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A decision-making approach for a multi-objective multisite supply network planning problem

Houssem Felfel*, Omar Ayadi and Faouzi Masmoudi

Mechanics, Modeling and Production Research Laboratory, National Engineering School of Sfax (ENIS), University of Sfax, Sfax, Tunisia

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The current manufacturing environment has changed from traditional single plant to multisite supply network where multiple plants are serving customer demands. In this paper, a multi-objective, multistage, multi-product and multi-period production and transportation planning problem is considered in the context of a multisite supply network. The developed optimisation model aims simultaneously to minimise the total cost and to maximise products quality level. The main purpose of this paper is to provide the planner with a front of Pareto solutions and to help him to select a fair optimal solution that satisfies equitably the two considered objectives. A modified version of the epsilon-constraint method (AUGMECON) is applied in this paper to generate an efficient set of Pareto solutions. Then, the lexicographic minimax method is used in order to find the fair solution. A numerical example from a real textile and apparel industry is presented to illustrate the planning model and the solution approach.

Keywords: multisite supply network; multi-objective optimisation; efficient epsilon-constraint method; lexicographic minimax method; Pareto-optimal solutions

1. Introduction

In the face of today's highly competitive and global markets, companies no longer operate as independent entities, but rather as multi-plant structures. Therefore, companies are increasingly willing to reconfigure their supply and production strategies to coordinate all production resources of multiple plants in order to avoid inefficient capacity utilisation, excessive inventories and poor customer service.

To achieve the optimum operating efficiency of the system and the desired consumer satisfaction level, supply chain management (SCM) is considered to be a key area for improvement. According to Simchi-Levi, Kaminsky, and Simchi-Levi (1999),

> Supply chain management is a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system wide costs while satisfying service level requirements.

The SCM problem may be considered at different levels depending on the time horizon, namely, strategic, tactical and operational (Fox, Barbuceanu, and Teigen 2000). The operational level considers short-term decisions which do not exceed one week or even less. It deals with issues such as the sequencing of tasks in units and the assignment of tasks to each unit. At the strategic level, the time horizon could take more than one year and the decisions concern the design and the structure of a supply chain (SC). The tactical level is found between these two extremes and involves production, inventory and distribution decisions. The focus of this work addressed the tactical level of the SC.

In traditional SCM problem, maximising profit or minimising the total cost is the most usually considered objective function. Moreover, products' quality level represents an important performance metric in the formulation of the SC model in order to cope with high competition and to respond to customer requirements. By analysing these two criteria, it can be noted that total cost and products quality conflict with each other. Indeed, the best product quality has usually a higher cost.

In this paper, a multi-objective optimisation model for a multistage, multi-product, multi-period, multisite supply network production and transportation planning problem is developed. The network partners need to define their optimal workloads and inventories in order to optimise the whole network performances. Two objective functions are considered: the minimisation of the total cost and the maximisation of product's quality level. The main purpose of this paper is to provide the network planner with a front of Pareto solutions and to help him to choose a fair solution that satisfies equitably the considered objective functions. A modified version of the epsilon-constraint method (augmented e-constraint method AUGMECON) is applied to generate an efficient set of Pareto. Moreover, the considered objectives are supposed to be

*Corresponding author. Email: houssem.felfel@gmail.com

equally important. Then, the lexicographic minimax method is used in order to find a 'fair' solution where all normalised objective functions are as close to one another as possible. To the best of the authors' knowledge, AUGMECON method and the lexicographic minimax method have not been applied in the optimisation of multi-objective multisite supply network planning problem. A real case study from the textile and apparel industry is illustrated to explain the planning model and the solution approach.

The main scientific contribution of this paper is to generate a front of Pareto optimal efficient solutions for a multi-objective multisite supply network production and transportation planning problem and to select a fair optimal solution that satisfies equitably the considered objectives. Although many works in the literature dealt with the multi-objective SC planning problem, but to the best of the authors' knowledge, none of them has addressed the choice of a solution from the front of Pareto optimal solutions. Moreover, the proposed approach has been applied to a real case study from textile and apparel industry.

The remainder of the paper is organised as follows. Section 2 is devoted to the literature review of related topics. Section 3 describes the problem statement. The mathematical formulation of the supply network planning problem is shown in Section 4. In Section 5, the solution approaches, AUGMECON method and lexicographic minimax method, are presented. Section 6 describes and discusses the computational results of the case study. Finally, Section 7 draws the conclusions of this work and suggests future research directions.

2. Literature review

To cope with the continuously high competition, manufacturing structure has changed from traditional single-plant to multi-plant structure. Therefore, decision-making at different levels in the organisation should be well coordinated to achieve optimal performance such as total cost, manufacturing lead time and to satisfy customer demands. According to Bhatnagar, Chandra, and Goyal (1993), SC coordination planning can be classified into two categories: general coordination and multi-plant coordination. General level coordination seeks to integrate different decisions such as facility location, inventory and production planning, marketing and distribution. The multi-plant coordination aims to link together the same function of several manufacturing plants which are part of a vertically integrated firm. In this paper, the considered problem belongs to multi-plant coordination problem.

In the last decades, multisite production planning problems have attracted many researchers' attention. According to Harland (1997), the multisite conceptual models can be classified into four categories: (1) internal chain, (2) external relationship, (3) dyadic chain and (4) network. Internal chain model implies that there exists only a single production plant. External (serial) model indicates that there are several manufacturing plants which have sequential relationships; that is output from one plant becomes an input into another plant. Dyadic (parallel) model indicates that the plants have the same manufacturing processes and can produce the same products. The manufacturing plants have a complementary relationship. The network model is a mixture of the external (serial) and dyadic (parallel). In this work, a multisite supply network planning model is proposed.

Most multisite planning and optimisation models in the literature considered only a single-objective function, usually total cost minimisation or profit maximisation of and other important criteria such as products' quality level are not considered. Different solution approaches have been proposed in the literature to solve the multisite planning problem.

Roux, Dauzere-Peres, and Lasserre (1999) proposed an integrated planning and scheduling model in a multisite environment. The main goal is to determine an optimal plan for a multisite structure where each site is a multi-machine work centre. The considered objective function aims to minimise a given total cost including inventory cost, backlog cost and production cost. A sophisticated local search heuristic is used to efficiently solve job-shop problems with resource assignment. Vercellis (1999) dealt with a capacitated master production planning and capacity allocation problem for a multi-plant supply network from a real-world process industry. The author considers the minimisation of the sum of different cost factors as objective including the costs of production in different stages, inventory, lost demand, transportation and overtime. To solve this problem, two iterative LP-based heuristic algorithms were developed.

Moon, Kim, and Hur (2002) proposed an integrated process planning and scheduling model for a dyadic multi-plant SC. The developed model aims to minimise the total tardiness by determining a global optimal schedule for machine assignments and operations sequences using a genetic algorithm-based heuristic approach.

Gnoni et al. (2003) studied an external multisite model in the automobile industry in the case of an uncertain, multi-period and multi-product demand. The developed model aims to minimise the sum of set-up, inventory and fixed costs of the production sites. The analytical model of the lot sizing and scheduling problem was solved using LINDO software and the simulation model is coded in ARENA.

Jackson and Grossmann (2003) proposed a multi-period non-linear programming optimisation model for the planning and coordination of production, transportation and sales of geographically distributed multi-plant facilities. The considered objective aims to maximise the profits of the entire production and distribution network. To solve the resulting large-scale non-linear multi-period optimisation problem, spatial and temporal decomposition schemes based on Lagrangian decomposition were developed.

Lin and Chen (2006) proposed a multistage multisite monolithic model for a production planning problem of a real thin film transistor–liquid crystal display (TFT-LCD) SC network. A single-objective function was designed to minimise the total cost including production cost, storage cost, shortage cost of unfulfilled demands, purchase cost and transportation cost. The final decision variables were obtained using LINGO software.

Ryu and Pistikopoulos (2007) proposed a multi-period planning model for an enterprise that consists of multiple plants. The problem is transformed into a set of two optimisation problems. The authors considered single-objective functions in every optimisation problem which are respectively profit maximisation and operating cost minimisation. The problem was solved using CPLEX software.

Shah and Ierapetritou (2012) studied the integrated planning and scheduling problem for the multisite, multi-product using the augmented Lagrangian decomposition method. Given the fixed demand forecast, the model minimised the total costs which include production costs, variable inventory costs, backorder costs and transportation costs.

Chen and Lu (2012) studied a multisite capacity planning problem in the TFT-LCD manufacturing industry by means of a decomposition algorithm and stochastic optimisation model. The proposed stochastic multisite capacity planning problem considered only one objective function which is the maximisation of the expected total net profit.

Lin, Chen, and Chu (2014) dealt with a dynamic multisite capacity planning problem in the TFT-LCD industry. To solve this problem, a stochastic dynamic programming model was developed considering one objective function which is the maximisation of the total marginal profit.

However, several multi-objective multisite planning and optimisation models have been proposed in the literature. Leung et al. (2007) developed a robust optimisation model to solve a multi-site production problem with uncertain parameters for a multinational lingerie company located in Hong Kong. The developed model aimed to minimise the total cost as well as the variance of the total cost. The optimisation model is solved using a single-objective function. Torabi and Hassini (2009) developed a multisite multi-echelon SC production planning model including distribution and procurement plans. Four objective functions were considered which are the minimisation of logistics cost, the minimisation of the amount of defective products, the maximisation of the purchasing value of and the minimisation of the late deliveries. A novel fuzzy approach is developed to solve the multi-objective optimisation problem. Verderame and Floudas (2010) addressed an operational planning of a production and distribution multisite SC under demand and transportation time uncertainty by means of a robust optimisation model and conditional value at risk theory. The proposed model attempted to minimise the overproduction and the underproduction of bulk products, to minimise the underproduction of finished product, to minimise the unit underutilisation of each production site, to minimise the transportation cost and to maximise the total profit. Each of the aforementioned terms was associated with a weighting coefficient determined by the decision maker and the optimisation problem was solved with a single-objective function using GAMS and CPLEX software.

Mirzapour Al-e-Hashem, Malekly, and Aryanezhad (2011b) proposed a multisite, multi-product, multi-period aggregate production planning problem. To solve this problem, a new robust multi-objective mixed integer non-linear programming model was developed taking into two objective functions simultaneously. The first objective function aimed to minimise the total losses of the SC and the second aimed to maximise the customer satisfaction. The proposed multi-objective model was then solved as a single-objective function using LP-metrics method.

For the multi-objective problems, the objective functions usually conflict with each other and there are no solutions that optimise all objective functions simultaneously. Besides, there is no accepted definition of optimum for multi-objective optimisation in comparison with single-objective optimisation which it makes difficult to find the optimal solution. Instead, the solution of these problems is represented with a front of Pareto optimal solutions representing a trade-off between the different objectives rather than a single optimal solution. In this paper, the authors are interested in providing an exact Pareto front to the decision maker. Among exact methods to find the set Pareto, weighted sum and e-constraint are considered the most popular methods. The e-constraint method offers many advantages in comparison with the weighted sum method (Mavrotas 2009). Although there are advantages of ordinary e-constraint method, the main drawback of this method is the inefficiency of the generated set of Pareto solutions. In fact, there is no guarantee that the obtained solutions are efficient. In other words, it may exit another Pareto solution that can improve at least one objective function without deteriorating the other objective functions. The e-constraint method has widely been applied in the literature in order to generate a set of Pareto-optimal solutions for multi-objective SC optimisation and planning problems (Sabri and Beamon 2000; You and Grossmann 2008; Franca et al. 2010).

In a multi-objective optimisation problem, the task of the decision maker consists in finding the set of Pareto solutions and then choosing a single preferred alternative. Most of the existing literature in SC optimisation problem focused only on obtaining the Pareto optimal solution and not on selecting a compromise solution (Guillen et al. 2005;

Azaron et al. 2008; Franca et al. 2010; Mirzapour Al-e-Hashem et al. 2011a; Ben Yahia et al. 2013; Guo et al. 2013; Fahimnia et al. 2013). To the best of the authors' knowledge, there is no prior work dealing with selecting a solution from the Pareto set in SC planning problems.

3. Problem statement

The considered network involves several manufacturing plants needing to enlarge their corresponding capacities and competences. The plants are arranged in a multistage structure with respect to their competences and the physical flow, as shown in Figure 1. The efficient management of the network activities necessitates coordinating the corresponding decisions through an integrated multisite planning approach. The considered supply network is managed in a centralised way. The centralisation occurs by considering the entire system as a single entity managed by a central agent. Information related to each plant and necessary for the development of optimal planning are gathered and managed by the central agent. The information sharing can be supported by an information system (IS). The central managing agent takes different decisions including production, inventory and transportation amounts for different entities of the SC. The centralised management of the network presents different advantages compared to the decentralised way. Indeed, it optimises the performances of the whole SC, avoids the duplication of activities and offers better coordination with minimum transaction efforts and costs.

The considered problem attempts simultaneously to minimise the total system cost and to maximise products' quality level. The total cost includes production, inventory and transportation costs. Particular constraints such as manufacturers' production capacities in normal working time and overtime as well as balancing inventory and transportation of finished and semi-finished products are considered. A delivery lead time corresponding to transportation of semi-finished products between upstream and downstream plants has to be respected. Decision makers in the SC system under concern aim to make the following decisions:

- The production amount in normal working hours and overtime at each plant in each period.
- The amount of inventory of each finished or semi-finished product that should be maintained at each plant within a certain planning period.
- The amount of each product to be transported between upstream and downstream plants in each period.

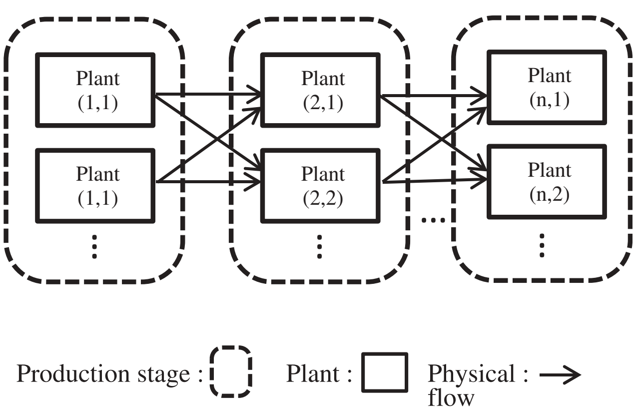

Figure 1. Multistage and multisite production environment.

4. Mathematical formulation

In this section, a multi-objective linear programming model is developed to address the multisite network problem defined in the previous section. The developed model requires the following indices, sets, parameters and variables.

Indices	
L_i	Set of direct successor plant of i.
ST_j	Set of stages (j = 1, 2, …, N).
i, i'	Production plant index (i, i' = 1, 2, …, I) where i belongs to stage n and i' belongs to stage n + 1.
k	Product index (k = 1, 2, …, K).
t	Period index (t = 1, 2, …, T).
Decision variables	
P_{ikt}	Production amounts of product k at plant i in period t in normal working hours.
H_{ikt}	Production amounts of product k at plant i in period t in overtime.
S_{ikt}	Amounts of end of period inventory of product k at plant i in period t.
JS_{ikt}	Amounts of end of period inventory of semi-finished product k at plant i in period t.
$TR_{i->i',kt}$	Amounts of product k transported from plant i to i' in period t.
$Q_{i,k}$	Amounts of product k received by plant i in period t.
Parameters	
cp_{ik}	Unit cost of production for product k in normal working hours at plant i.
ch_{ik}	Unit cost of production for product k in overtime at plant i.
$ct_{i->i',k}$	Unit cost of transportation between plant i and i' of production for product k.
cs_{ik}	Unit cost of inventory of product or component k at plant i.
$capp_{it}$	Production capacity at plant i in normal working hours in period t.
$caph_{it}$	Production capacity at plant i in overtime in period t.
$caps_{it}$	Storage capacity at plant i in period t.
$capt_{i->i',t}$	Transportation capacity at plant i in period t.
D_{kt}	Demand of finished product k in period t.
b_k	Time needed for the production of a product entity k [min].
α_{kt}	Quality grade to produce a product k in plant i.
DL	Delivery time of the transported quantity.
β	Percentage of demand to address the non-quality.

4.1. Formulation

$$\text{Min}\, F1 = \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{i=1}^{I} cp_{ik}P_{ikt} + ch_{ik}H_{ikt} + cs_{ik*}(S_{ikt} + JS_{ikt}) + ct_{i->i',k}TR_{i->i',kt} \tag{1}$$

$$\text{Max}\, F2 = \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{i=1}^{I} \alpha_{ik}(P_{ikt} + H_{ikt}) \tag{2}$$

$$S_{ik,t} = S_{i,kt-1} + P_{ikt} + H_{ikt} - \sum_{i'\in L_i} TR_{i->i',kt}, \quad \forall i \in ST_{j<N},\ \forall k, t \tag{3}$$

$$\sum_{i=1}^{I} S_{ik,t} = \sum_{i=1}^{I} (S_{ik,t-1} + P_{ikt} + H_{ikt}) - D_{kt}, \quad \forall i \in ST_{j=N}, k, t \tag{4}$$

$$JS_{ik,t} = JS_{ik,t-1} + Q_{ikt} - (P_{ikt} + H_{ikt}), \quad \forall i, k, t \tag{5}$$

$$\sum_{t=1}^{T} P_{ikt} + H_{ikt} = \sum_{t=1}^{T} (1+\beta)D_{kt}, \quad \forall i, k \tag{6}$$

$$Q_{i'k,t+DL} = \sum_{i'\in L_i} TR_{i->i',kt}, \quad \forall i', k, t \tag{7}$$

$$\sum_{k=1}^{K} b_k P_{ikt} \le capp_{it}, \quad \forall i, t \tag{8}$$

$$\sum_{k=1}^{K} b_k H_{ikt} \le caph_{it}, \quad \forall i, t \tag{9}$$

$$\sum_{k=1}^{K} S_{ikt} + JS_{ikt} \le caps_{it}, \quad \forall i, t \tag{10}$$

$$\sum_{k=1}^{K} TR_{i->i',kt} \le captr_{it}, \quad \forall i, t \tag{11}$$

$$P_{ikt}, H_{ikt}, S_{ikt}, JS_{ikt}, TR_{i->i',kt} \ge 0, \quad \forall i, k, t \tag{12}$$

The objective function (1) aims to minimise the total costs associated with production in normal working hours and overtime, inventory holding and transporting of semi-products between upstream and downstream plants. The second objective function (2) aims to maximise the products' quality level. Equation (3) provides the balance for the inventory of products in every production stage except for the last stage. Constraint (4) is the balance equations for the inventory for the last production stage, considering customer demands. Constraint (5) is the inventory balance equation for the semi-finished products. Equation (6) makes sure that the quantity of products should be equal to customer needs taking into account the percentage of demand to address the non-quality. Constraint (7) represents the balance equations for the transportation between the different production stages. The set of constraints (8) and (9) are the production capacity constraints in normal working hours and overtime. Constraints (10) ensure that the storage capacity is respected. Constraints (11) make sure that the transportation capacity is respected. Constraint (12) is the non-negativity restriction on the decision variables.

5. Solution approaches

Most real-world decision problems involve multiple and conflicting objective functions. The main goal for the optimisation problem is to provide the decision makers with a set of efficient solutions to choose the best one.

Many solution methods have been proposed to solve multi-objective optimisation problems (Miettinen 1999). Among these approaches, there are scalarization methods that change the multi-objective problem into a single-objective one. The most popular scalarization methods are the weighted sum method and the e-constraint method. A modified version of the e-constraint (AUGMECON) method is applied to generate a set of Pareto in this paper.

Before applying this approach, the Pareto optimality in the multi-objective optimisation is reviewed. The set Pareto points are non-dominated solutions in the sense that there are no other points that dominate them. Consider a multi-objective optimisation problem with M objective functions $f(x)$ as below:

$$min_x\{f(x) = (f_1(x), \ldots, f_M(x))\} \tag{13}$$

Theorem 1: x^* is said to be a Pareto optimal (efficient, non-inferior or non-dominated) solution of multi-objective problem, if and only if there does not exist another $x \in X$ where X is the space of feasible solutions such that

$$\begin{aligned} &f_i(x) \le f_i(x*) \text{ for all } i \\ &\text{And } f_j(x) < f_j(x*) \text{ for at least one } j \end{aligned} \tag{14}$$

In the proposed approach, the decision maker needs to define an exact front of Pareto corresponding to the planning problem. The e-constraint method is considered among the most popular method to find a set of exact Pareto solutions. The ordinary and augmented e-constraint techniques are presented in the next two subsections.

5.1. Epsilon-constraint method

The e-constraints method proposed by Chankong and Haimes (1983) is a non-dominated method to generate a set of Pareto optimal solutions for multi-objective problems. In the e-constraint method, only one objective function is selected to be optimised and the others are transformed into constraints by setting an upper bound to each of them. Then, the level of ε_j is altered to generate the entire set of Pareto solutions. The e-constraint problem can be formulated as follows:

$$\begin{aligned}&\text{Minimize } f_1(x)\\&\text{Subject to } f_j(x) \le \varepsilon_j \quad \forall j = 2, \ldots, M\\&x \in X\end{aligned} \tag{15}$$

5.2. Efficient epsilon-constraint method

In spite of the advantages of the e-constraint method, three points about the implementation of this method should be taken into account (Mavrotas 2009):

(1) The estimation of the range of objective functions over the efficient set.
(2) The increased solution time for problems containing more than two objectives.
(3) The guarantee of efficiency of the obtained Pareto solutions.

In order to tackle all these issues, an improved version of the conventional e-constraint method called the augmented e-constraint (AUGMECON) method was developed. The augmented e-constraint method can improve the preference of the multi-objective optimisation problem solution in comparison with the traditional e-constraint method because it generates only efficient Pareto optimal solutions. Otherwise, the efficient solutions of the considered problem in comparison with inefficient solutions can enhance both competitiveness and quality level of the obtained solutions.

In this approach the inequality constraints of the ordinary e-constraint method are transformed into equality constraints by introducing positive surplus or slack variables. The optimal solution of the optimisation problem is guaranteed to be an efficient solution only if the values of the slack variables of all the associated $M - 1$ objective functions' constraints are equal to zero. So, the augmented e-constraint method can be formulated as

$$\begin{aligned}&\text{Min} f_1(x) + \delta * \left(\frac{s_2}{r_2} + \frac{s_3}{r_3} + \cdots + \frac{s_M}{r_M}\right)\\&\text{Subject to } f_i(x) + s_i = \varepsilon_i \quad \forall i \in \{2, \ldots, M\}\\&x \in X,\ s_i \in R^+\end{aligned} \tag{16}$$

where δ is a small positive number usually between 0.001 and 0.000001 and r_i the range of the ith objective function. This range is obtained from the pay-off table by individually optimising each objective function. The minimum and maximum values of ith objective function $f_i^{\max}$ and $f_i^{\min}$ are individually calculated and the range of ith objective function is determined as follows:

$$r_i = f_i^{\max} - f_i^{\min}$$

5.3. The lexicographic minimax method

In some multi-objective optimisation problems, the decision maker considers the objectives as equally important, so, no preference is attributed to any of them. In this case, a 'fair' solution, where the normalised objective functions are as close to each other as possible, should be defined. The lexicographic minimax method is a popular approach in the literature to generate a 'fair' solution (Ogryczak 1997; Luss 1999). This approach has been applied for telecommunication network design (Ogryczak, Pióro, and Tomaszewski 2005). It was used also to determine an equitable solution for a resource allocation problem (Luss 1999; Klein, Luss, and Smith 1992).

Considering that all objective functions $f_1, \ldots, f_M$ are in the same scale (if they are not in the same scale, normalisation should be applied), a feasible solution $x \in X$ is called the minimax solution of the multi-objective optimisation problem (13), if it is an optimal solution to the problem:

$$min_x\{max_{i=1,\ldots,M}\, f_i(x) : x \in X\} \tag{17}$$

The minimax solution aims to minimise the worst objective value. Despite the equity property of the minimax method, the optimal solution is not unique and some of them may not be efficient. To resolve this problem, a lexicographic minimax problem is proposed as a refinement technique. If the second worst objective value is also minimised, the third worst objective value, and so on, then a lexicographic minimax solution will be obtained.

Let $\Theta : R^M \to R^M$ a map which orders the components of vectors in a non-increasing order, i.e. $\Theta(e_1, e_2, \ldots, e_M) = \Theta\left(e_{\langle 1\rangle}, e_{\langle 2\rangle}, \ldots, e_{\langle M\rangle}\right)$ with $e_{\langle 1\rangle} \ge e_{\langle 2\rangle} \ge \ldots \ge e_{\langle M\rangle}$, where $e_{\langle 1\rangle}$ presents the ith component of $\Theta(e)$.

The lexicographic minimax problem could be formulated as

$$lex\ \min_x\{\Theta(f_1(x), \ldots, f_M(x)) : x \in X\} \tag{18}$$

The lexicographic minimax model generates efficient Pareto solutions with perfect equity (Erkut et al. 2008). So, the following theorem is obtained:

Theorem 2: $x^* \in X$ is a Pareto optimal solution with perfect equity $f_1(x^*) = f_2(x^*) = \ldots = f_M(x^*)$, if it is an optimal solution of the lexicographic minimax problem.

Erkut et al. (2008) and Liu and Papageorgiou (2013) proposed a formulation that transfers the lexicographic minimax problem to a lexicographic minimisation problem. $x^* \in X$ is an optimal solution of lexicographic minimax problem (18) if and only if it is the optimal solution of the following optimisation problem:

$$\begin{aligned} &\min_{x\in X} \sum_{n=1}^{M} n * \lambda_n + \sum_{m=1}^{M}\sum_{n=1}^{M} d_{mn} \\ &\text{s.}t.\ \ d_{mn} + \lambda_n \geq f_m(x) \quad \forall m, n = 1, \ldots, M \\ &d_{mn} \geq 0, \quad \forall m, n = 1, \ldots, M \end{aligned} \tag{19}$$

To avoid dimensional inconsistency among the different objectives, the values of $f_1(x), \ldots, f_M(x)$ are scaled into the interval [0, 1]. $\overline{f_1}(x), \ldots, \overline{f_M}(x)$ are defined as the normalised objective functions of $f_1(x), \ldots, f_M(x)$ respectively.

If the original objective is minimisation, the normalised objective function i is defined as

$$\overline{f_i(x)} = \frac{f_i(x) - f_i^{\min}}{f_i^{\max} - f_i^{\min}} \tag{20}$$

and if the original objective is maximisation, it is defined as

$$\overline{f_i(x)} = \frac{f_i^{\max} - f_i(x)}{f_i^{\max} - f_i^{\min}} \tag{21}$$

To obtain $f_i^{\min}$ and $f_i^{\max}$ which are respectively the minimum and the maximum values of $f_i(x)$:

(1) First, the problem $\{\min_{x\in X} f_1(x)\}$ is solved where $x1$ is its optimal solution and $f_1^{\min} = f_1(x1)$, $f_2^{\min} = f_2(x1)$.
(2) Then the problem $\{\max_{x\in X} f_2(x)\}$ is solved where $x2$ is its optimal solution and $f_1^{\max} = f_1(x2)$, $f_2^{\max} = f_2(x2)$.

6. Application of the proposed approach to a real-world case

The studied case is a five-stage supply network formed of small and medium enterprises from the textile and apparel industry located in Tunisia. The manufacturing process consists of five main sub-processes corresponding to considered stages: knitting and dyeing, cutting, embroidery, cloth making and packaging. The first three processes provide semi-finished products, while cloth making converts the semi-finished products into finished products that are packaged and delivered to the final customers. The products are manufactured in a make-to-order policy. The structure of the considered network consists of a central cloth making plant (Textile-International Company 'TE-INTER') and five subcontractors as illustrated in Figure 2. TE-INTER is composed of three internal production departments: cutting, cloth making and packaging. TE-INTER subcontracts part of its activities for two main reasons. The first reason is the lack of skills and resources in the fields of embroidery, printing and dyeing. The second reason is the need of expansion of production capacity of cloth making in order to satisfy customer demands. In other words, TE-INTER can plan and execute some of the operations of cloth making and leave the remaining production activities to one or more of its subcontractors. The optimisation problem is to determine how to satisfy the customer demand in the SC network so that either total costs are minimised or products' quality level is maximised. The proposed approach has been evaluated with data from a real supply network in the textile and apparel industry. The planning horizon of the multisite planning problem covers six weeks and the time period is one week. The plant indices are described in Table 1. The estimated demands of the finished product P1 of the first tasted case are presented in Table 2. Tables 3 and 4 give information about the production capacities of subcontractors and TE-INTER in normal working hours and overtime. As it is seen from Tables 3 and 4, the capacities

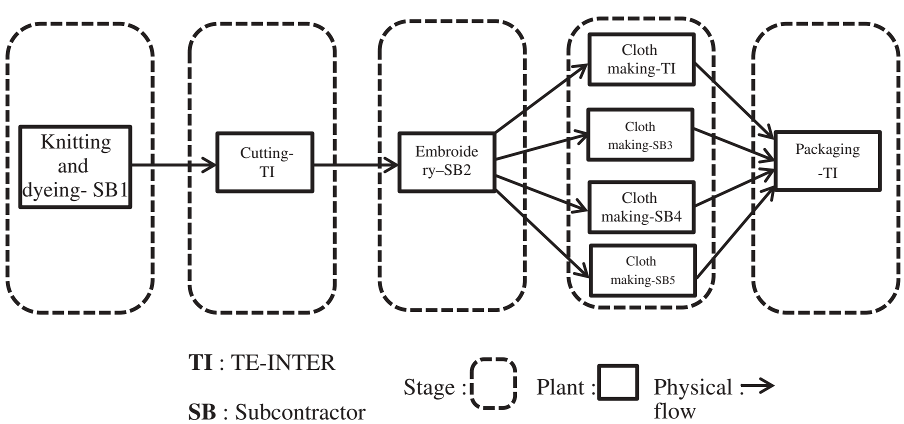

Figure 2. Textile supply network structure.

Table 1. Plant indices.

Plants	Designation
I1	Knitting and dyeing – Subcontractor 1
I2	Cutting – TE-INTER
I3	Embroidery Subcontractor 2
I4	Cloth making – TE-INTER
I5	Cloth making – Subcontractor 3
I6	Cloth making – Subcontractor 4
I7	Cloth making – Subcontractor 5
I8	Packaging – TE-INTER

Table 2. Finished product P1 demand.

Product	T1	T2	T3	T4	T5	T6
P1	0	0	0	0	7500	8000

Table 3. Production capacity in normal working hours [min].

Plants	T1	T2	T3	T4	T5	T6
I1	57600	54720	57600	60480	51840	54720
I2	28800	31680	34560	25920	28800	23040
I3	43200	40320	46080	37440	43200	40320
I4	86400	77760	74880	83520	89280	83520
I5	31680	34560	25920	28800	31680	37440
I6	54720	48960	46080	60480	51840	63360
I7	17280	20160	20160	14400	23040	17280
I8	17280	20160	14400	17280	20160	23040

Table 4. Production capacity in overtime [min].

Plants	T1	T2	T3	T4	T5	T6
I1	15120	13680	15840	13680	12960	14400
I2	6480	7200	7920	8640	7200	5040
I3	10080	11520	10800	12240	7920	8640
I4	20160	20880	21600	20880	22320	21600
I5	7200	6480	7920	7200	7920	8640
I6	12960	12240	12960	14400	15120	14400
I7	3600	4320	4320	5040	5760	4320
I8	3600	2880	3600	4320	5760	5040

of these sites are different in each period because of the absenteeism. Table 5 gives information about unit cost of production in normal working hours and overtime and inventory cost. Table 6 gives the transportation unit cost and transportation capacity from upstream plants to downstream plants. Table 7 details the processing time in different plants. Table 8 provides the quality grade of every product in every cloth making plant. The percentage of demand to address the non-quality (β) is equal to 5% and delivery time (DL) is equal to one week.

Table 5. Unit cost of production in normal working hours and overtime and inventory unit cost.

Unit cost	Products	I1	I2	I3	I4	I5	I6	I7	I8
cp	P1	1.72	0.72	0.9	1.75	1.9	1.65	1.5	0.38
	P2	2.5	0.57	1.42	2.6	2.3	2.83	2.1	0.29
ch	P1	3.01	1.26	1.58	3.06	3.33	2.89	2.63	0.67
	P2	4.38	1	2.49	4.55	4.03	4.95	3.68	0.51
cs	P1, P2	0.3	0.1	0.15	0.12	0.1	0.11	0.1	0.2

Table 6. Unit cost and capacity of transportation.

	Capacity	Unit cost (P1, P2)
I1 → I2	9100	0.6
I2 → I3	8700	0.45
I3 → I4	7500	0.37
I3 → I5	7500	0.52
I3 → I6	7500	0.65
I3 → I7	7500	0.34
I4 → I8	–	0
I5 → I8	2500	0.49
I6 → I8	5000	0.35
I7 → I8	2000	0.27

Table 7. Processing time.

Product	I1	I2	I3	I4	I5	I6	I7	I8
P1	8	4	4.5	11	10.5	12	13	3
P2	10	2.5	6.5	16.5	15.5	14	16	2.5

Table 8. Quality grade.

Products	I4	I5	I6	I7
P1	8	9	7	6
P2	8.5	7	9	5.5

6.1. *Model results*

In this section, the developed model is illustrated as a tool for making decisions related to production and transportation planning considering only the first objective function which is the minimisation of the total cost. The model example is solved using LINGO 14.0 and MS-Excel 2010 on a 32-bit Windows 7 based computer with an INTEL(R) Core (TM) 2Duo CPU,T5670@1.8 GHZ, 1.8 GHZ, 2 GB

RAM. Through the calculation of mathematical programming optimisation software *LINGO 14.0*, the final decision information such as the production amounts in normal working hours and overtime of the product #1 at each plant can be obtained as shown in Tables 9 and 10. Material flows from upstream plants to downstream plants are detailed in Table 11. Table 12 shows the inventory generated throughout the planning horizon at each plant. The inventory of semi-finished products *JS* is null.

According to the results obtained by LINDO 14.0, the optimal total cost is equal to 115,550.4 including production cost, inventory cost and transportation cost. As seen in Tables 9 and 10, the production amounts in normal working hours and overtime in each stage represent 105% of the product demand to address the non-quality.

Table 9. Production amounts in normal working hours of product 1.

Plants	T1	T2	T3	T4	T5	T6
I1	7200	6840	0	0	0	0
I2	0	7920	8320	0	0	0
I3	0	0	7955	8320	0	0
I4	0	0	0	6848	6548	0
I5	0	0	0	0	0	0
I6	0	0	0	0	0	0
I7	0	0	0	1107	1772	0
I8	0	0	0	0	6720	7680

Table 10. Production amounts in overtime of product 1.

Plants	T1	T2	T3	T4	T5	T6
I1	755	1480	0	0	0	0
I2	0	35	0	0	0	0
I3	0	0	0	0	0	0
I4	0	0	0	0	0	0
I5	0	0	0	0	0	0
I6	0	0	0	0	0	0
I7	0	0	0	0	0	0
I8	0	0	0	0	1155	720

Table 11. Transportation amounts between upstream and downstream plants of product 1.

Plant i → Plant i′	T1	T2	T3	T4	T5	T6
I1 → I2	7955	8320	0	0	0	0
I2 → I3	0	7955	8320	0	0	0
I3 → I4	0	0	6848	6548	0	0
I3 → I5	0	0	0	0	0	0
I3 → I6	0	0	0	0	0	0
I3 → I7	0	0	1107	1772	0	0
I4 → I8	0	0	0	6848	6548	0
I5 → I8	0	0	0	0	0	0
I6 → I8	0	0	0	0	0	0
I7 → I8	0	0	0	1027	1852	0

Table 12. Amounts of inventory of product 1.

Plants	T1	T2	T3	T4	T5	T6
I1	0	0	0	0	0	0
I2	0	0	0	0	0	0
I3	0	0	0	0	0	0
I4	0	0	0	0	0	0
I5	0	0	0	0	0	0
I6	0	0	0	0	0	0
I7	0	0	0	80	0	0
I8	0	0	0	0	0	0

The flow of products between upstream and downstream is equal to the total production amounts. The big amounts of production in cloth making stage are assigned respectively to TE-INTER and subcontractor #1 in normal working hours. So, it is more beneficial for TE-INTER to engage subcontractor #1 than to use overtime despite the transportation cost.

6.2. *The AUGMECON method application*

The AUGMECON method was coded using LINGO 14.0 software package. Several scenarios were considered based on various customer demands as shown in Table 13. The first step in applying AUGMECON method is to determine the pay-off table for the optimisation problem. The pay-off table is obtained by individually optimising each objective function as shown in Table 14. It should be noted that the total cost (*F1*) is the objective to be optimised and the product's quality level (*F2*) is transformed into constraint. From this table, the range r_2 of the objective function *F2* which is considered as constraint is determined as follows:

$$r_2 = f_2^{\max} - f_2^{\min} \tag{20}$$

Table 13. Investigated scenarios.

		Final product demand					
Scenarios	Products	T1	T2	T3	T4	T5	T6
1	P1	0	0	0	0	7500	8000
	P2	0	0	0	0	0	0
2	P1	0	0	0	0	3000	6500
	P2	0	0	0	0	1500	0
3	P1	0	0	0	0	3500	4000
	P2	0	0	0	0	1000	3000
4	P1	0	0	0	0	1700	5200
	P2	0	0	0	0	0	7900
5	P1	0	0	0	0	2700	6500
	P2	0	0	0	0	1200	3800
6	P1	0	0	0	0	2500	0
	P2	0	0	0	0	0	8900

Table 14. Pay-off table for each scenario.

Scenario		Pay-off table		Range: r_2
		F1	*F2*	
1	Min *F1*	115550.4	124442	12956
	Max *F2*	123956.4	137398	
2	Min *F1*	82336.03	86943.5	14229.5
	Max *F2*	102364.5	101173	
3	Min *F1*	90714.15	91680	16318
	Max *F2*	114039	107998	
4	Min *F1*	128698.2	120978	18835
	Max *F2*	148499.5	139813	
5	Min *F1*	115560.7	114885	16843
	Max *F2*	139486.8	131728	
6	Min *F1*	100487	93412.5	14317.5
	Max *F2*	123569	107730	

The ranges (r_2) obtained for different customer demand scenarios are presented in Table 14. Then, the obtained range of the objective function is divided into q equal intervals (10 intervals in our case). Then, ε_2 is calculated to these $q + 1$ grid points as follows:

$$\varepsilon_2^k = f_2^{\min} + k * \frac{r_2}{q}; \quad k = 0, 1, \ldots, q \tag{21}$$

By varying the values of ε_2, the different Pareto optimal solutions for each demand scenario are obtained as illustrated in Figure 3. As it is seen in Figure 3, every point of the front of Pareto curve represents a set of planning decisions and a specific SC plan. In addition, there is a significant conflict between the two objective functions. Indeed, when the product's quality level increases the total cost increases too.

In order to evaluate the performance of this method, the Pareto curves were generated through the AUGMECON method and the weighted sum method (WSM) for the different customer demand scenarios. The computational results are summarised in Table 15 and the obtained Pareto curves are drawn in Figure A1 (Appendix 1). As shown in Figure A1, the spread of solutions generated by the AUGMECON method is better than the one obtained using WSM. Moreover, Table 15 shows that the AUGMECON outperforms the WSM method since it generates more efficient Pareto solutions in less computational time for all scenarios except scenario #5. The reader can also refer to Felfel, Ayadi, and Masmoudi (2014) for a deep comparison between different multi-objective methods applied to the considered SC

Table 15. Computational results of AUGMECON and weighted sum method for the different scenarios.

Scenario	Method	CPU time (seconds)	No. of efficient Pareto solutions
S1	AUGMECON	2	11
	WSM	8	4
S2	AUGMECON	2	11
	WSM	11	5
S3	AUGMECON	5	11
	WSM	10	7
S4	AUGMECON	55	11
	WSM	39	10
S5	AUGMECON	163	11
	WSM	140	7
S6	AUGMECON	3	11
	WSM	11	8

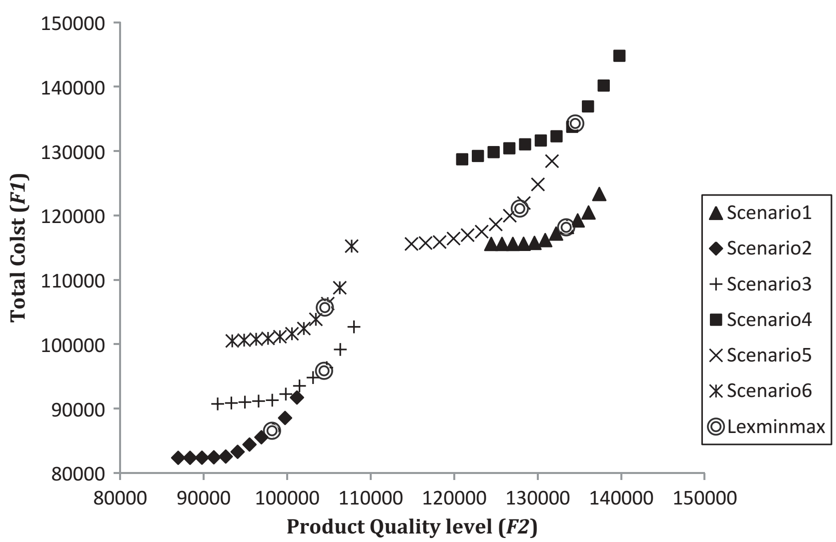

Figure 3. Pareto set curves and lexicographic minimax solutions.

planning problem. This paper shows the efficiency of AUGMECON method in generating optimal Pareto solutions compared to well-known methods.

6.3. Lexicographic minimax method

Now, a fair solution should be selected from the front of Pareto optimal solutions, where the normalised objective functions are as close to one another as possible. The multi-objective problem is so formulated as a lexicographic minimisation problem. Six scenarios were investigated with different final products' demands as described in Table 13. Table 16 reports the objective functions *F1* and *F2* using the lexicographic minimax method described in Section 5.3. The obtained objective functions in each scenario represent the equitable solution of the SC planning problem from the front of Pareto. Table 16 lists also the scaled objective functions calculated as detailed in Equations (20) and (21). It can be noticed from this table the equality of the scaled objective values as it proved in Theorem 2. The lexicographic minimax solutions belong to the efficient Pareto curves as shown in Figure 3. Hence, the obtained lexicographic minimax solutions are Pareto optimal with perfect equity which is consistent with Theorem 2.

In order to implement the proposed methodology in the context of the studied case, the planner of TE-INTER company, as a central partner, collects the information data through an IS (i.e. production, inventory and transport capacity as well as processing time from the different partners). Then, he solves the multi-objective planning problem and generates the front of Pareto optimal solutions as described in Section 6.2. Subsequently, the lexicographic minimax method is applied to select a fair solution from the front of Pareto as shown in Section 6.3. This solution involves a set of decisions related to production amounts in normal working hours and overtime, amounts of inventory of each finished or semi-finished product and amounts of each product to be transported between upstream and downstream plants. Corresponding values of decision variables are then distributed to their respective plants through the IS.

Table 16. Lexicographic minimax solutions for each scenario.

	Objective functions values		Scaled objective functions values	
Scenario	*F1*	*F2*	*F1*	*F2*
1	118127.7	133426	0.306	0.306
2	86538.54	98188.5	0.209	0.209
3	95840.99	104412	0.219	0.219
4	134274	134509	0.281	0.281
5	121054	127861	0.229	0.229
6	105680	104509	0.224	0.224

7. Conclusion

In this study, a collaborative decision-making approach for a multi-objective, multistage, multi-product and multi-period planning problem is proposed. The approach allows the decision maker to generate a front of Pareto optimal efficient solutions for the considered problem and equips him with a procedure to select a fair optimal solution that satisfies equitably the considered objectives. Two evaluation criteria, including total cost and products' quality level, are considered. To effectively solve this multi-objective optimisation problem, the AUGMECON method is applied in which total cost is the objective to be optimised and product's quality level is transformed into constraint. An efficient set of Pareto optimal solutions were obtained. Computational results show the efficiency of AUGMECON method in solving the considered problem by outperforming the well-known weighted sum method. In order to choose a fair solution from the generated front of Pareto, a formulation that transfers the lexicographic minimax problem to a lexicographic minimisation problem is proposed. Finally, a real case study from textile and apparel industry using several scenarios is presented for explaining the planning model and the solution approaches. In practice, the collaborated enterprises could either nominate one of the partners to make all the planning decisions such as the case of the studied network or engage an external neutral planner in order to ensure their total confidentiality.

In the textile and apparel industry, several uncertainties that are mainly related to demand, production capacities and unit costs exist. Thus, decisions based on deterministic assumptions neglecting these uncertainties may lead to non-optimal results. Therefore, the incorporation of uncertainties into the proposed decision-making approach represents an interesting future work that should yield more realistic results. This perspective can be addressed by adopting corresponding approaches such as stochastic programming approach.

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Appendix 1. Comparison between the results obtained by AUGMECON and weighted sum method

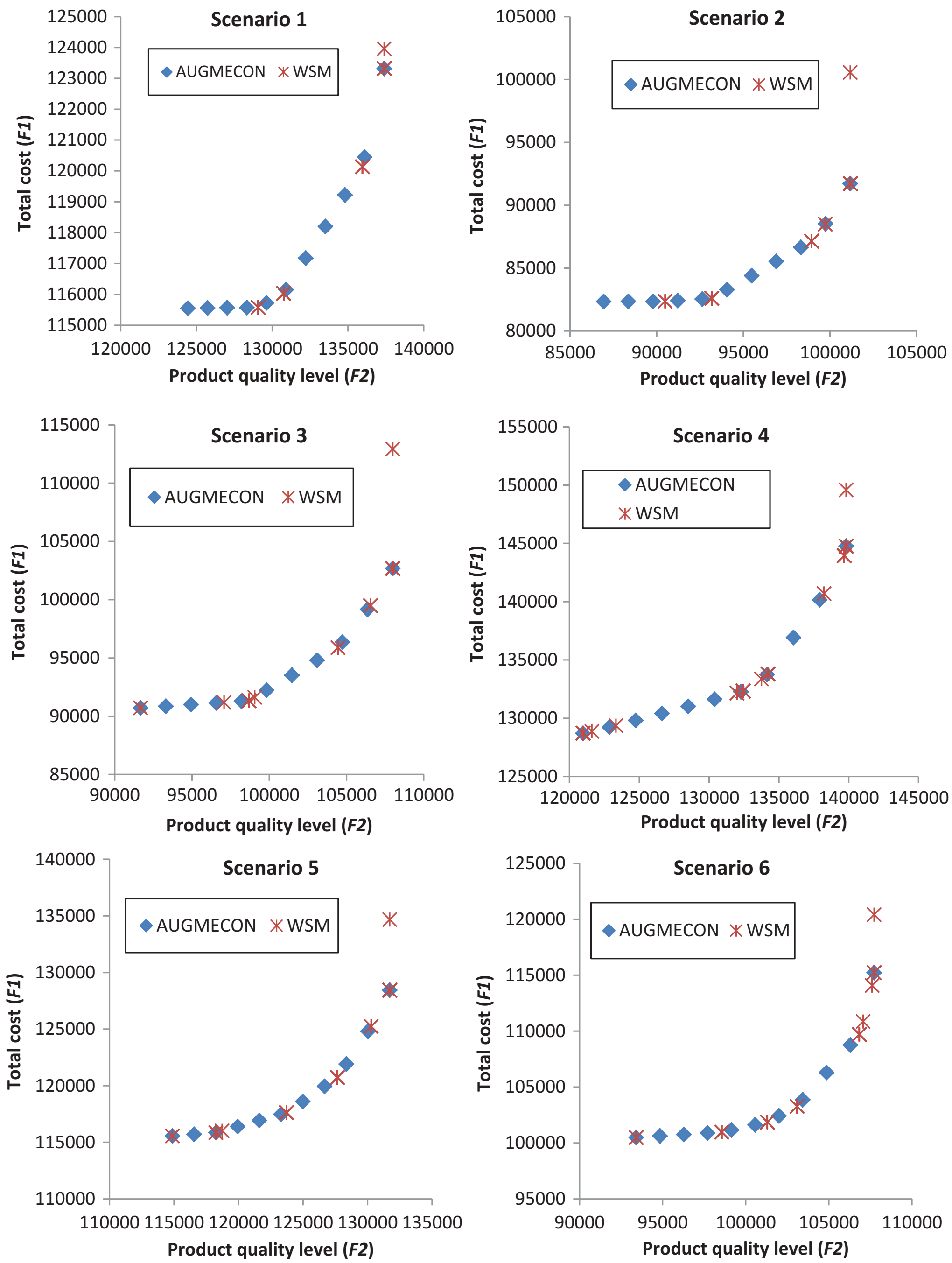

Figure A1. Pareto set curves generated by AUGMECON and weighted sum method (WSM) for the different scenarios.