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Solving a New Multi-Period Multi-Objective Multi-Product Aggregate Production Planning Problem Using Fuzzy Goal Programming

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ABSTRACT

This paper introduces a new multi-product multi-period multi-objective aggregate production planning problem. The proposed problem is modeled using multi-objective mixed-integer mathematical programming. Three objective functions, including minimizing total cost, maximizing customer services level, and maximizing the quality of end-product, are considered, simultaneously. Several constraints such as quantity of production, available time, work force levels, inventory levels, backordering levels, machine capacity, warehouse space and available budget are also considered. Some parameters of the proposed model are assumed to be qualitative and modeled using fuzzy sets. Then, a fuzzy goal programming approach is proposed to solve the model. The proposed approach is applied on a real-world industrial case study of a color and resin production company called Teiph-Saipa. The approach is coded using LINGO software. The efficacy and applicability of the proposed approach are illustrated in the case study. The results of proposed approach are compared with those of the existing experimental methods used in the company. The relative dominance of the proposed approach is revealed in comparison with the experimental method. Finally, a data dictionary, including the way of gathering data for running the model, is proposed in order to facilitate the re-implementation of the model for future development and case studies.

Keywords: Aggregate Production Planning, Goal Programming, Mathematical Modeling, Fuzzy Goal Programming

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1. INTRODUCTION

Aggregate production planning (APP) is a low-resolution and high-level plan for determining the work force level, production rate, back order level, inventory level, volume of hiring, volume of firing, over time work, under capacity working, and sub-contracting level over a medium or long period of time in an organization. Market demands and the production strategy in order to satisfy the demand are the main inputs of APP (Leung *et al*., 2003). Several methods and approaches including heuristics, mathematical formulations, and experimental methods have been proposed to handle APPs to date, and among them, the mathematical models have been successful as they can properly handle the real life situations (Mirzapour Al-e-Hashem *et al*., 2012).

In this paper we propose a new multi-product multi-period multi-objective APP problem. The proposed problem is modeled using multi-objective mixed-integer mathematical programming. Three objective functions, including minimizing total cost, maximizing customer services level, and maximizing the quality of end-product, are considered concurrently. Several constraints, such as regarding the quantity of production, available time, work force levels, inventory levels, backordering levels, machine capacity, warehouse space and available budget, are also considered. Then, a fuzzy goal programming (FGP) is proposed to solve the proposed model. The proposed approach is used in a real case study in a color and resin production company. The results of proposed approach are compared with those of the existing experimental method used in the company.

The main contributions of this study are to 1) propose a new multi-product multi-period multi-objective APP problem through mathematical modeling, 2) develop a FGP approach to solve the multi-period, multi-product, and multi-objective APP problem, 3) propose a dictionary for data collection, 4) apply the proposed method in a real case study, and 5) compare the results of the proposed approach with those of an existing experimental method in the case study.

The parts of this paper are organized as follows. In Section 2, the literature of past works is presented. The proposed mathematical model for multi-objective multi-period multi-product APP is developed in Section 3. A FGP approach is also developed to solve the proposed model in Section 3. The case study, results, and the dictionary of parameters are presented in Section 4. Section 5 is allocated to present the conclusions and the recommendations for future research directions.

2. LITERATURE OF PAST WORKS

In this paper, the literature of past works has been reviewed in two main categories. In the first category the APP and its variants are reviewed. In the second category the goal programming method is reviewed. Literature of APP has been reviewed in three main subcategories as: 1) the classic APP models which address planning horizons of 3–18 months, 2) the APP models considering uncertainty, and 3) multi-objective APP models applied on real-world industrial problems.

2.1 Classic Aggregate Production Planning

In general, APP is defined as one of the major production planning categories (Giannoccaro and Pontrandolfo, 2001; Mula *et al*., 2006). Since classic model of linear decision rule for production and employment scheduling proposed by Holt *et al*. (1955, 1961) the APP problem has been studied extensively by many researchers (Jain and Palekar, 2005; Leung and Wu, 2004; Wang and Liang, 2004). According to Wang and Liang (2004) APP is one of the most important functions in production and operations management. Nam and Logendran (1992) reviewed APP models and classified them in categories of optimal and near-optimal. The overview of mathematical optimization models including the APP showed that the linear programming has been used as a conventional method and has received the most widespread acceptance. Baykasoglu (2001) defined APP model as medium-term capacity planning during a planning horizon of 2–18 months. Fung *et al*. (2003) defined APP as a plan to determine production, inventory, and labor levels required to responding to all market demands. Corominas *et al.* (2012) discussed the joint aggregate planning of a production system with manufacturing new units and remanufacturing, and focuses on the cases in which remanufactured units are sold as new. Junior and Filho (2012) reviewed the literature on production planning and control for remanufacturing. Karmarkar and Rajaram (2012) discussed a competition version of APP model with capacity constraints. Ramezanian *et al.* (2012) focused on systems with multi-period, multi-product, and multi-machine with setup decisions. Zhang *et al*. (2012) introduced a mixed integer linear programming model for APP problem with expansion of capacity in the production system. Jamalnia and Feili (2013) proposed a hybrid discrete event simulation and system dynamics methodology to model and simulate APP problem. The main objective of their study was to determine the effectiveness of APP strategies regarding the Total Profit. Tonelli *et al*. (2013) proposed an optimization approach to face aggregate planning problems in a mixed model production environment. They addressed the model flexibility challenge and discussed the planning problem of a real world assembly manufacturing system.

Fortunately, the APP models can deal with details of real-world problems while often efficient algorithms are proposed in order to solve them. As identified by many researchers (Bushuev 2014), the APP cost function is convex and piecewise. Bushuev (2014) proposed a new convex optimization approach for solving the APP problem. Hassan Zadeh *et al*. (2014) developed a model for integrating process planning and production planning and control. Their comprehensive framework focused on the area of cellular manufacturing systems.

2.2 Fuzzy Aggregate Production Planning

Mula *et al.* (2006) introduced a classification scheme for production planning models under uncertainty. In order to deal with the problems under uncertainty, fuzzy set theory is commonly used to describe the imprecise characteristics (Abass and Elsayed, 2012). Rinks (1981) described the gap between theory and reality in APP problems. Rinks (1981) developed some algorithms for fuzzy aggregate planning by using <If-Then> fuzzy conditional statements. Turksen (1988a) used membership functions with distance value to define linguistic terms for APP problems. Lee (1990) proposed single-product APP model under fuzzy goals, fuzzy demand, and fuzzy workforce levels in different periods. Tang *et al*. (2000) proposed a fuzzy approach to modeling multi-product APP problems with fuzzy demands and fuzzy capacities to minimize the total costs of quadratic production costs and linear inventory holding costs. Lin and Liang (2002) developed a multiple fuzzy objective linear programming model for APP problem, that their model can measure decision-maker's decision satisfaction degree level. Leung and Wu (2004) considered APP problem with uncertain parameters. Leung and Chan (2009) developed a preemptive goal programming model for APP problem to maximize profit, minimize repairing cost and maximize utilization of machinery. Sakallı *et al.* (2010) discussed a possibilistic APP model for blending problem in a brass factory. They determined the optimal raw material purchasing policies. Li *et al*. (2013) proposed a new hierarchical belief-rule-based inference method for APP problem with uncertainty.

2.3 Multi-Objective Aggregate Production Planning

Filho (1999) formulated a stochastic optimization model with inventory, production and workforce constraints to describe a multi-period and multi-product APP problem. Wang and Fang (2001) solved a multiple objective APP problem using fuzzy linear programming method in fuzzy environment. Jamalnia and Soukhakian (2009) developed a hybrid (including qualitative and quantitative objectives) fuzzy multi-objective nonlinear programming model with different goal priorities (fuzzy goals) for APP problem in a fuzzy environment. Liang and Cheng (2011) presented a two-phase FGP method for solving the multi-objective APP problems with multi-product and multi-time period. Mirzapour Al-e-Hashem *et al*. (2011) solved the multi-site, multi-period and multi-product APP problem under uncertainty for a supply chain consisting of multiple-supplier, multiple-producer and multiple-customer. Mirzapour Al-e-Hashem *et al*. (2011) also considered the costs related to supply chain and demands as the uncertain parameters. Ghasemy Yaghin *et al*. (2012) proposed a fuzzy multi-objective APP model with qualitative and quantitative objectives for a two-level supply chain. Mirzapour Al-e-Hashem *et al.* (2012) developed a multi-site, multi-period, multi-product, and multi-objective robust APP with regard to conflicts among total costs of supply chain, customer service level, and productivity of workers during medium-term planning horizon in an uncertain environment. Mirzapour Al-e-Hashem *et al*. (2013) developed a stochastic APP approach in a green supply chain.

The main pitfalls and disadvantages of previous APP models in the literature are as follow. 1) Most APP models with GP approach are deterministic. 2) The majority of non-deterministic models consider only one or two parameters as the sources of uncertainty. 3) In the most of the past works minimizing total cost of planning and minimizing the rate of changes in labor levels were optimized. 4) Maximizing quality of end-products and customer satisfaction level are neglected in APP models as the two significant issues in competitive world especially in companies that quality control department is a subset of the production department, such as paint manufacturing plants. 5) There is no comprehensive instruction to guide how the data for various parameters of the APP models should be collected in real-cases. In this paper we are going to address and enhance all of the aforementioned issues in a new APP modeling.

2.4 Fuzzy Goal Programming

In cases where there are several conflicting objectives and goals decision-makers, including production managers, are met with tough choices to prioritize the goals. In order to overcome this issue, the goal programming (GP) may be proposed as a practical and applicable approach. The idea of GP was first by Charnes *et al.* (1955) as an efficient multi-criteria and multi-objective planning technique. Then, Cooper (1961) formulated GP in 1961. In fact, GP is development of linear programming. According to Chen and Tsai (2001), the GP model is useful for decision-makers to consider simultaneously several objectives to achieve acceptable solutions. GP models based on combination of deviations from the goals are classified as: 1) weighted GP, 2) lexicographic, and 3) min-max. Among the classes, weighted GP minimizes the weighted sum of the deviations from the goals. The weighted GP can achieve efficient and high quality compromise solutions.

Since introduction of fuzzy set theory, several decision-making approaches have been extended in fuzzy environment in order to handle the uncertain situation of real-world problems. A fuzzy goal is an objective with an imprecise aspiration level (Jamalnia and Soukhakian, 2009; Rinks, 1982). There are several FGP approaches in the literature. Among them the method proposed by the following researchers are interesting: 1) Zimmermann (1975, 1978), 2) Narasimhan (1980), 3) Hannan (1981), and 4) Tiwari *et al*. (1987). The proposed model by Tiwari *et al.* (1987) is a simple and efficient method and considers different priority to each of goals. Therefore, we try to develop a weighted FGP model based on proposed model by Tiwari *et al.* (1987) with high efficiency to solve APP problem in real world.

According to aforementioned literature, a gap has been recognized in past works. So, in this paper, a multi-objective multi-period multi-product APP problem is proposed. The uncertainty of parameters is modeled using fuzzy sets. A FGP is proposed to solve the proposed problem. A real case study will be discussed. The results of proposed approach will be compared with those of experimental methods.

3. MULTI-OBJECTIVE MULTI-PERIOD MULTI-PRODUCT AGGREGATE PRODUCTION PLANNING PROBLEM

3.1 Problem Definition and Assumptions

The mathematical model of proposed APP problem is constructed based on the following assumption. It is notable that the assumptions are formed based on real-case study of the research.

- Planning is accomplished in a horizon consists of T time periods ($t = 1, \cdots, T$).
- Batch production system with the capability of producing several kinds of the product is considered.
- The producer can produce N types of products to response market demand.
- Demand can be either satisfied or backordered, but no backorder is allowed in last period.
- No subcontracting is allowed for products.
- Two working shifts are considered in a day ($q \in \{1, 2\}$). Regular time production ($q = 1$) and overtime production ($q = 2$).
- The producer has warehouses to hold final products.
- The holding cost of inventory of products are predetermined and known in advance.
- Several skill levels (k-level) are considered for workforce.
- During the planning horizon, training courses are accomplished and the skill level of workforce is improved.
- There are also several (i.e., $l = 1, 2, \cdots, L$) types of training courses. The first type of training ($l = 1$) enhances the workers from level $k = 1$ to level $k = 2$. The second type of training ($l = 1$) enhances the workers from level $k = 2$ to level $k = 3$, and so on.
- Salary of workers is independent of unit production cost.
- Quantity of production in each period can be considered more of the safety stock for finished products.
- According to demand of market, hiring and firing of manpower is eligible and also has allowable limit.
- In each period of planning, the nominal and actual capacity of production machines is not the same due to unexpected failures. So the actual capacity of production is usually decreased by a fixed failure percentage.
- If an unexpected failure occurs during a shift the repair process is accomplished in the next shift. This may stop, reduce, or decrease the production rate during maintenance actions.
- In each period of planning, the shortage of production is recovered by overtime production in each shift.
- Due to inflation and low holding costs, keeping finished products is economic.
- Three objective functions are considered as total cost, satisfaction level of customers, and improvement of quality of products.

Table 1. Notation of objective functions

Objective function	Definition
Z_1	Total costs
Z_2	Customer satisfaction
Z_3	Quality of products
ZMF	Objective function of FGP model

Table 2. Set of indices

Index	Definition
t	Number of periods in the planning horizon; $t = 1, \cdots, T$
i	Number of product types; $i = 1, \cdots, I$
m	Raw material type; $m = 1, \cdots, M$
q	Types of shifts $q \in \{1, 2\}$. (q = 1; regular time, and q = 2; overtime)
w	Types of warehouse; $w = 1, 2, \cdots, W$
k	Skill levels of workers; $k = 1, 2, \cdots, K$
l	Types of training; $l=1, 2, \cdots, L$
j	Number of objective Functions; $j = 1, 2, 3.$

- The uncertainty of real-world problem and confliction of different objectives are modeled using fuzzy goals.
- Linear membership functions are defined for fuzzy goals.
- Weighted FGP used to solve the problem.

3.2 Parameters, Indices, Decision Variables and Notations

Notations used in the proposed multi-objective mathematical programming are summarized in Tables 1–4 as follows.

3.3 Model Formulation

3.3.1 Objective functions

Three objective functions are simultaneously considered for the proposed model of this research as follows.

3.3.1.1 Minimize total costs

$$\begin{aligned} Min\, Z_1 = & \sum_{i \in I} \sum_{q \in \{1,2\}} \sum_{t \in T} CO_{iq} X_{iqt} + \sum_{k \in K} \sum_{t \in T} CL_{kt} XL_{kt} \\ & + \sum_{k \in K} \sum_{t \in T} CH_{kt} XH_{kt} + \sum_{k \in K} \sum_{t \in T} CF_{kt} XF_{kt} \\ & + \sum_{l \in L} \sum_{t \in T} CT_{lt} XT_{lt} + \sum_{i \in I} \sum_{t \in T} \sum_{w \in W} CP_{itw} XP_{itw} \\ & + \sum_{m \in M} \sum_{t \in T} \sum_{w \in W} CR_{mtw} XR_{mtw} + \sum_{i \in I} \sum_{t \in T} CB_{it} B_{it} \end{aligned} \tag{1}$$

The objective function (1) is total cost of production. This includes eight terms as follow: production costs per unit, costs of salary of workers, costs of hiring,

Table 3. Notation for parameters

Parameter	Definition
CO_{iq}	Production cost per hour for product *i* in shift *q*
Ω_t	Upper limit of budget in period *t*
DE_{it}	Demand of product *i* in period *t*.
Θ_{it}	Allowable shortage of product *i* in period *t*
CB_{it}	Backordering cost of product *i* in period *t*
A_{it}	Process time of product *i* in period *t*
$\overline{HR}_t$	Maximum workforce available in period t
$\underline{HR}$	Minimum workforce available
CL_{kt}	Cost workforce of level *k* in period *t*
CH_{kt}	Hiring cost workforce of level *k* in period *t*
CF_{kt}	Firing cost workforce of level *k* in period *t*
CT_{lt}	Training cost of type *l* in period t
α_t	Fraction of the workforce variation allowed in period *t*
MT_{it}	Required machine hours to produce unit of product *i* in period *t*
ε_t	Percentage of machine capacity that is lost due to interruption in period *t*
μ_t	Percentage of machine capacity that is lost due to repairs in period *t*
MC_{qt}	Maximum of machine capacity that is available in shift *q* in period *t*
AT_{qt}	Available regular time in both shifts in period *t*
γ_{im}	Units of raw material type *m* required to produce unit of product *i*
SSR_m	Safety stock of raw material type *m*
MS_w	Maximum available space of warehouse *w*
CR_{mtw}	Holding cost for raw material type *m* in period *t* in warehouse *w*
VR_{mtw}	Capacity of warehouse *w* for storage of raw material type *m* in period *t*
CP_{itw}	Holding cost of unit of product *i* in period *t*
VP_{itw}	Capacity of warehouse *w* for storage of finished-product *i* in period *t*
SS_i	Safety stock of product *i*
DU_i	Due date of product *i*
β_i	Batch size of product *i*
DR_i	Defect rate of finished product *i*
Δ	Percentage of machines capacity that is available for overtime.
OL	Percentage of workforce that are available for overtime.
τ	Minimum percentage of workers that are available for training.

Table 4. Notation for decision variables

Decision variable	Definition
X_{iqt}	Number of product *i* produced in shift *q* of period *t*
$X\beta_{iqt}$	Number batches of product *i* produced in shift *q* of period *t*
B_{it}	Backorder level of product *i* in period *t*
XL_{kt}	Number of available workers of level *k* in period *t*
XH_{kt}	Number of hired workers of level *k* in period *t*
XF_{kt}	Number of fired workers of level *k* in period *t*
XT_{lt}	Number of workers trained course level *l* in period *t*
XR_{mtw}	Inventory level of raw material type *m* at the end of period *t* in warehouse *w*
XP_{itw}	Inventory level of finished-product *i* in period *t* in warehouse *w*

costs of firing, costs of training, holding costs of products, holding costs of raw materials, and backordering costs. The sum of these eight terms is called as total cost (TC).

3.3.1.2 Maximize customer satisfaction level

$$Min\, Z_2 = \sum_{i\in I}\left|\sum_{q\in\{1,2\}}\sum_{t\in T} A_{it} X_{iqt} - DU_i\right| \tag{2}$$

The objective function (2) minimizes the difference between delivery time of all products and due date for all type of products. Minimizing the aforementioned difference is interpreted as maximizing the customer satisfaction level. This goal includes two terms as actual delivery time of product *i* and due date of delivery of products *i* to customer according to contract.

On the other hand the customers are supposed receive their required products according to their associated due dates. Delivery of product to customers earlier than due date, which is called earliness, is not suitable while delivery of product to customers later then due date, which is called tardiness, is not also suitable. So, the objective function (2) minimizes both earliness and tardiness simultaneously.

Since the production system is batch type in this study, the following equation is implicitly considered among product numbers and batch numbers: $X_{iqt} = \beta_i \cdot X\beta_{iqt}$.

3.3.1.3 Maximize the quality of products

In most of the production systems, including job-shop, batch, mass, and continuous production systems, the level of skill of workers effects on quality of final products. In this research we have related the quality of final products with number of workers which are trained in each period of planning. We proposed our interpretation form this effect as follows. We, first calculate the ratio of workers which have been trained in comparison with all workers of the company using Eq. (3).

$$TMP_t = \left(\sum_{l\in L} XT_{lt} \Big/ \sum_{k\in K}(XL_{kt} + XH_{kt} - XF_{kt})\right)\times 100, \quad t = 1, \cdots, T \tag{3}$$

where, the parameters in Eq. (3) were described in Table 4.

Then, the fuzzy objective function (4) is defined as follows:

$$Z_3 \cong Max \sum_{t\in T} \frac{T2 - TMP_t}{T2 \quad T} \tag{4}$$

where Z_3 is a fuzzy objective function which maximizes the membership degree of different trained manpower percentages (TMP_t) as desirability set during all periods.

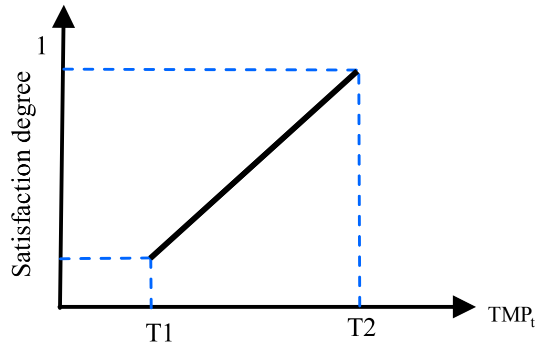

Figure 1. Degree of satisfaction of the high quality objective. TMP_t : trained manpower percentage.

It is notable that *T2* is the maximum percentage of workers can be trained while *T1* is the minimum percentage of workers can be trained. Figure 1 presents the schematic view of membership function of 'high quality' linguistic term. On the other hand, the degree of satisfaction of the high quality objective is related to the different 'Trained Manpower Percentages' in each period.

We have considered a linear membership function for quality of finished-product. The values of *T1* and *T2* are determined based on the expectation of the decision maker.

In this research, based on evidence achieved from real case study, training is considered as an applicable method to improve quality of products. Although this interpretation have also been mentioned in the literature before. Hence, the proposed model attempts to increase the skill level of workers through setting up training course (Mirzapour Al-e-Hashem *et al*., 2012).

3.3.2 Constraints

The workforce level constraints are considered using (5)–(9).

$$\sum_{k\in K} XL_{kt} \le \overline{HR}_t, \qquad \forall t \tag{5}$$

$$\underline{HR} \le \sum_{k\in K} XL_{kt}, \qquad \forall t \tag{6}$$

$$XL_{kt} = XL_{k(t-1)} + XH_{kt} - XF_{kt} - XT_{lt}, \quad \forall k, \forall t,\ t>1 \tag{7}$$

$$\left|XL_{kt} - XL_{k(t-1)}\right| \le \alpha_t \cdot XL_{kt}, \quad \forall k, \forall t,\ t>1 \tag{8}$$

$$\tau \cdot \underline{HR} \le \sum_{l\in L} XT_{lt}, \qquad \forall t \tag{9}$$

Set of constraints (5), which are written for all periods of planning, assure that utilized work force in a period of planning should not be greater than maximum available human resource. Set of constraints (6), which are written for all periods of planning, assure that a minimum number of workers should be utilized in a period of planning. Set of constraints (7) is a balance equation for workforce level and ensures that the available workforce with skill level *k* in a certain period are equal to the workforce with the same skill level k in previous period plus the change of workforce level in current period. Set of constraint (8) describe the change in workforce level in each period of planning cannot exceed a predetermined proportion of workers in current period. Set of constraint (9) assure that in all periods of planning, the trained workforce should be greater than or equal to a predetermined percentage of the minimum available workers during all periods.

The available time limit of working shifts is presented using constraints (10) and (11).

$$\sum_{i \in I} A_{it} \cdot X_{iqt} \le \sum_{k \in K} AT_{qt} \cdot XL_{kt}, \qquad \forall t, q = 1 \tag{10}$$

$$\sum_{i \in I} A_{it} \cdot X_{iqt} \le \sum_{k \in K} AT_{qt} \cdot OL \cdot XL_{kt}, \qquad \forall t, \ q = 2 \tag{11}$$

Set of constraints (11) and (12) assure that the required production time for all periods of planning and in each working shifts are less than or equal to available regular production time and overtime, respectively.

The inventory level situations are demonstrated using constraints (12)–(14).

$$XP_{itw} = XP_{i(t-1)w} + \sum_{q \in \{1, 2\}} X_{iqt} - B_{it} - DE_{it}, \ \forall i, \forall w, \ t > 1 \tag{12}$$

$$XR_{mtw} = XR_{m(t-1)w} + \sum_{q \in \{1, 2\}} X_{iq(t-1)} \cdot \gamma_{im}, \ \forall i, \forall w, \ t > 1 \tag{13}$$

$$SSR_m \le \sum_{w \in W} XR_{mtw}, \qquad \forall m, \forall t \tag{14}$$

Set of constraints (12), which are written for all products, all periods of planning, and all warehouses assure that the amount of inventory of finished product type i in period t in warehouse w is equal to the amount of inventory of finished product type i in period t-1 in warehouse w plus the amount of produced finished-goods type i in period t in both working shifts minus backorder of product type i in period t and demand of product type i in period t. Set of constraint (13) assure that balance of raw materials. Set of constraints (14) assure the satisfaction of safety stock of raw materials in warehouses.

The production limitations for each product and in each period of planning are presented using constraints (15) and (16).

$$SS_i \le \sum_{q \in Q} X_{iqt}, \qquad \forall i, \forall t \tag{15}$$

$$DE_{it} \le \left(1 - \frac{DR_i}{\beta_i}\right) \cdot \sum_{q \in Q} X_{iqt} + XI_{i(t-1)}, \ \forall i, \forall t, \ t > 1 \tag{16}$$

Set of constraints (15), which is written for all product types and all periods of planning, guarantee the satisfaction of safety stock of finished-products in working shifts. Set of constraints (16) represents the total production of non-defected final products plus the inventory of finished-product in previous period should be greater than or equal to demand of the finished-product in current period.

The capacity of machines for each planning periods for both working shifts are presented using constrains (17) and (18).

$$\sum_{i \in I} MT_{it} \cdot X_{iqt} \le MC_{qt} - \varepsilon_t \cdot MC_{qt}, \qquad \forall t, q = 1 \tag{17}$$

$$\sum_{i \in I} MT_{it} \cdot X_{iqt} \le \delta \cdot MC_{qt} - \mu_t \cdot \delta \cdot MC_{qt}, \quad \forall t, q = 2 \tag{18}$$

Set of constraints (17) and (18) assures that satisfaction of the maximum available capacity of machines in regular time and overtime, respectively.

The limitation of warehouse space for all warehouses in all periods of planning and for each product are presented using constrains (19)–(21).

$$\sum_{w \in W} XP_{itw} \le \sum_{w \in W} VP_{itw}, \qquad \forall t, \forall i \tag{19}$$

$$\sum_{m \in M} \sum_{w \in W} XR_{mtw} \le \sum_{m \in M} \sum_{w \in W} VR_{mtw}, \quad \forall t \tag{20}$$

$$\sum_{i \in I} VP_{itw} + \sum_{m \in M} VR_{mtw} \le MS_w, \qquad \forall t, \forall w \tag{21}$$

Set of constraints (19) represent the limitation of actual inventory levels of finished-products. Set of constraints (20) also represent the limitation of actual inventory levels of raw materials. Set of constraints (21) guarantee products storage capacity plus raw materials storage capacity cannot exceed the maximum warehouse space available of each warehouse in each period.

The backorder are accepted and the associated constraints are presented as constraints (22) and (23).

$$\sum_{i \in I} B_{it} \le \sum_{i \in I} \theta_{it} \cdot DE_{it}, \quad \forall t, t \ne T \tag{22}$$

$$B_{iT} = 0, \quad \forall i \tag{23}$$

Set of constraints (22) represent the backorder level at the end of period t cannot exceed the certain percentage of the demand which determines the upper limit of shortage. Set of constraints (23) assure that there is no possibility for backordering at the end of time horizon.

Available budget in all period of planning has a limitation which is presented using (24).

$$TC \le \sum_{t \in T} \Omega_j \tag{24}$$

Set of constraints (24) guarantee that the total cost of system (i.e., Eq. (1)) cannot exceed the pre-specified budget for the time horizon.

Non-negativity constraints on decision variables are presented in (25) and (26).

$$X_{iqt}, X\beta_{iqt}, B_{it}, XR_{mtw}, XP_{itw} \geq 0, \quad \forall i, \forall q, \forall t, \forall m, \forall w \qquad (25)$$

$$XL_{kt}, XH_{kt}, XF_{kt}, XT_{lt} \geq 0, \quad \forall k, \forall l, \forall t \qquad (26)$$

4. SOLUTION PROCEDURE

In this paper, a FGP is used to solve the problem (1)–(26). In order to use FGP approach with fuzzy goals, the aspiration levels should be calculated. In general, if the decision maker has no enough view point to determine the aspiration levels, payoff table is used. Inaccuracies in achieving the objectives are allowed by specifying an acceptable range instead of a certain value. Membership function for the fuzzy goals can be formulated using the upper and lower limits achieved by payoff table (Zimmermann, 1978). In this study, the following general form of FGP model is considered in order to solve the problem (1)–(26).

$$\begin{aligned}
&\textit{Find} \quad X\\
&\textit{to satisfy};\\
&\qquad G_j(X) \gtrsim g_j \qquad j = 1, \cdots n\\
&\qquad G_j(X) \lesssim g_j \qquad j = n+1, \cdots J \qquad (27)\\
&\textit{subject to};\\
&\qquad AX \leq b\\
&\qquad X \geq 0
\end{aligned}$$

The symbol "~" is used to illustrate the fuzzy form of "=," "≤," and "≥" (Zimmermann, 1978). In general form (27), the purpose of FGP is to find compromise solution X such that all fuzzy goals are satisfied. g_j is the aspiration level for *j*-th goal, $AX \leq b$ are system constraints in vector notation. $G_j(X) \lesssim g_j$ Means that the *j*-th fuzzy goal is approximately less than or equal to the aspiration level g_j, and $G_j(X) \gtrsim g_j$ Means that the *j*-th fuzzy goal is approximately greater than or equal to the aspiration level g_j (Hannan, 1981).

The proposed multi-objective APP problem (1)–(26) can be solved using the fuzzy decision-making concept of Bellman and Zadeh (1970) together with the weighted additive model of Tiwari *et al*. (1987). The weighted additive model is used to indicate the relative weight of the goals. In this approach the objective function is formulated by multiplying each membership of the fuzzy goal with a suitable weight and then adding them together (Tiwari *et al*., 1987). We use membership functions to represent the fuzzy goals of decision makers. Linear membership functions of proposed by Zimmermann (1978) can be used for fuzzy goals. For the fuzzy goals, linear membership functions are defined as Eqs. (28) and (29). They are also depicted in Figure 2.

$$\mu_j = \frac{\overline{Z}_j - Z_j}{\overline{Z}_j - \underline{Z}_j}, \qquad j = 1, 2, \cdots, n \qquad (28)$$

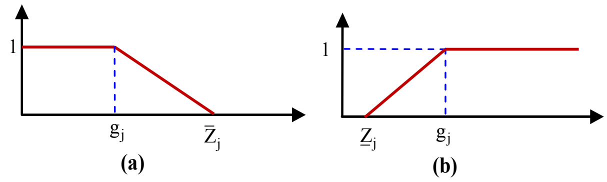

Figure 2. Linear membership functions (a) minimization, (b) maximization.

$$\mu_j = \frac{Z_j - \underline{Z}_j}{\overline{Z}_j - \underline{Z}_j}, \qquad j = n+1, \cdots, J \qquad (29)$$

where $\underline{Z}_j$ (or $\overline{Z}_j$) is lower (upper) tolerance limit for *j*-th fuzzy goal. Decision problems can be demonstrated in payoff table (Madadi and Wong, 2013). So $\underline{Z}_j$ and $\overline{Z}_j$ are chosen by decision-makers considering to payoff table. Eq. (28) is used for minimization objectives and for these goals we can consider $g_j = \underline{Z}_j$. Eq. (29) is used for maximization objectives and for these objective functions we can consider $g_j = \overline{Z}_j$.

Therefore, the associated FGP model for the multi-objective APP problem (1)–(26) is formulated as follows:

$$\textit{Maximize} \sum_{j=1}^{J} w_j \cdot \mu_j \qquad j = 1, 2, 3 \qquad (30)$$

Subject to:

Constraints (5)–(26) (32)

$$\mu_1 = \frac{\overline{Z}_1 - Z_1}{\overline{Z}_1 - \underline{Z}_1} \qquad (33)$$

$$\mu_2 = \frac{\overline{Z}_2 - Z_2}{\overline{Z}_2 - \underline{Z}_2} \qquad (33)$$

$$\mu_3 = \frac{Z_3 - \underline{Z}_3}{\overline{Z}_3 - \underline{Z}_3} \qquad (34)$$

$$\mu_j \leq 1, \quad j = 1, 2, 3 \qquad (35)$$

$$\sum_{j=1}^{3} w_j = 1 \qquad (36)$$

$$w_j, \mu_j \geq 0, \quad j = 1, 2, 3 \qquad (37)$$

where w_j, $j = 1, 2, 3$ is the relative weight of the *j*-th fuzzy goal. According to proposed approach, aspiration levels of goals are calculated by payoff table and weights of goals are determined by DM. Note that to solve the proposed FGP problem, the systematic constraints of original model, i.e., constraints (5)–(26), are also considered.

4.1 Data Dictionary

In this sub-section the source of gathering data for proposed model (1)–(26) is illustrated. This may cause ease of re-implementation of the proposed algorithm in other application area. We call this data dictionary. Based on parameters defined in Table 3, the data dictionary is proposed in Table 5. The Table 5 can be used as a general user guide of data gathering of proposed model (1)–(26). The source of parameters of the model, the responsible for confirmation, the method of gathering data, the availability level, the application of data, the responsible for modification of data and so on are all described in this data dictionary.

It is notable that in some real cases the parameters

Table 5. Data dictionary of parameters

Row no.	Parameter	Data source	Responsible for confirming	Data collection methods	Availability	Applications	Responsible for modification	Data generation	Data relations
1	CO	FD	FM	MIS	AA	AC	FM	IEP	6-7-8-9-10
2	Ω	FD/SD	MD	ME	AA	PP/SP	MD	Y	3
3	DE	SD	SM	CR	AA	PP	SM	MO	2-4-5
4	Θ	SD	SM	MIS	AA	PP	SM	MO	2-3
5	CB	FD	FM	RS	AA	PLS	FM	MO	2-3-4
6	A	PD	PM	RPD	AA	PP	PPM	CF	2
7	$\overline{HR}$	PD	PM	RPD	AA	PP	PM	MO	2-6
8	$\underline{HR}$	PD	PM	RPD	AA	PP	PM	MO	2-6
9	CL	FD	FM	MIS	AA	AC	FM	MO	1
10	CH	FD	FM	MIS	AA	AC	FM	IEP	1
11	CH	MO	FM	PLS	AA	BL	FM	FD	1
12	CT	FD	FM	TUR	AA	AC	FM	MO	1
13	A	HRD	HRM	RHF	AA	AC	FM	MO	1
14	MT	PPD	PPM	TF	AA	AC	PM	MO	1
15	ε	MPD	PM	PR	AA	OEE	MM	MO	1
16	μ	MPD	PM	PR	AA	OEE	MM	MO	1
17	MC	PD	PM	TF	AA	BA	PM	MO	2-1
18	AT	AD	AM	BL	AA	BA	AM	MO	2-1
19	Γ	PD	PM	BOM	AA	AC	EM	BOC	1
20	SSR	PD	PM	OFM	AA	PP	PM	MO	2
21	MS	SU	WM	MOW	AA	PP/AC	BD	QD	2
22	CR	FD	FM	RCU	AA	AC	FM	MO	1
23	VR	SU	WM	MP/PC	AA	PP	PM	QD	2
24	CP	FD	FM	FR/SR	AA	AC	FM	MO	1
25	VP	SU	WM	MP/PC	AA	PP/AC	BD	QD	2-1
26	SS	SD	SM	POF	AA	SP	SM	MO	24
27	DU	SD	SM	CUR	AA	SP	SM	MO	24
28	B	PD	PM	PR	AV	PP	PM	MO	2
29	DR	QC	QM	PR	AV	AC/PLS	PPM	MO	1
30	Δ	PD/PRD	PM	PP	AV	PP	PM	MO	2
31	OL	AP	AM	PP	AV	PP	PM	MO	1-2
32	T	TU/AU	HRM	ATP	AV	PRP	PM	MO	1-2

AA: always available, AC: actual cost, AD: department of administrative, AM: administrative manager, ATP: the aim of training plan, AU: administrative unit, AV: available, BA: budget allocation, BD: board of directors, BL: by-low, BOC: based on the changes, BOM: bill of materials, CF: changing the formulation, CR: customers report, CUR: customer reports, EM: engineering manager, FD: finance department, FM: finance manager, FR: finance reports, HRD: department of human resources, HRM: human resources manager, IEP: in each production, MD: managing director, ME: meetings, MIS: management information system, MM: maintenance manager, MO: monthly, MOW: map of warehouses, MP: maps, MPD: department of maintenance planning, OEE: overall equip, OFM: order form of raw materials, PC: the rate of products circulation, PD: planning department, PLS: profit and loss statement, PM: planning manager, POF: production orders report, PP: production planning, PPD: department of plans and programs, PPM: plans and programs manager, PR: production reports, PRD: production department, PRP: production process, QC: quality control, QD: quarter day (Seasonal), QM: quality manager, RCU: reports of commerce unit, RHF: rate of hiring and firing, RPD: reports of planning department, RS: reports of sales department, SD: sales department, SM: sales manager, SP: sales planning, SR: sales reports, SU: storage unit, TF: timing forms, TU: training unit, TUR: training unit reports, WM: warehouses manager, Y: yearly.

in Table 5 may be mixed with some grade of uncertainty. In order to gather such data in real case studies, the linguistic terms in questionnaires are assumed to be a proper choice. On the other hand there is no need to involve the workers and staff with complicated fuzzy sets. The required data are gathered using qualitative linguistic terms, for instance a 5-point Likert, and then they are associated to some fixed and predefined fuzzy sets.

Moreover, in real life cases we may need to get weight factors for different parts of objective functions from decision-makers or staff. Usually decision-makers have enough knowledge to give weights of objective functions. But occasionally, decision-makers or staff may have no enough knowledge about behavior of objective functions, so they cannot give the weight factors explicitly in real cases. Under such situations, using pairwise comparison matrix in which the relative importance of a pair of objectives are gathered, is proposed. Several pairwise comparison matrix are prepared. Then, the each of them is filled out by a decision-maker. The consistency of each decision-maker is calculated and the matrices which have less consistency ratio are deleted. An integrated pairwise comparison matrix is formed based on remaining matrices. Finally, the eight of each objective is calculated based on the information in the integrated pairwise comparison matrix. More details can be found in Barzilai, 1997.

4.2 Model Implementation

The proposed model (1)–(26) is coded and implemented in LINGO software. Results of the proposed model are compared with the experimental model that was used in the factory. In order to demonstrate effectiveness and validation of the proposed model, in this section we implement the model for a real case study. We gathered the preference of DM on priority of objective functions. According to decision-maker request, the weights of goals are: $\mathrm{w}_1 = 0.2$, $\mathrm{w}_2 = 0.5$, and $\mathrm{w}_3 = 0.3$.

4.2.1 A real-world industrial case study

In order to illustrate the applicability and efficacy of proposed methodology, the proposed model is applied in Teiph-Saipa Company. Teiph-Saipa is currently the producer of industrial and automotive colors and resins in Iran. Products of Teiph-Saipa Company are mainly distributed throughout Iran and Middle-East.

Recently, the company has faced with several issues and problems, such as decrease of customer satisfaction levels, high backordering levels, and high total costs.

The following assumptions are considered for planning in Teiph-Saipa Company. The planning horizon consists of six periods. There are two family groups of products. Aggregate unit of production is Ton. Demand can be either satisfied or backordered, but the end backordering volume in the last period of planning should be equal to zero. Two working shifts are considered in a day. Regular production time is 8 hours per shift and overtime production is approximately 3 hours per shift. There are two separate warehouse; the warehouse 1 (w = 1) inside the factory and the warehouse 2 (w = 2) is located outside. To produce these products, 24 types of raw materials are required. Four skill levels are considered for workers as low ($k = 1$), medium ($k = 2$), good ($k = 3$), and high ($k = 4$). There are 3 types of training ($l = 1, 2, 3$). Repairs are done just in shift 2 (i.e., overtime). Since the filters of reservoirs should occasionally be replaced, inevitable stops are usually occurred during shift 1 (regular times). If the demand of one period is higher than production capacity in regular times and on hand inventory levels also unable to satisfy this demand, the production is continued in overtime. The holding cost of inventory is low during the planning horizon. Five operators are working in each site. Maximum available budget is 9,000,000,000 (Rials) over the planning horizon.

4.3 Computational Results

As mentioned LINGO software is used to code and run of the proposed APP. According to payoff matrix, minimum and maximum values for objectives are determined as $Z_1 \in [53.7\times10^8,\ 90\times10^8]$, $Z_2 \in [658,\ 978]$, and $Z_3 \in [0, 15]$. So, the goals and aspiration levels have been determined as $g_1 = 53.7\times10^8$, $g_2 = 658$, and $g_3 = 15$. The membership functions of objective functions considering aspiration levels are shown in Figure 3. Finally, computational results of proposed FGP approach are represented in Table 6.

As it can be concluded form content of Table 6 the proposed FGP is capable to find high quality compromise solution in presence of several conflictive objective functions and constraints. As it is clear, the satisfaction levels of all objective functions are high and this is interpreted as a suitable compromising solution for the problem.

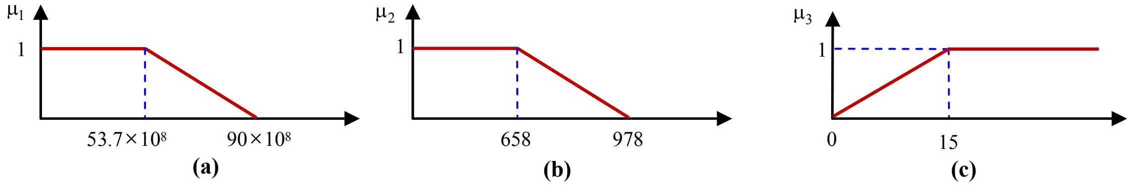

Figure 3. Aspiration levels of fuzzy goals. (a) First objective, (b) second objective, and (c) third objective.

Table 6. Results of fuzzy goal programming

Satisfaction level			Objective value			Weighted	CPU time (second)
μ_1	μ_2	μ_3	Z_1	Z_2	Z_3	ZMF	
0.9331725	1	0.9333333	5634733000	658	14	0.9666345	18213

4.4 Comparing the Results

Comparing the results of proposed model and current applied empirical model in the company is reported in Table 7. In this table, total cost is calculated during all periods of planning horizon.

Table 7. Comparison of results

Model	Cost (rials)	Delivery (day)	Trained workers (man)
The Proposed FGP	5634733000	10	14
The Empirical Model	6742169000	16	3

It can be concluded form content of Table 7 that the achieved solution by proposed FGP dominates the empirical solution currently are used in the company. The cost, delivery, and training are all better in the solution proposed by the FGP.

In order to further investigation the plans proposed by both methods (i.e., the FGP and empirical method) the delivery time of product to customers are plotted in Figure 4 for both methods against due date.

Effect of number of trained manpower on the quality of final product is presented in Figure 5. The results show that total costs will be reduced 20%, quality of finished products will be increased 43%, and customers will be satisfied in situation we act using generated production plan of proposed FGP.

The following points are also achieved based on implementation of proposed approach in real case study.

- No hiring and firing is allowed for the next six periods.

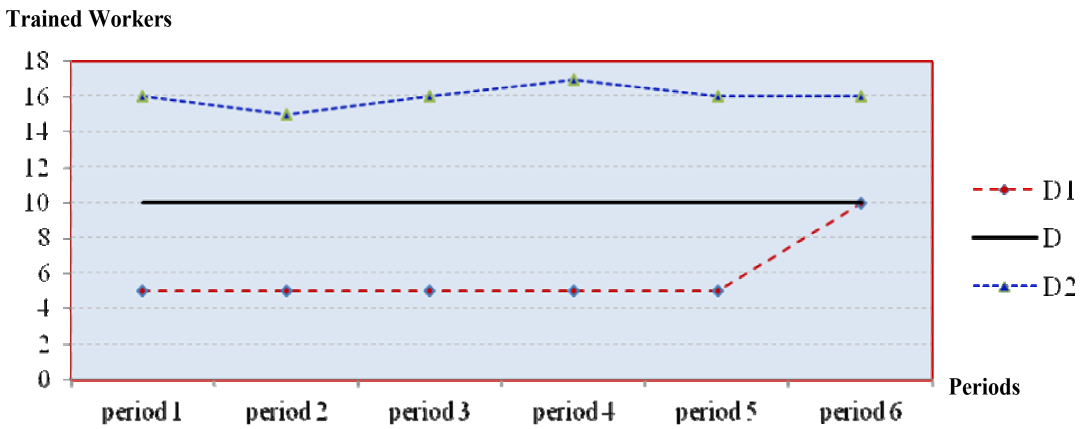

Figure 4. Comparison of delivery times and due date. D1: delivery time of proposed model, D2: delivery time of empirical model, D: due date of products considering contracts.

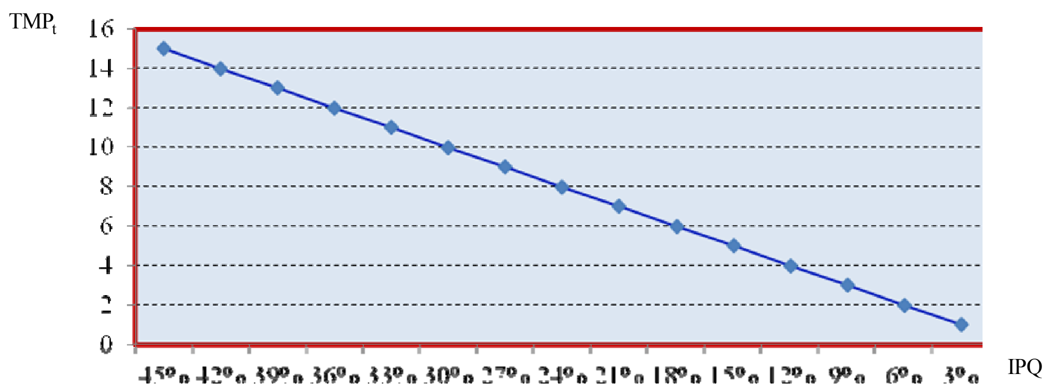

Figure 5. Effect of TMP_t on the quality of products. TMP_t : trained manpower percentage, IPQ: increasing product quality.

- The overtime-shift is used when the regular time cannot satisfied the demands, or handling the training programs.
- Training if required is allowed in all periods of planning.
- The cross-functional quality teams are formed in order to learn new techniques for activities.
- The performance and experiments of workers are shared during implementation phase.
- The employee engagement with the new production plan is measured frequently in order to motivate them to move and to feedback the success of plan.
- All workers are trained based on their performance records in order to improve the quality of products and to enhance the learning curves which are related to production time and quality.
- The products quality is measured through customer's feedback and distributed questionnaires among clients.
- The customer satisfaction level is measured frequently through a survey questionnaire about quality of delivery, quality of product, and time of delivering.

The above mentioned notes will help the execution team to check whether the plan is implemented correctly or a deviation is occurred. The results of the questionnaires are analyzed. The main results include (1) company spent huge costs for hiring and firing his staff. All these costs were reduced during a proper plan proposed by the approach of this study, (2) although the training courses imposed costs to company, but its positive effects on quality and learning curves of workers was illustrated, (3) company acquired 78% customer satisfaction and 40% increase in the quality of end-products.

5. CONCLUSIONS

In this paper we proposed a new real APP problem. The problem considered a multi-objective multi-period multi-product situation considering several constraints on budget, workforce, working shift, capacity of machines, capacity of warehouses, rate of production, due dates, quality of products, process times, and inventory levels. The proposed problem was modeled using mixed integer multi-objective mathematical model. The proposed model attempts to simultaneously minimize total costs, maximize customer satisfaction level, and achieving high quality of product. The on time delivery along with high quality and low cost was considered as a main factor which satisfies the customer. The relation of the number of trained workers on quality of final products was also considered in this study. Then, a FGP approach was proposed to solve the model. The proposed FGP was used to generate compromising solutions for the multi-objective mathematical programming.

A real-case study of color and resin company called Teiph-Saipa, which produces several products was selected as a practical environment in order to test the suitability and applicability of proposed model and the solution approach. A data dictionary, which facilitates the re-implementation of the proposed model in other real cases and applications, was also proposed. The proposed FGP approach was coded in LINGO software. The results of proposed method and those of an existing experimental method were compared on the case study. This comparison revealed that the production plans generated by the proposed approach outperformed those of the experimental production plans. The total costs of production plans, quality of products, and delivery times were improved by using the proposed approach. As the modeling of the proposed approach was developed for general purposes, it can be used in other industrial cases with minimum customization.

The APP is a non-deterministic polynomial hard problems, so heuristic or meta-heuristic methods may find high quality solution for large size instances in a more reasonable CPU time. Generating several sets of non-dominated solutions on Pareto front of such problem may be another interesting research. Some parameters of the model, such as process times, may be modeled in uncertain environment in future researches. Since the production time is not always fixed, it can be modeled using fuzzy sets. The warehouse space can also be considered for each unit of product, separately. The model can be improved by adding constraints on skill level of workers and their learning curves. Since many companies may outsource some of the works, it can also be considered in the model. The failure of facilities and production machines, and the rate of products returned from customers can be considered in future research works.

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