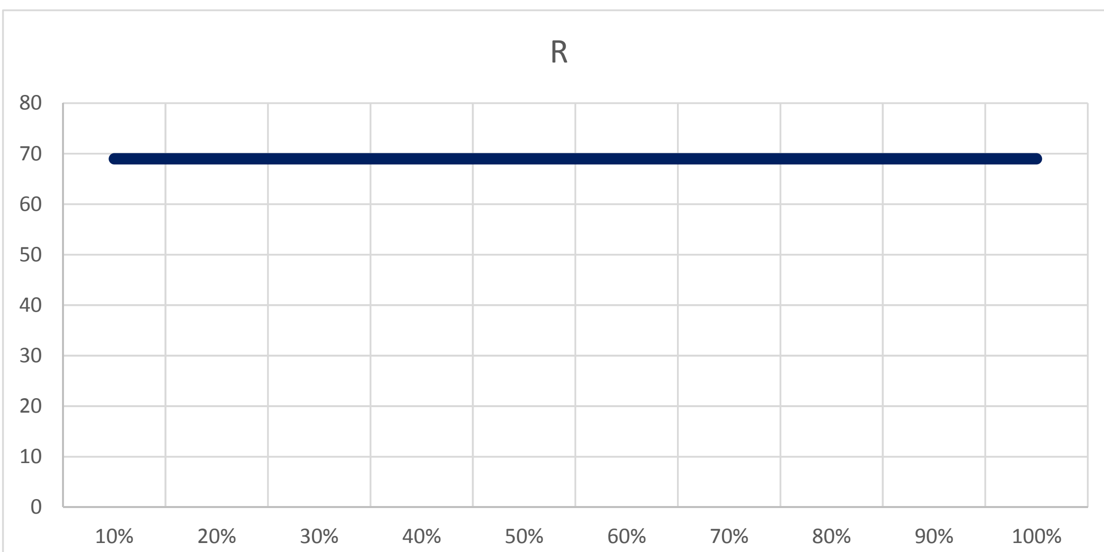

Fig 5. The effect of demand of distribution centre parameter on R based on w4

Also, we followed up the effect of changes in the maximum capacity of production in plant i during time period t ($\tilde{cap1}_{it}$) on the objective functions (Tables 12-15). The results demonstrate that the changes in the parameter cause change in the related objective functions. As Table 11 shows, the increase in the capacity of plant i will cause increase in the variable and fixed costs. It can be said that the growth in capacity will need more investment in setting up warehouses and distribution centres, and that the amount of production will increase which will, consequently, cause increase in in the total costs.

Table 12. The effect of increasing the capacity of plant i parameter on the first objective function

$\tilde{cap1}_{it}$	W1 L	R	U
10%	32,800,334,400	86,749,310,000	3,120,365,000,000
20%	43,800,335,400	86,749,470,000	3,120,369,000,000
30%	49,210,324,510	86,774,900,000	3,120,423,000,000
40%	53,290,970,000	86,789,400,000	3,120,468,000,000
50%	54,320,910,000	86,789,900,000	3,120,481,000,000
60%	56,442,900,000	86,912,400,000	3,120,496,000,000
70%	56,943,200,000	86,929,800,000	3,120,520,000,000
80%	57,041,600,000	86,949,310,000	3,120,568,000,000
90%	59,021,800,000	86,999,310,000	3,120,574,000,000
100%	62,029,800,000	87,900,310,000	3,120,620,000,000

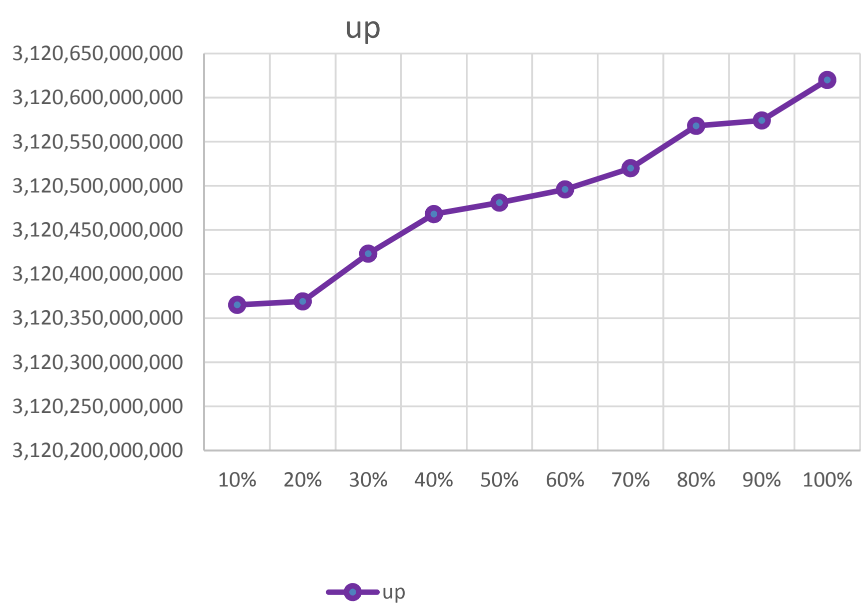

Fig 6. The effect of increasing the capacity of plant i parameter on up based on w1

Also, as a result of increase in the capacity, the amount of air pollution and industrial dust will increase (see tables 13 and 14). This is because of the growth in the amount of production which not only causes increase in the amount of industrial dust but also results in air pollution through increase in the distribution of raw materials among the plants or transportation of products to the customers.

Table 13. The effect of increasing the capacity of plant i parameter on the second objective function W2

$\bar{cap1}_{it}$	L	R	U
10%	21.16479	24.74590	57.26884
20%	21.17490	24.74590	57.30812
30%	21.21470	24.74590	57.34234
40%	21.26479	24.74590	57.36884
50%	21.27312	24.74590	57.39832
60%	21.29402	24.74590	57.41246
70%	21.31908	24.74590	57.43347
80%	21.38479	24.74590	57.46884
90%	21.41257	24.74590	57.49347
100%	21.45297	24.74590	57.52307

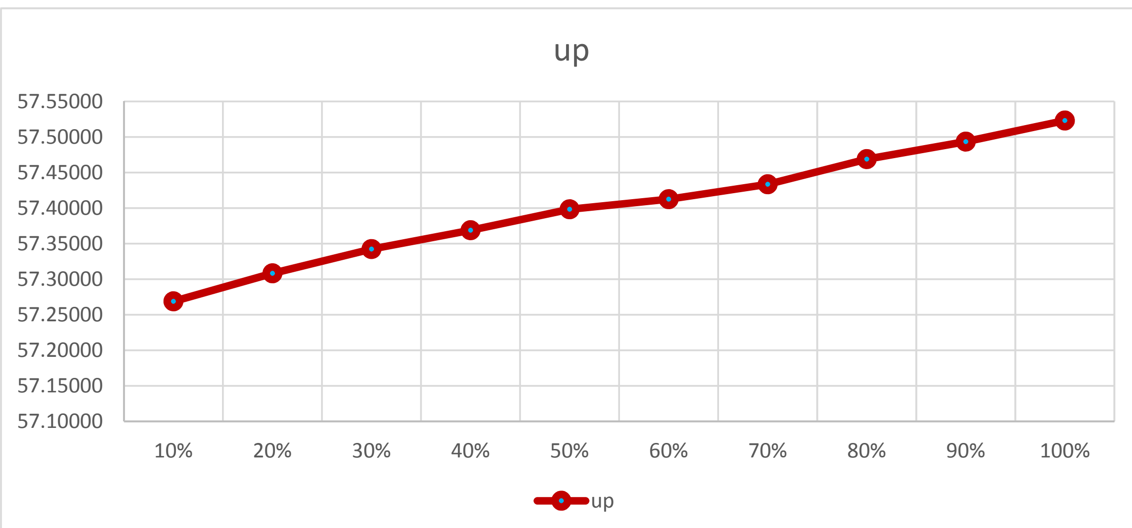

Fig 7. The effect of increasing the capacity of plant i parameter on up based on w2

Table 14. The effect of increasing the capacity of plant i parameter on the third objective function

	W3		
$c\tilde{a}p1_{it}$	L	R	U
10%	33930.00000	278214.90000	463672.60000
20%	33930.00000	278250.00000	463672.68000
30%	33930.00000	278261.00000	463670.12000
40%	33930.10000	278263.30000	463672.90000
50%	33961.00000	278286.90000	463689.00000
60%	33994.20000	278293.10000	463991.40000
70%	34008.20000	278312.60000	470157.30000
80%	34030.10000	278359.30000	473673.60000
90%	34068.00000	278389.40000	477812.90000
100%	34075.40000	279221.70000	479536.40000

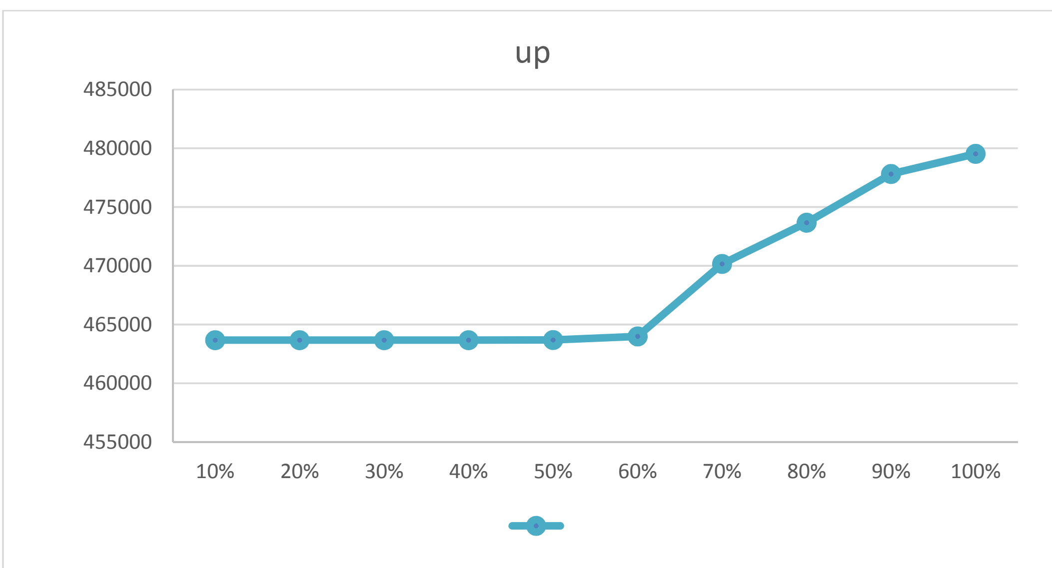

Fig 8. The effect of increasing the capacity of plant i parameter on up based on w3

Also, the social responsibility which is defined as creation of job opportunities does not change due to increase in capacity (W4). This is because of the kind of chosen parameter which is not under the influence of capacity (see Table 15).

Table 15. The effect of increasing the capacity of plant i parameter on the fourth objective function

	W4		
$\tilde{cap1}_{it}$	L	R	U
10%	69	72	912
20%	69	72	912
30%	69	72	912
40%	69	72	912
50%	69	72	912
60%	69	72	912
70%	69	72	912
80%	69	72	912
90%	69	72	912
100%	69	72	912

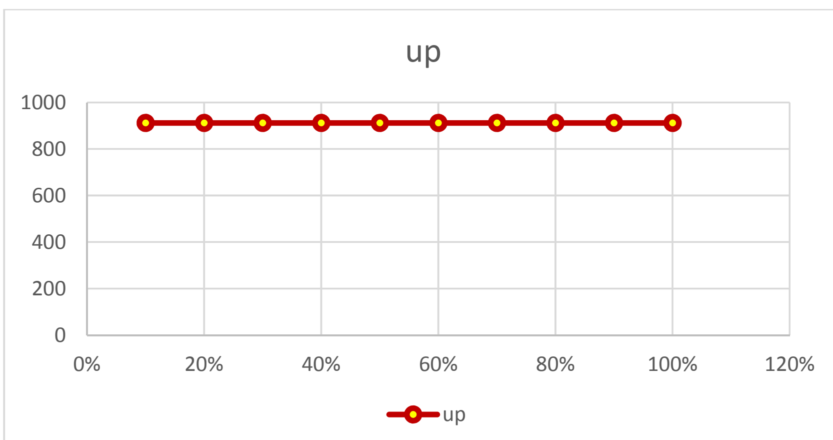

Fig 9. The effect of increasing the capacity of plant i parameter on up based on w4

6- Conclusion

In this research, a mathematical model is proposed for multi-period, multi-echelon, and multi-product considering technology and quality in order to create a sustainable supply chain model in CTI. The model includes five layers in a forward flow including suppliers, manufacturing centres, warehouses, distribution centres and end users. The model objectives are to minimize the variable and fixed costs and air pollution and maximize social responsibility. Moreover, the kind of technology, transportation mode and product quality are considered. The selection of the supplier, manufacture centre, warehouse, distribution centre and end user are other issues which are considered. Therefore, this paper designs a SSCMM in CTI. The fuzzy logic approach is utilized in order to show the real values of imprecise parameters. Finally, the provided nonlinear model is solved using the goal programming approach. In order to validate the model and show the application of the model, a numerical example in CTI is performed by LINGO. As the number of the fuzzy parameters is high, the results are reported fuzzily. Also, sensitivity analysis is carried out on some parameters and validates their performance. The results demonstrate that any changes in the minimum product demand cause increase in the cost of supplying raw materials, in the amount of production, the cost of production and the cost of transportation of raw materials and final products. As the results show, on the one hand, increase in demand causes relatively mild increase in dust pollution which causes environmental pollution, because CTI has a mass production system and the amount of supplied raw materials is not under the effect of demand level. On the other hand, increase in demand has a significant effect on increase in the number of transportation modes for transporting raw materials and final products along the supply chain. The results are along with Gabaldón-Estevan et al. (2016). They concluded that the production in CTI has major impact on the cost of production and environment. Also, they showed that the production technology has major rule in being environmental friendly. Also, Gabaldón-Estevan et al. (2014) demonstrated that production capacity has great effect on the environmental and economic costs of the supply chain. They concluded that the managers should force a convergence between economic and environmental sustainability. What is surprising is that increase in demand does not affect job opportunity because employees work in various work shifts and increase in demand will not affect employment rate. Also, the results demonstrate that increase in the capacity of production centres increases the costs of establishing production centres, warehouses, and distribution centres, environmental pollution including industrial dusts, by products and carbon dioxide emissions. The surprising thing is that it is not effective on job opportunities. Hence, managers should provide a balance between demand and production capacity. Consequently, they can enhance cost-effective, environment- and society-friendly activities. The sensitivity analysis demonstrates that any changes in the minimum demand for products or increase in the capacity of plants cause steady increase in the cost of production, carbon dioxide emission and industrial dust. It can be concluded that there should be a balance between the amount of emissions resulting from production and social responsibility. Managers should not only focus on economic benefits but also consider the environment. In addition, managers should ignore production and focus on costs and technology, and move towards adjusting production capacity and increasing production flexibility, value added and stronger brand and distribution channel control, including design and aesthetics. A good strategy might be production and promotion of ‘green’ ceramic tiles. Moreover, working on robust, stochastic optimizations to obtain more realistic results is recommended. In addition, considering a discount offered by suppliers on raw materials or by the manufacture centre on products for end users makes the model more possible.

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Appendix A

The parameters and decision variables, which have imprecise number, are shown with ~ sign.

Parameters

$\tilde{b}_{psit}$	Cost of providing raw material p from supplier s for plant i in time period t
$\tilde{\delta}_{psit}$	Cost of transmitting a unit of raw material p from supplier s for plant i in time period t
$\tilde{V}_{rt}$	Fixed cost of establishment of warehouse r in time period t
$\tilde{G}1_{jt}$	Fixed cost of establishment of distribution centre j in time period t
$\tilde{P}1_{mit}$	Cost of producing product in plant i in time period t which produced by technology m
$\tilde{C}1_{irt}$	Cost of transmitting product from plant i to warehouse r in time period t
$\tilde{M}2_{rt}$	Cost of storing product in warehouse r in time period t
$\tilde{C}2_{rjt}$	Cost of transmitting product from warehouse r to distribution centre j in time period t
$\tilde{M}1_{jt}$	Cost of storing product in distribution centre j in time period t
$\tilde{P}2_{mrjt}$	The fixed price of every unit of transmitted product, which produced with technology m, from warehouse r to distribution centre j in time period t.
$\tilde{\omega}_{pst}$	The maximum capacity of supplying raw material p by supplier s in time period t
$\tilde{cap}1_{it}$	The maximum capacity of producing product in plant i in time period t
$\tilde{cap}2_{rt}$	The maximum capacity of storing in warehouse r in time period t
$\tilde{cap}3_{jt}$	The maximum capacity of storing product in distribution centre j in time period t
$\tilde{cap}4_{gt}$	The maximum capacity of transportation's vehicle g in time period t
$\tilde{D}_{ct}$	The potential demand of end-user c in time period t

$\tilde{gh}_{it}$	The mean amount of emission of industrial dust per crush of tone of raw material in plant i in time period t
$\tilde{WH}_{it}$	The maximum allowable emission of industrial dust in plant i in time period t.
$\tilde{S1}_{mit}$	The mean amount of produced hazardous by product which using technology m in plant i in time period t.
$\tilde{HM}_{it}$	The maximum allowable emission of hazardous by product in plant i in time period t.
$\tilde{CE}$	The amount of carbon dioxide emission of transmitting per gram to kilometre
$\tilde{HE}_{gt}$	The maximum allowable carbon dioxide emission for transporting with vehicle g in time period t.
$d1_{si}$	The distance (kilometre) between supplier s and plant i
$d2_{ir}$	The distance (kilometre) between plant i and warehouse r
$d3_{rj}$	The distance (kilometre) between warehouse r and distribution centre j
$d4_{jc}$	The distance (kilometre) between distribution centre j and end-user c
$\tilde{O1}_{mit}$	The total provided job opportunities in plant i with technology m in time period t
$\tilde{O2}_{rt}$	The total provided job opportunities in warehouse r in time period t
$\tilde{O3}_{jt}$	The total provided job opportunities in distribution centre j in time period t
$\tilde{I1}_{mit}$	The mean of lost work day which caused by using technology m in time period t
ke_{gsit}	The fare of transmitting with vehicle g from supplier s to plant i in time period t
$ke1_{girt}$	The cost of transmitting per tones of product with vehicle g from plant i to warehouse r in time period t
$ke2_{grjt}$	The cost of transmitting per tones of product with vehicle g from warehouse r to distribution centre j in time period t
$\tilde{D4}_{rt}$	The minimum demand of warehouse r in time period t.
$\tilde{D6}_{jt}$	The minimum demand of distribution centre j in time period t.
$\tilde{ub}_{it}$	The mean number of required workforce for producing a unit of product in plant i in time period t.
$\tilde{B1}_{it}$	The minimum number of required workforce in plant i in time period t.
$\tilde{uo}_{rt}$	The mean number of required workforce for storing every unit of product in warehouse r in time period t.
$\tilde{ur}_{jt}$	The mean number of required workforce for storing every unit of product in distribution centre j in time period t.
$\tilde{Goal1}$	The goal of the all costs of supply chain

$\bar{Goal}2$	The goal of amount emission of industrial dusts and hazardous emissions in production centres
$\bar{Goal}3$	The goal of the amount of carbon dioxide emission
$\bar{Goal}4$	The goal of the employment opportunity in supply chain

Decision variables

χ_{psit}	The amount of raw materials p (per tones) which is supplied by supplier s to plant i in time period t
$Q4_{mit}$	The amount of produced product with technology m in plant i in time period t
Q_{mirt}	The amount of produced product with technology m in plant i and transmitted to warehouse r in time period t
L_{mrjt}	The number of transmitted produced products with technology m from warehouse r to distribution centre j in time period t.
$Q1_{mir,t-}$	The amount of product in warehouse r in time t-1.
$L1_{mrj,t-1}$	The amount of product in distribution centre in time t-1.
$H3_{mjct}$	The amount of transmitted produced product with technology m from distribution centre j to end-user c in time period t
XV_{gsit}	The number of vehicle g for transmitting raw material from supplier s and plant i in time period t
YV_{girt}	The number of vehicle g for transmitting product from plant i to warehouse r in time period t
ZV_{grjt}	The number of vehicle g for transmitting product from warehouse r to distribution centre j in time period t
MV_{gjct}	The number of vehicle g for transmitting product from j to end-user c in time period t.

$$W1_{rt} \begin{cases} 1 & \text{if warehouse establish in potential location r in time period t} \\ 0 & \text{othewise} \end{cases}$$

$$y_{jt} \begin{cases} 1 & \text{if distribution centre establish in potential location j in time period t} \\ 0 & \text{otherwise} \end{cases}$$

$$X_{mit} \begin{cases} 1 & \text{if the plant i use the technology m in time period t} \\ 0 & \text{otherwise} \end{cases}$$

Appendix B

fuzzy-GP objective function

$$Min\,W\,l = d1^{-}/Goal1l + d2^{-}/Goal2l + d3^{-}/Goal3l + d4^{+}/Goal4l$$

$$Min\,W\,r = d1^{+}r/Goal1r + d2^{+}r/Goal2r + d3^{+}r/Goal3r + d4^{-}r/Goal4r$$

$$Min\,W\,u = d1^{+}u/Goal1u + d2^{+}u/Goal2u + d3^{+}u/Goal3u + d4^{-}u/Goal4u$$

The first *minimization fuzzy-GP constraint*

$$\begin{aligned}
&\sum_{g}^{G}\sum_{p}^{P}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left(((b^{r}_{psit}-b^{l}_{psit})\times\chi_{psit})+((\delta^{r}_{psit}-\delta^{l}_{psit})\times(cap4^{r}_{g}-cap4^{l}_{g})\times XV_{gsit})\right)\\
&+\sum_{r}^{R}\sum_{t}^{T}\left((V^{r}_{rt}-V^{l}_{rt})\times W1_{rt}\right)+\sum_{j}^{J}\sum_{t}^{T}\left((G1^{r}_{jt}-G1^{l}_{jt})\times Y_{jt}\right)\\
&+\sum_{g}^{G}\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left(((P1^{r}_{mit}-P1^{l}_{mit})\times Q_{mirt})+((C1^{r}_{irt}-C1^{l}_{irt})\times(cap4^{r}_{g}-cap4^{l}_{g})\times YV_{girt})\right)\\
&+\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left((M1^{r}_{rt}-M1^{l}_{rt})\times Q_{mirt}\right)+\sum_{g}^{G}\sum_{m}^{M}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\begin{pmatrix}((P2^{r}_{mrjt}-P2^{l}_{mrjt})\times L_{mrjt})\\+((C2^{r}_{rjt}-C2^{l}_{rjt})\times(cap4^{r}_{g}-cap4^{l}_{g})\times ZV_{grjt})\end{pmatrix}\\
&+\sum_{m}^{M}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\left((M2^{r}_{jt}-M2^{l}_{jt})\times L_{mrjt}\right)-d1^{+}l+d1^{-}l=Goal1l.
\end{aligned}$$

$$\begin{aligned}
&\sum_{g}^{G}\sum_{p}^{P}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left((b^{r}_{psit}\times\chi_{psit})+(\delta^{r}_{psit}\times cap4^{r}_{g}\times XV_{gsit})\right)+\sum_{r}^{R}\sum_{t}^{T}\left(V^{r}_{rt}\times W1_{rt}\right)\\
&+\sum_{j}^{J}\sum_{t}^{T}\left(G1^{r}_{jt}\times Y_{jt}\right)+\sum_{g}^{G}\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left((P1^{r}_{mit}\times Q_{mirt})+(C1^{r}_{irt}\times cap4^{r}_{g}\times YV_{girt})\right)\\
&+\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left(M1^{r}_{rt}\times Q_{mirt}\right)+\sum_{g}^{G}\sum_{m}^{M}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\left((P2^{r}_{mrjt}\times L_{mrjt})+(C2^{r}_{rjt}\times cap4^{r}_{g}\times ZV_{grjt})\right)\\
&+\sum_{m}^{M}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\left(M2^{r}_{jt}\times L_{mrjt}\right)-d1^{+}r+d1^{-}r=Goal1r.
\end{aligned}$$

$$\begin{aligned}
&\sum_{g}^{G}\sum_{p}^{P}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left(((b^{u}_{psit}-b^{r}_{psit})\times\chi_{psit})+((\delta^{u}_{psit}-\delta^{r}_{psit})\times(cap4^{u}_{g}-cap4^{r}_{g})\times XV_{gsit})\right)\\
&+\sum_{r}^{R}\sum_{t}^{T}\left((V^{u}_{rt}-V^{r}_{rt})\times W1_{rt}\right)+\sum_{j}^{J}\sum_{t}^{T}\left((G1^{u}_{jt}-G1^{r}_{jt})\times Y_{jt}\right)\\
&+\sum_{g}^{G}\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left(((P1^{u}_{mit}-P1^{r}_{mit})\times Q_{mirt})+((C1^{u}_{irt}-C1^{r}_{irt})\times(cap4^{u}_{g}-cap4^{r}_{g})\times YV_{girt})\right)\\
&+\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left((M1^{u}_{rt}-M1^{r}_{rt})\times Q_{mirt}\right)+\sum_{g}^{G}\sum_{m}^{M}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\begin{pmatrix}((P2^{u}_{mrjt}-P2^{r}_{mrjt})\times L_{mrjt})\\+((C2^{u}_{rjt}-C2^{r}_{rjt})\times(cap4^{u}_{g}-cap4^{r}_{g})\times ZV_{grjt})\end{pmatrix}\\
&+\sum_{m}^{M}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\left((M2^{u}_{jt}-M2^{r}_{jt})\times L_{mrjt}\right)-d1^{+}u+d1^{-}u=Goal3u.
\end{aligned}$$

The second *minimization*

fuzzy-GP constraint

$$\begin{aligned}
&\sum_{p}^{P}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left((gh^{r}_{it}-gh^{l}_{it})\times\chi_{psit}\right)+\left[\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left((S1^{r}_{mit}-S1^{l}_{mit})\times Q_{mirt}\right)\right]\\
&-d2^{+}l+d2^{-}l=Goal2l.
\end{aligned}$$

$$\sum_{p}^{P}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left(gh^{r}_{it}\times\chi_{psit}\right)+\left[\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left(S1^{r}_{mit}\times Q_{mirt}\right)\right]-d2^{+}r+d2^{-}r=Goal2r.$$

$$\begin{aligned}
&\sum_{p}^{P}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left((gh^{u}_{it}-gh^{r}_{it})\times\chi_{psit}\right)+\left[\sum_{m}^{M}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left((S1^{u}_{mit}-S1^{r}_{mit})\times Q_{mirt}\right)\right]\\
&-d2^{+}u+d2^{-}u=Goal2u.
\end{aligned}$$

The third *minimization fuzzy-GP constraint*

$$\begin{aligned}
&\sum_{g}^{G}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left((CE^{r}-CE^{l})\times d1_{si}\times XV_{gsit}\right)\\
&+\sum_{g}^{G}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left((CE^{r}-CE^{l})\times d2_{ir}\times YV_{girt}\right)\\
&+\sum_{g}^{G}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\left((CE^{r}-CE^{l})\times d3_{rj}\times ZV_{grjt}\right)\\
&+\sum_{g}^{G}\sum_{j}^{J}\sum_{c}^{C}\sum_{t}^{T}\left((CE^{r}-CE^{l})\times d4_{jc}\times MV_{gjct}\right)-d3^{+}l+d3^{-}l=Goal3l.
\end{aligned}$$

$$\begin{aligned}
&\sum_{g}^{G}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left(CE^{r}\times d1_{si}\times XV_{gsit}\right)+\sum_{g}^{G}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left(CE^{r}_{g}\times d2_{ir}\times YV_{girt}\right)\\
&+\sum_{g}^{G}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\left(CE^{r}\times d3_{rj}\times ZV_{grjt}\right)\\
&+\sum_{g}^{G}\sum_{j}^{J}\sum_{c}^{C}\sum_{t}^{T}\left(CE^{r}\times d4_{jc}\times MV_{gjct}\right)-d3^{+}r+d3^{-}r=Goal3r.
\end{aligned}$$

$$\sum_{g}^{G}\sum_{s}^{S}\sum_{i}^{I}\sum_{t}^{T}\left((CE^{u}-CE^{r})\times d1_{si}\times XV_{gsit}\right) +\sum_{g}^{G}\sum_{i}^{I}\sum_{r}^{R}\sum_{t}^{T}\left((CE^{u}-CE^{r})\times d2_{ir}\times YV_{girt}\right) +\sum_{g}^{G}\sum_{r}^{R}\sum_{j}^{J}\sum_{t}^{T}\left((CE^{u}-CE^{r})\times d3_{rj}\times ZV_{grjt}\right) +\sum_{g}^{G}\sum_{j}^{J}\sum_{c}^{C}\sum_{t}^{T}\left((CE^{u}-CE^{r})\times d4_{jc}\times MV_{gjct}\right)-d3^{+}u+d3^{-}u=Goal3u.$$

$$\left[\sum_{m}^{M}\sum_{i}^{I}\sum_{t}^{T}\left((O1^{r}_{mit}-O1^{l}_{mit})\times X_{mit}\right)+\sum_{r}^{R}\sum_{t}^{T}\left((O2^{r}_{rt}-O2^{l}_{rt})\times W1_{rt}\right) +\sum_{j}^{J}\sum_{t}^{T}\left((O3^{r}_{jt}-O3^{l}_{jt})\times Y_{jt}\right)\right] -\left[\sum_{m}^{M}\sum_{i}^{I}\sum_{t}^{T}\left((I1^{r}_{mit}-I1^{l}_{mit})\times X_{mit}\right)\right]-d4^{+}l+d4^{-}l=Goal4l.$$

The fourth *maximization fuzzy-GP constraint*

$$\left[\sum_{m}^{M}\sum_{i}^{I}\sum_{t}^{T}\left(O1^{r}_{mit}\times X_{mit}\right)+\sum_{r}^{R}\sum_{t}^{T}\left(O2^{r}_{rt}\times W1_{rt}\right)+\sum_{j}^{J}\sum_{t}^{T}\left(O3^{r}_{jt}\times Y_{jt}\right)\right] -\left[\sum_{m}^{M}\sum_{i}^{I}\sum_{t}^{T}\left(I1^{r}_{mit}\times X_{mit}\right)\right]-d4^{+}r+d4^{-}r=Goal4r.$$

$$\left[\sum_{m}^{M}\sum_{i}^{I}\sum_{t}^{T}\left((O1^{u}_{mit}-O1^{r}_{mit})\times X_{mit}\right)+\sum_{r}^{R}\sum_{t}^{T}\left((O2^{u}_{rt}-O2^{r}_{rt})\times W1_{rt}\right) +\sum_{j}^{J}\sum_{t}^{T}\left((O3^{u}_{jt}-O3^{r}_{jt})\times Y_{jt}\right)\right] -\left[\sum_{m}^{M}\sum_{i}^{I}\sum_{t}^{T}\left((I1^{u}_{mit}-I1^{r}_{mit})\times X_{mit}\right)\right]-d4^{+}l+d4^{-}l=Goal4l.$$

$$\sum_{i}^{I}\chi_{psit}\leq\omega^{l}_{pst}$$

$$\sum_{i}^{I}\chi_{psit}\leq\omega^{r}_{pst}\qquad\forall\ p,s,t$$

$$\sum_{i}^{I}\chi_{psit}\leq\omega^{u}_{pst}$$

$$\sum_{m}^{M}\left(Q4_{mit}\right)\leq cap1^{r}_{it}$$

Fuzzy constraints

$$\sum_{m}^{M}\left(Q4_{mit}\right)\leq cap1^{u}_{it}\qquad\forall\ i,t$$

$$\sum_{m}^{M}\sum_{j}^{J}\left(L_{mrjt}\right)\leq cap2^{l}_{rt}\qquad\forall\ r,t$$

$$\sum_{m}^{M}\sum_{j}^{J}\left(L_{mrjt}\right)\leq cap2^{r}_{rt}\qquad\forall\ r,t$$

$$\sum_{m}^{M}\sum_{j}^{J}\left(L_{mrjt}\right)\leq cap2^{u}_{rt}\qquad\forall\ r,t$$

$$\sum_{m}^{M}\sum_{c}^{C}\left(H3_{mjct}\right)\leq cap3^{l}_{jt}\qquad\forall\ j,t$$

$$\sum_{m}^{M}\sum_{c}^{C}\left(H3_{mjct}\right)\leq cap3^{r}_{jt}$$

$$\sum_{m}^{M}\sum_{c}^{C}\left(H3_{mjct}\right)\le cap3^{u}_{jt}$$

$$\sum_{g}^{G}(cap4^{l}_{g}\times XV_{gsit})\ge \chi_{psit} \qquad \forall\, p,s,i,t$$

$$\sum_{g}^{G}(cap4^{r}_{g}\times XV_{gsit})\ge \chi_{psit}$$

$$\sum_{g}^{G}(cap4^{u}_{g}\times XV_{gsit})\ge \chi_{psit}$$

$$\sum_{g}^{G}(cap4^{l}_{g}\times YV_{girt})\ge Q_{mirt} \qquad \forall\, m,i,r,t$$

$$\sum_{g}^{G}(cap4^{r}_{g}\times YV_{girt})\ge Q_{mirt}$$

$$\sum_{g}^{G}(cap4^{u}_{g}\times YV_{girt})\ge Q_{mirt}$$

$$\sum_{g}^{G}(cap4^{l}_{g}\times ZV_{grjt})\ge L_{mrjt} \qquad \forall\, m,r,j,t$$

$$\sum_{g}^{G}(cap4^{r}_{g}\times ZV_{grjt})\ge L_{mrjt}$$

$$\sum_{g}^{G}(cap4^{u}_{g}\times ZV_{grjt})\ge L_{mrjt}$$

$$\sum_{g}^{G}(cap4^{l}_{g}\times MV_{gjct})\ge H3_{mjct} \qquad \forall\, m,j,c,t$$

$$\sum_{g}^{G}(cap4^{r}_{g}\times MV_{gjct})\ge H3_{mjct}$$

$$\sum_{g}^{G}(cap4^{u}_{g}\times MV_{gjct})\ge H3_{mjct}$$

$$\sum_{m}^{M}\sum_{i}^{I}Q_{mirt}\ge D4^{l}_{rt} \qquad \forall\, r,t$$

$$\sum_{m}^{M}\sum_{i}^{I}Q_{mirt}\ge D4^{r}_{rt}$$

$$\sum_{m}^{M}\sum_{i}^{I}Q_{mirt}\ge D4^{u}_{rt}$$

$$\sum_{m}^{M}\sum_{r}^{R}L_{mrjt}\ge D6^{l}_{jt} \qquad \forall\, j,t$$

$$\sum_{m}^{M}\sum_{r}^{R}L_{mrjt}\ge D6^{r}_{jt}$$

$$\sum_{m}^{M}\sum_{r}^{R}L_{mrjt}\ge D6^{u}_{jt}$$

$$\sum_{m}^{M}\sum_{j}^{J}H3_{mjct}\ge D^{l}_{Ct} \qquad \forall\, c,t$$

$$\sum_{m}^{M}\sum_{j}^{J} H3_{mjct} \geq D^{r}_{Ct}$$

$$\sum_{m}^{M}\sum_{j}^{J} H3_{mjct} \geq D^{u}_{Ct}$$

$$\sum_{p}^{P}\sum_{s}^{S} gh^{l}_{it} \times \chi_{psit} \leq WH^{l}_{it} \qquad \forall i,t$$

$$\sum_{p}^{P}\sum_{s}^{S} gh^{r}_{it} \times \chi_{psit} \leq WH^{r}_{it}$$

$$\sum_{p}^{P}\sum_{s}^{S} gh^{u}_{it} \times \chi_{psit} \leq WH^{u}_{it}$$

$$\sum_{m}^{M} S1^{l}_{mit} \times Q4_{mit} \leq HM^{l}_{it} \qquad \forall i,t$$

$$\sum_{m}^{M} S1^{r}_{mit} \times Q4_{mit} \leq HM^{r}_{it}$$

$$\sum_{m}^{M} S1^{u}_{mit} \times Q4_{mit} \leq HM^{u}_{it}$$

$$\sum_{g}^{G}\sum_{s}^{S}(CE^{l} \times d1_{si} \times XV_{gsit}) + \sum_{g}^{G}\sum_{r}^{R}(CE^{l} \times d2_{ir} \times YV_{girt}) + \sum_{g}^{G}\sum_{j}^{J}(CE^{l} \times d3_{rj} \times ZV_{grjt}) + \sum_{g}^{G}\sum_{c}^{C}(CE^{l} \times d4_{jc} \times MV_{gjct}) \leq HE^{l}_{gt} \qquad \forall i,t$$

$$\sum_{g}^{G}\sum_{s}^{S}(CE^{r} \times d1_{si} \times XV_{gsit}) + \sum_{g}^{G}\sum_{r}^{R}(CE^{r} \times d2_{ir} \times YV_{girt}) + \sum_{g}^{G}\sum_{j}^{J}(CE^{r} \times d3_{rj} \times ZV_{grjt}) + \sum_{g}^{G}\sum_{c}^{C}(CE^{r} \times d4_{jc} \times MV_{gjct}) \leq HE^{r}_{gt}$$

$$\sum_{g}^{G}\sum_{s}^{S}(CE^{u} \times d1_{si} \times XV_{gsit}) + \sum_{g}^{G}\sum_{r}^{R}(CE^{u} \times d2_{ir} \times YV_{girt}) + \sum_{g}^{G}\sum_{j}^{J}(CE^{u} \times d3_{rj} \times ZV_{grjt}) + \sum_{g}^{G}\sum_{c}^{C}(CE^{u} \times d4_{jc} \times MV_{gjct}) \leq HE^{u}_{gt}$$

$$\sum_{m}^{M}(Q4_{mit} \times ub^{l}_{it}) = B1^{l}_{it} \qquad \forall i,t$$

$$\sum_{m}^{M}(Q4_{mit} \times ub^{r}_{it}) = B1^{r}_{it}$$

$$\sum_{m}^{M}(Q4_{mit} \times ub^{u}_{it}) = B1^{u}_{it}$$

$$\sum_{m}^{M}\sum_{i}^{I}(uo^{l}_{rt} \times Q_{mirt}) = O2^{l}_{rt} \qquad \forall r,t$$

$$\sum_{m}^{M}\sum_{i}^{I}(uo^{r}_{rt} \times Q_{mirt}) = O2^{r}_{rt}$$

$$\sum_{m}^{M}\sum_{i}^{I}(uo^{u}_{rt} \times Q_{mirt}) = O2^{u}_{rt}$$

$$\sum_{m}^{M}\sum_{r}^{R}(ur^{l}_{jt} \times L_{mrjt}) = O3^{l}_{jt} \qquad \forall j,t$$

$$\sum_{m}^{M}\sum_{r}^{R}(L_{mrjt} \times ur^{r}_{jt}) = O3^{r}_{jt}$$

$$\sum_{m}^{M}\sum_{r}^{R}(L_{mrjt}\times ur^{u}_{jt}) = O3^{u}_{jt}$$

$$ke_{gsit}\times cap4^{l}_{g}\times XV_{gsit}\leq \delta^{l}_{psit} \qquad \forall_{g,p,s,i,t}$$

$$ke_{gsit}\times cap4^{r}_{g}\times XV_{gsit}\leq \delta^{r}_{psit}$$

$$ke_{gsit}\times cap4^{u}_{g}\times XV_{gsit}\leq \delta^{u}_{psit}$$

$$ke1_{girt}\times cap4^{l}_{g}\times YV_{girt}\leq C1^{l}_{irt} \qquad \forall_{g,i,r,t}$$

$$ke1_{girt}\times cap4^{r}_{g}\times YV_{girt}\leq C1^{r}_{irt}$$

$$ke1_{girt}\times cap4^{u}_{g}\times YV_{girt}\leq C1^{u}_{irt}$$

$$ke2_{grjt}\times cap4^{l}_{g}\times ZV_{grjt}\leq C2^{l}_{rjt} \qquad \forall_{g,r,j,t}$$

$$ke2_{grjt}\times cap4^{r}_{g}\times ZV_{grjt}\leq C2^{r}_{rjt}$$

$$ke2_{grjt}\times cap4^{u}_{g}\times ZV_{grjt}\leq C2^{u}_{rjt}$$

Non-fuzzy constraints

$$Q_{mirt} = Q1_{mir,t-1} - L_{mirt} \qquad \forall_{m,i,r,t}$$

$$L_{mrjt} = L1_{mrj,t-1} - H3_{mjct} \qquad \forall_{m,r,j,c,t}$$