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An integrated supplier selection and procurement planning model using product predesign and operational criteria

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Abstract The literature of supply chain management and concurrent engineering indicates that many benefits can be achieved if suppliers are involved in product design and development. This paper proposes a single product, multiple sourcing model for evaluating and ranking potential suppliers using a multi-criteria decision making tool, the analytic hierarchy process (AHP). In addition to the criteria related to the operational aspects of the production process, such as quality and price, AHP considers other criteria related to the early stage of product design, such as end customer requirements satisfaction, technical product specifications, and supplier flexibility. The integration between operational criteria and predesign criteria, gives the decision makers the opportunity to select the suppliers that have the potential to satisfy their future demand of raw materials, components, subassemblies or services effectively and efficiently, as well as the capability to satisfy the end customers' requirements by positively affecting the design of the finished products. The output from AHP is then used in a two-stage optimization model where a utility function that includes suppliers' relative weights is first maximized to select the best suppliers, then a cost function is minimized to determine the amounts of raw materials, components, subassemblies or services to be ordered from every selected supplier. An application to the lubricants industry is carried out where predesign criteria such as base oil dynamic viscosity and kinematic viscosity are taken into account in the supplier selection phase to show the effectiveness of the model.

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1 Introduction

Supply chain management can be defined as the process that includes the events related to the flow and transformation of goods and services from the point of origin to the point of usage [1]. It aims to plan, implement and control the supply chain network operations efficiently [2]. The main objectives of supply chain management are to reduce supply chain risks, reduce production costs, improve customer service, provide competitiveness, customer satisfaction and profitability [3]. One of the most important processes of supply chain management is supplier selection, which is a process through which buyers identify, evaluate, and contract with suppliers. It deploys significant amount of organizations financial resources and in return, organizations expect adequate benefits in the form of on-time delivery, minimum rejections, durability and reliability. Different types of criteria, including tangible and intangible factors [4], are usually considered while selecting suppliers. These criteria comprise traditional criteria such as price, quality and lead-time, in addition to other criteria such as the green performance of suppliers or their capability to satisfy the finished product design requirements. Therefore, supplier selection is a process to select the best suppliers that can submit the best deal on all required criteria among other suppliers.

Supplier selection and management can be applied to a variety of suppliers throughout a product life cycle from the product design phase, passing through the initial raw material acquisition, to the end-of-life service providers. Thus, the breadth and diversity of suppliers, and the involvement of many uncontrollable and unpredictable factors makes the process even more cumbersome [5]. More specifically, supplier selection is a mean to better satisfy the end customers by selecting the suppliers at an early stage of the product or service design based on criteria such as flexibility, satisfaction and risk [6]. Supplier selection may also be used to design product lines [7]. Organizations with complex decisions typically have numerous factors to consider and evaluate in the management of their suppliers and supply chains. Eventually managing these suppliers requires a careful balance when seeking to procure supplier's services or products.

Furthermore, due to globalization, organizations are forced to consider many factors in their strategic decision making. In this context, supplier selection is one of the most important decisions that has to be taken by the supply chain manager and one of the most essential aspects of supply chain management. It plays an important role in today's competitive market, in the success and overall performance of the supply chain for any organization.

Another aspect that makes supplier selection important to organizations is the continuously changing customer's demands and its diversification. The ever changing demand of customers leads to increase in overall cost. Therefore, for company's survivals and meeting customers' demands effectively and efficiently, supplier selection is a strategic decision to ensure adequate profit. Most of the companies are trying to reduce their operating costs while satisfying customer needs by increasing their core competencies and outsourcing other functions [8].

In this paper, we propose a methodology to select the best suppliers and to allocate the future orders using an integrated approach based on analytic hierarchy process (AHP) and two-stage mixed integer linear programming (MILP) model. First, the potential suppliers are ranked based on a set of criteria including product predesign and operational ones such as flexibility, end customer requirements satisfaction, product technical specifications, quality, and price. In the second step, the best suppliers are selected so that the preference is maximized and then, the optimal total amounts to be procured from every selected supplier are calculated. A case study on the selection of base oil for the redesign and manufacturing of a lubricant is carried out where operational criteria such as quality, price and on-time delivery are considered as well as predesign criteria such as base oil viscosity.

The remainder of this paper is further organized as follows: Sect. 2 provides a literature review and the paper contributions; Sect. 3 details the proposed integrated approach including AHP and the two-stage optimization models; Sect. 4 represents a case study with numerical applications. Finally, Sect. 5 concludes the paper.

2 Literature review

The first supplier selection models were introduced in the 1950s, where the first recorded model is the one that was proposed by the National Bureau of Standards in the United States of America with the objective of achieving the lowest costs for purchasing contracts at the American Department of Defense [9]. However, most researchers believe that the starting point for the supplier selection problem was in the middle of the 1960s [9]. Allahyari et al. [10] divide supplier selection problems into two categories: *single sourcing problem* in which all suppliers are able to satisfy the buyer's requirements on quantity, quality, delivery, etc. The only decision that should be taken by the buyer is to choose the best supplier from which all the requirements will be satisfied; *multiple sourcing problem* in which some limitations, such as supplier's capacity, quality and delivery are considered. In other words, no supplier can satisfy the buyer's total requirements and the buyer needs to distribute his needs among different suppliers to compensate for the shortage of capacity or low quality of suppliers. Under these circumstances, the buyer needs to choose the best suppliers from which the requirements will be fulfilled and distribute the total requirements among the selected suppliers.

In the next sections, the literature related to this paper is reviewed and divided into four categories: supplier selection with multi-criteria decision making (MCDM), supplier selection with integrated AHP and optimization techniques, supplier selection with production planning and inventory management and finally integrated AHP and design.

2.1 Supplier selection as a multi-criteria decision making (MCDM) problem

Many researchers and practitioners consider supplier selection as a MCDM problem, which includes both qualitative and quantitative factors. In order to select the best suppliers it is necessary to make a trade-off between these tangible and intangible factors where some of them may conflict with each other. Among the MCDM methods that are used for selecting suppliers one may cite the technique for order of preference by similarity to ideal solution, fuzzy logic, and more specifically AHP. For instance, Rodriguez et al. [11], considered the supplier selection for customized equipment supplier's problem as a MCDM problem. The authors discussed about the possible and adequate MCDM tools. Similarly, Parthiban et al. [12] dealt with the factors affecting the supplier selection and the interaction between each factor that have an effect on overall supplier selection.

A particular MCDM tool, namely the AHP, was widely used in supplier selection problems. This method balances the interactions among decision criteria and synthesizes the information into vector of preference among the alternatives. The AHP is a theory of measurement through pairwise comparisons and relies on the judgment of experts to derive priority scales. These scales are used then to measure intangibles in relative terms. The comparisons are made using a scale of absolute judgments that represent, how much more, one element dominates another with respect to a given attribute [13]. AHP is one of the most widely used MCDM tools [14]. Many outstanding works have been published based on AHP. They include applications of AHP in different fields, such as planning, resource allocations, resolving conflict, etc., as well as numerical extensions of AHP [15].

Akarte et al. [16] developed a web-based AHP system to evaluate the casting suppliers with respect to 18 criteria. In the system, suppliers have to register, and then input their casting specifications. To evaluate the suppliers, buyers have to determine the relative importance weightings for the criteria based on the casting specifications, and then assign the performance rating for each criterion using a pairwise comparison. Moreover, Muralidharan et al. [17] proposed a five-step AHP-based model to aid decision makers in rating and selecting suppliers with respect to nine evaluating criteria. People from different functions of the organizations, such as purchasing, stores, and quality control, are involved in the selection process. Furthermore, Chan [18] developed an interactive selection model with AHP to facilitate the decision making process for the selection of suppliers. The model was so-called because it incorporated a method called chain of interaction, which was deployed to determine the relative importance of evaluating criteria without subjective human judgment. AHP was only applied to generate the overall score for alternative suppliers based on the relative importance. Similar to Chan [18], Liu and Hai [19] applied AHP to evaluate and select suppliers. The authors did not apply the AHP's pairwise comparison to determine the relative importance ratings among the criteria and sub-factors. Instead, the authors used Noguchi's voting and ranking method, which allowed every manager to vote or to determine the order of criteria instead of the weights.

In addition, Chan et al. [20] developed an AHP-based decision making approach to solve the supplier selection problem. Potential suppliers were evaluated based on 14 criteria. A sensitivity analysis using Expert Choice was performed to examine the response of alternatives when the relative importance rating of each criterion was changed.

2.2 Supplier selection with integrated AHP and optimization techniques

Several optimization techniques have been applied to supplier selection such as dynamic programming [21], linear programming [22], and multi-objective optimization [23]. Kokangul and Susuz [24] developed a combined approach including AHP, non-linear integer programming and multi-objective optimization for a supplier selection problem. Both quantitative and qualitative data were taken into account via the developed approach. Ghodsypour and O'Brien [22] integrated AHP with linear programming in supplier selection. They used AHP to determine the relative importance weightings of the suppliers with respect to three major criteria, which are: cost, quality, and service. They incorporated then these weights into the objective function of a linear programming model. Similarly, Saaty et al. [25] integrated AHP with linear programming for a resource allocation problem. AHP was used to obtain the relative importance of major criteria such as markets, innovations and cost reduction. The obtained weightings were then used as the weighting factors in the objective function of the linear programming model, with the objective of maximizing the benefits of the merged organizations.

Many other authors integrated AHP with different mathematical programming techniques for applications in project selection [26], facility location selection [27], scheduling plan selection [28], maintenance strategy selection [5].

2.3 Supplier selection with production planning and inventory management

The literature on combined supplier selection, order allocation with inventory management is limited. For example, Razmi and Maghool [29] developed fuzzy bi-objective mixed integer multi-item, multi-period supplier selection and order sizing model under dynamic demand, which is not deterministic and varies in each period, capacity and budget limitation. The first objective function is to minimize total purchasing cost while the second is to maximize total value of purchasing taking into account the impact of qualitative performance criteria in purchasing decision. Rezaei and Davoodi [30] proposed multi-item, multi period mathematical model to solve supplier selection problem assuming that the received item is not necessary of a perfect quality; imperfect quality item is sold as single batch at discounted price. The proposed model maximizes total profit that is revenue from selling good quality items and revenue of selling imperfect quality items minus total cost which consists of supplier dependent transaction cost, product dependent holding cost, screening cost and purchasing cost. Che [31] proposed a mathematical model to solve single product, multi-period supplier selection and assembly sequence problem. They assumed that parts assembly is in series mode that starts only after all parts are delivered. The model considers single objective function that minimizes cost and time while maximizing quality and reliability. The four criteria are combined in a single objective function by considering an equal weight for each criterion. Ware et al. [32] developed a mixed integer non-linear program that minimizes total cost of purchasing in order to solve dynamic supplier selection problem. The developed model considers multi-product, multi-period situation in which purchasing cost, total transportation cost, penalty cost for not meeting quality requirements and delay cost are considered in the objective function. Li et al. [33] proposed two stages mathematical model to deal with material supplier selection and order allocation problem over a planning horizon in short product life cycle environment. They applied fuzzy extended analytical hierarchy process to generate risk weights for different suppliers among five criteria which are: cost, quality, risk, profile and service performance. Then, in the second stage, bi-objective mathematical model is developed to minimize risk and cost. Viswanadham and Gaonkar [34] developed MILP model that maximizes profit for vendor selection and scheduling problem in a web-enabled dynamic manufacturing environment. The model not only solves supplier selection problem but also provides supply chain configuration for every customer order and schedule for manufacturing, assembly, in-bound transportation and out-bound transportation. Mafakheri et al. [35] proposed a two-stage bi-objective multiple criteria dynamic programming model for supplier selection and order allocation. The problem objectives are to maximize utility function and minimize total purchasing cost (purchasing cost and Inventory holding cost) which later are combined into one objective function and solved using dynamic programming algorithm. Moreover, Parhizkari et al. [36] proposed a MCDM technique for supplier selection and inventory management strategy in which they considered a case of multi-product and multi-supplier problem. The proposed model is formulated as a mixed integer programming problem and it is converted into an ordinary single objective function using Lp-Norm. Finally, Sharma and Dubey [37] solved the problem of supplier selection and order allocation using an integrated AHP and Knapsack model approach.

2.4 Multi-criteria decision making and design

Many works were published on the integration of decision support systems including MCDM with design [38].

For instance, many authors used AHP in a design context in many fields such as manufacturing, assembly, and ergonomics. For instance, Koganti et al. [39] used AHP in a design for assembly context of an automotive component. They validated their design with a case study involving car front-end component. Similarly, Ong et al. [40] and Liu et al. [41] used AHP in a design for manufacturing environment in order to evaluate a system based on manufacturability index. Moreover, Laemlaksakul and Bangsarantrip [42], used AHP in ergonomics to design bamboo chair based on different criteria.

Hambali et al. [43] used the AHP method to select the best design of wheelchair from eight design alternatives. The selection was performed by using AHP without integration with any other design tool. Similarly, Hambali et al. [44] proposed a concept selection model called concurrent design concept selection and material selection at the conceptual design stage using AHP. Finally, Ariffi et al. [45] presents the methodology of selecting design concepts using AHP. The results of a case study illustrates that AHP concept can assist designers to effectively evaluate various conceptual design alternatives at the conceptual design stage.

Moreover, fuzzy AHP has been compared with Pugh's controlled convergence in order to select alternatives in conceptual design phase in products development [46]. MCDM tools have been used also in other aspects of the design such as to select the most suitable CAD/CAM packages to help manufacturing firms [47]. In another context, Le Dain et al. [48] proposed a multi-objective framework to evaluate customer's performance in collaborative product development where suppliers were integrated in the process. On the other hand, customers' preferences were taken into account through decision support systems to choose the most suitable products to satisfy their requirements in terms of quality, price, availability and customer service while measuring the relative difference between the different characteristics [49].

2.5 Contribution

After comparing the proposed approach in this paper with the literature, the main contributions of this paper are a combination of different aspects that may be summarized as follows:

- To the best of our knowledge, this study is the first that allows the decision makers to include, in comparing potential suppliers, criteria related to product or service predesign phase. This flexibility allows the decision makers to guarantee in an early stage of the product life cycle, that the selection of future suppliers takes into consideration criteria related to predesign such as end customer requirements satisfaction, which makes the future product design, manufacturing and production phases smoother.
- The two-stage optimization model proposed in this paper is different from those encountered in the literature:
  - A first optimization model maximizes a utility function constituted of suppliers' preferences taken from AHP, which leads to identify the selected suppliers and the total amounts to be purchased from every supplier over a mid-term planning horizon.
  - An inventory management model determines the optimal quantities to be purchased from every supplier in each period of the planning horizon taking into account the selected suppliers and their total quantities decided in the previous model.

– In the inventory management model, shortages are allowed and a penalty shortage cost is charged, which also differs from the similar models in the literature.
– An application on the selection of base oil supplier for the redesign of a lubricant taking into consideration suppliers' performance in terms of operational criteria and some predesign criteria.

Furthermore, interactive design is an approach that fosters innovation by improving user-integration in the design process and providing new powerful ways for collaborative design initiatives [50]. The present paper differs from the previous efforts in supplier selection and order allocation, in the fact that it offers user interactivity regarding design choices through two factors:

– The users of the products (for instance the main customers of the organization) can be involved in the design through the participation of the definition of the predesign characteristics (or design targets) of the product to be manufactured. Through these design characteristics, these main customers affect the choice of the suppliers of the product components and raw materials.
– The major users (the main customers of the organization) may participate in the decision making process and play the role of decision makers contributing in the suppliers evaluation process using AHP. These users can evaluate the suppliers based on all the criteria including the predesign criteria through the pair-wise comparison of AHP.

Therefore, compared with the traditional supplier selection and order allocation literature, this paper proposes a methodology that allows the decision makers, including main customers, to select suppliers based on design criteria which are determined by the users in an interactive design context.

3 Model

3.1 Analytical hierarchy process (AHP)

The objective of this section is to show how AHP calculates a relative weight for each supplier "i", w_i, based on two sets of criteria including operational and predesign ones. To calculate the relative weights, different importance can be given by experts to operational and to predesign criteria based on the organization's objectives. AHP is a common MCDM method that was developed by Saaty [51] to assist in solving complex decision problems by capturing both subjective and objective evaluation measures. It breaks a complex problem into hierarchy or levels as shown in Fig. 1.

AHP uses a pairwise comparison of the criteria importance with respect to the goal. This pairwise comparison allows

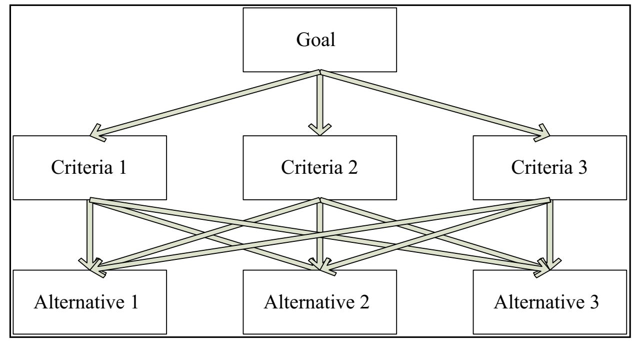

Fig. 1 AHP structure of goal criteria and alternatives

Table 1 Importance scale of factors in pairwise comparison

Importance scale, "a_{ij}"	Importance description
1	Equal importance of "i" and "j"
3	Week importance of "i" over "j"
5	Strong importance of "i" over "j"
7	Demonstrated importance of "i" over "j"
9	Absolute importance of "i" over "j"

2, 4, 6 and 8 are intermediate values

finding the relative weight of the criteria with respect to the main goal. If quantitative data is available, the comparisons can be easily performed based on a defined scale or ratio and this causes the inconsistency of the judgment to be close to zero, which leads to perfect judgment.

If quantitative data is not available, a qualitative judgment can be used for the pairwise comparison. This qualitative pairwise comparison for two criteria "i" and "j" for example follows the importance scale suggested by Saaty [51] in order to give a relative importance "a_{ij}" of criterion "i" compared to criterion "j" with respect to the goal, as shown in Table 1. The values of "a_{ij}" are usually determined by experts.

The same process of pairwise comparison is used to find the relative importance of the alternatives with respect to each of the criteria. For example, each child has a local (immediate) and global priority (weight) with respect to the parent. The sum of priorities for all the children of the parents must equal one. The global priority shows the alternatives relative importance with respect to the main goal of the model. The pairwise comparison is performed in matrix format to check the consistency of the judgment.

The size of the comparison matrix A is $n \times n$ where n is the number of children (criteria or alternatives) being compared with relative to a specific parent (goal or criterion). The elements of the matrix A are a_{ij}. The matrix A is considered to be consistent if all of its elements are transitive and reciprocative so that

$$a_{ij} = a_{ik} \times a_{kj}, \tag{1}$$

and

$$a_{ij} = \frac{1}{a_{ji}}, \quad (2)$$

with i, j and k = $1, \ldots, n$. It is worth noting that in the matrix A, $a_{ij} = 1$ when $i = j$.

To determine the relative weight of alternative "i", w_i, a normalized matrix N is first computed from A by dividing every column of A by the sum of the elements of that column. The elements of the matrix N are noted "w_{ij}". Therefore, one has

$$w_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}. \quad (3)$$

The relative weight w_i of alternative "i" is then calculated as the average of the elements of row "i" of N:

$$w_i = \frac{\sum_{j=1}^{n} w_{ij}}{n} \quad (4)$$

where

$$\sum_{i=1}^{n} w_i = 1. \quad (5)$$

Notice that A is considered to be consistent if $A \cdot W = n \times W$, where W is the vector whose elements are $w_i, i = 1, \ldots, n$.

In the case where A is not consistent, the consistency ratio (CR) is calculated as follows

$$CR = \frac{CI}{RI} \quad (6)$$

where CI is the consistency index of A and RI is the random consistency of A with

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (7)$$

$$RI = \frac{1.98(n - 2)}{n} \quad (8)$$

where λ_{max} is obtained so that $A \cdot W = \lambda_{max} \times W$, with $\lambda_{max} \geq n$. The closer λ_{max} to n, the more consistent is A. If $CR \leq 0.1$, the level of inconsistency is considered as acceptable. Otherwise, the decision maker needs to revise the judgment on the values of a_{ij}.

3.2 Two stage optimization model

In this section, we use the suppliers' weights obtained from AHP, w_i, as utility scores to develop a two-stage optimization model. The first stage objective is to select the suppliers with which the company contracts over a mid-term planning horizon, usually of a duration of one year, as well as the total amounts that will be ordered from every selected supplier, so that the total utility function is maximized. An emphasis is put on the difference between operational criteria and predesign criteria and the impact of their relative importance on the selected suppliers. In this first stage, in order to account for the purchasing cost, a constraint is added to guarantee that the ordering cost of the quantities ordered from the selected suppliers does not exceed the purchasing budget. The selected suppliers in the first stage will be used in the second stage in which the objective will be to decide about the amounts to be ordered from these suppliers, in every period of the planning horizon, usually every month, so that the total operating cost is minimized.

3.2.1 First stage: mid-term utility function maximization

In this section, the objective is to select the panel of suppliers with which the company commits to work over a mid-term planning horizon. In this first stage, the planning horizon is assumed to be aggregated into a single period. In the second stage, the planning horizon is disaggregated into shorter planning periods.

Parameters

n	total number of potential suppliers from which the product or service can be purchased,
w_i	relative weight of supplier i obtained from AHP, $i = 1, \ldots, n$,
D	total demand to satisfy over the whole planning horizon for the product under consideration,
c_i	average variable unit purchasing cost from supplier i for the planning horizon, $i = 1, \ldots, n$,
F_i	average total fixed cost for contracting with supplier i for the whole planning horizon, i, $i = 1, \ldots, n$,
B	total purchasing budget for the product under consideration,
K_i	total production capacity of supplier i for the whole planning horizon i, $i = 1, \ldots, n$,
Q_i^{min}	minimum amount that can be purchased from supplier i, $i = 1, \ldots, n$, if selected,
n_{min}	minimum number of suppliers the company wants to contract with.

Decision variables

y_i	binary decision variable that is equal to 1 if supplier i is selected and 0 otherwise, $i = 1, \ldots, n$,
Q_i^G	total amount to be purchased from supplier i over the whole planning horizon, $i = 1, \ldots, n$.

First stage mixed integer linear program
The total utility function is maximized subject to constraints on suppliers' capacity, minimum number of suppliers predetermined by the company, demand, and total purchasing budget.

$$Max\ W = \sum_{i=1}^{n} w_i Q_i^G. \tag{9}$$

Subject to

$$0 \leq Q_i^G \leq K_i y_i, \quad i = 1, \ldots, n \tag{10}$$

$$\sum_{i=1}^{n} y_i \geq n_{min}, \tag{11}$$

$$\sum_{i=1}^{n} Q_i^G = D, \tag{12}$$

$$\sum_{i=1}^{n} (c_i Q_i^G + F_i y_i) \leq B, \quad i = 1, \ldots, n \tag{13}$$

$$Q_i^{min} y_i \leq Q_i^G, \quad l = 1, \ldots, n, \tag{14}$$

$$y_i \in \{0, 1\}, \quad Q_i^G \geq 0, \quad i = 1, \ldots, n. \tag{15}$$

Equation (9) represents the total utility function to maximize where the relative weight of every supplier, w_i, is multiplied by the amount that will be ordered from that supplier, Q_i^G. Constraint (10) represents the suppliers' capacity constraint. It also links the binary decision variables of the suppliers' selection with the continuous decision variables representing the amounts purchased from these same suppliers in order to guarantee that the ordered amounts from the non-selected suppliers are equal to zero. Constraint (11) forces the system to select a minimum number of suppliers predetermined by the company. This minimum number of suppliers maybe part of the company's strategy of not relying on one supplier only. If this is not the case, the model can be simply adapted by setting n_{min} equal to one. Constraint (12) ensures that the ordered quantity from all the selected suppliers is equal to the total demand, which ensures that over the planning horizon all the demand is satisfied. Constraint (13) ensures that the total fixed and variable purchasing cost from all suppliers is within the available budget. Constraint (14) ensures that the total ordered quantities from selected suppliers are greater than the minimum order quantities acceptable by these suppliers. Constraint (15) reflects the binary nature of the suppliers' selection decisions and ensures that the ordered amounts are either positive or equal to zero.

It is worth noting that the above model is an MILP. Since this model is a single product one, and because of the limited number of possible suppliers for a single product in real life applications, therefore this model can be solved using a commercial solver. The solution of this model is used as input for the second stage model.

3.2.2 Second stage: mid-term purchasing and inventory related cost minimization

The second stage problem is a multi-periodic planning problem whose objective is to optimize the operational ordering and inventory management decisions while taking into account the suppliers already selected as well as the total optimal quantities obtained in the first stage. The time horizon of the first stage, which is usually equal to one or many years, is divided into shorter time periods, usually months. The objective of the second stage is to minimize the total purchasing, inventory holding and shortage cost of every period of the planning horizon subject to constraints on suppliers capacity relative to every time period, storage capacity, and demand.

Parameters

- T total number of periods in the planning horizon,
- N_{Sel} number of suppliers selected in the first stage, $n_{min} \leq N_{Sel} \leq n$,
- D_t total demand to satisfy in period $t, t = 1, \ldots, T$,
- c_t^l unit purchasing price from supplier l in period $t, t = 1, \ldots, T, l = 1, \ldots, N_{Sel}$,
- h_t unit inventory holding cost in period $t, t = 1, \ldots, T$,
- b_t unit shortage cost in period $t, t = 1, \ldots, T$,
- F_t^l fixed cost of placing an order from supplier l in period $t, t = 1, \ldots, T, l = 1, \ldots, N_{Sel}$,
- K_t^l production capacity of supplier l in period $t, t = 1, \ldots, T, l = 1, \ldots, N_{Sel}$,
- I_t^M storage capacity in period $t, t = 1, \ldots, T$,
- Q_l^{G*} total optimal quantity to be ordered from supplier l over the whole planning horizon, obtained from the first stage, $l = 1, \ldots, N_{Sel}$,
- I_0 initial inventory level at the beginning of the first period of the planning horizon.

Decision variables

- y_t^l binary decision variable that is equal to 1 if an order is placed from supplier l in period t and 0 otherwise, $t = 1, \ldots, T, l = 1, \ldots, N_{Sel}$,
- Q_t^l quantity ordered from supplier l in period $t, t = 1, \ldots, T, l = 1, \ldots, N_{Sel}$.

State variables

- I_t available inventory level at the end of period $t, t = 1, \ldots, T$.

Second stage mixed integer linear program
The total purchasing and inventory management cost is minimized subject to constraints on suppliers' capacity, storage capacity and demand.

$$Min\ Z = \sum_{t=1}^{T}\sum_{l=1}^{N_{Sel}} c_t^l Q_t^l + 1\sum_{t=1}^{T}\sum_{l=1}^{N_{Sel}} F_t^l y_t^l + \sum_{t=1}^{T} h_t I_t^+ + \sum_{t=1}^{T} b_t I_t^- . \quad (16)$$

Subject to

$$0 \le Q_t^l \le K_t^l y_t^l, \quad t = 1, \ldots, T,\ l = 1, \ldots, N_{Sel}, \quad (17)$$

$$\sum_{t=1}^{T} Q_t^l = Q_l^{G*}, \quad l = 1, \ldots, N_{Sel}, \quad (18)$$

$$\sum_{l=1}^{N_{Sel}} Q_t^l + I_{t-1} - D_t = I_t, \quad t = 1, \ldots, T, \quad (19)$$

$$I_t \le I_t^M, \quad t = 1, \ldots, T, \quad (20)$$

$$y_t^l \in \{0, 1\},\ Q_t^l \ge 0, \quad t = 1, \ldots, T, l = 1, \ldots, N_{Sel} \quad (21)$$

where $I^+ = Max\ (I, 0)$ and $I^- = Max\ (-I, 0)$.

Equation (16) represents the total cost to minimize including the variable and fixed purchasing cost, inventory holding cost and shortage cost. Constraint (17) is the suppliers' capacity constraint for period t. It also links the binary decision variables of ordering from a supplier in a given period with the continuous decision variable representing the amount purchased from the same supplier in the same period. Constraint (18) ensures that the total quantity ordered from a supplier over the whole planning horizon is equal to the total optimal amount that should be ordered from the same supplier as obtained in the first optimization stage. Constraint (19) describes the dynamic aspect of the inventory level. Constraint (20) translates the limited storage capacity. Constraint (21) ensures that the ordering decision variables are of binary nature and that the ordered amounts from every supplier in each period are either positive or equal to zero.

The second stage cost optimization model is also an MILP and it can also be solved using a commercial solver.

4 Case study

4.1 Background

Our model will be applied to select suppliers and allocate orders for one of the ingredients of an XYZ Lubricants Company's finished product, which is being redesigned and will be commercialized in an Asian country. XYZ Lubricants Company is a multi-national lubricants company, recognized for its products performance and innovation, advanced technology and services. XYZ Lubricants Company conducts its business in that Asian country through a corporate office located in a major city and regional offices located in different cities of the country. XYZ Lubricants Company products have an extensive sales network throughout the country supplying lubricants to a wide range of automotive and industrial users. They have direct and indirect sales presence throughout the country. XYZ automotive lubricants range includes passenger vehicle oils, commercial vehicle oils, transmission oils, brake fluids and greases. For industrial applications, XYZ Lubricants have a broad product range including gas engine oils, heavy duty diesel engine oils, turbine oils, compressor oils, industrial gear oils and hydraulic oils.

The finished product being studied is a liquid lubricant made of base oil, SN 500, purchased from suppliers, blended with different types of additives in order to obtain a variety of levels of performance [52]. Blended products are usually a formulation of various chemicals in the liquid state blended together in order to obtain a set of characteristics. For example, a lubricant blend may be made of a specific base oil as a main ingredient and a set of additives. The base oil gives to the lubricant its main performance and the additives improve it [53]. At least two main phases exist in the design process of lubricants: first, the product needs are identified, translated into target properties with bounds for each target property. Secondly, using an algorithm a mixture/blend design is obtained so that design targets are achieved [53]. From this design, an acceptable range for each characteristic of the ingredients can be determined so that the design targets are met. In this work, we consider two characteristics of the base oil used in the production of XYZ Lubricants product as design criteria for the selection of base oil suppliers. In addition, other operational criteria will be considered.

4.2 Numerical data

XYZ Lubricants Company has five potential suppliers ($n = 5$) from which the base oil can be purchased. The demand forecast, the unit inventory holding cost and unit shortage cost for the next four quarters are given in Table 2.

The total demand to be satisfied during the planning horizon is equal to the sum of the quarter demands given in Table 2, which is equal to a total of D = 4040.89 barrels.

The unit variable purchasing cost for every potential supplier over the next four quarters is given by: $c_t^1 = 124.023$ USD/barrel, $c_t^2 = 124.852$ USD/barrel, $c_t^3 = 123.66$ USD/barrel, $c_t^4 = 125.207$ USD/barrel, and $c_t^5 = 125.443$

Table 2 Demand forecast and inventory management economic data

Quarter t	1	2	3	4
D_t (barrel)	880.71	1140.55	1443.05	576.58
h_t (USD/barrel/quarter)	0.27	0.27	0.27	0.27
b_t (USD/barrel/quarter)	25	25	25	25

USD/barrel for $t = 1, \ldots, 4$. Therefore, the average variable purchasing cost c_i, for $i = 1, \ldots, 5$, can be easily obtained as the average over all periods of the variable unit purchasing cost for every supplier. The fixed ordering cost per order is assumed to be the same for all suppliers and for all periods and is equal to $F_t^l = 46.8$ USD/order for $t = 1, \ldots, 4$ and $l = 1, \ldots, N_{Sel}$. The average total fixed cost for contracting with supplier i is assumed to be the same for all suppliers and is equal to four times the fixed ordering cost per order, which leads to $F_i = 187.2$ USD, for $i = 1, \ldots, 5$. The supplier capacity per quarter is also assumed to be the same for all suppliers and for all quarters $K_t^l = 800$ barrel/quarter for $t = 1, \ldots, 4$ and $l = 1, \ldots, N_{Sel}$. The total capacity for the planning horizon for all suppliers is considered to be equal and it is equal to the sum of the quarters capacities which gives $K_i = 3200$ barrel for $i = 1, \ldots, 5$. The maximum storage capacity is equal to $I_t^M = 1000$ barrels, for $t = 1, \ldots, 4$. The company has a policy that requires a minimum number of suppliers equal to $n_{min} = 2$. The minimum total order quantities for every supplier, if selected, are given by: $Q_1^{min} = 1000$, $Q_2^{min} = 500$, $Q_3^{min} = 500$, $Q_4^{min} = 700$, and $Q_5^{min} = 300$ barrels. The total inventory management available budget is $B = 550{,}000$ USD for the next four quarters. The initial inventory level is assumed to be $I_o = 0$ barrel.

4.3 Ranking of suppliers using AHP

In the this section the AHP process will be implemented as it was explained in Sect. 3.1 in order to determine the relative weights of suppliers, w_i, for $i = 1, \ldots, 5$. This process is constituted of three steps. In the first step, the criteria based on which suppliers will be ranked, are identified. The second step is to identify the experts who will perform the pairwise comparison of the suppliers. The last step is to calculate the relative weights.

4.3.1 Criteria identification

After having discussed with the experts of XYZ Lubricants and used the most common criteria encountered in the related literature, we identified two groups of criteria for the selection of base oil suppliers: operational criteria and predesign related criteria.

The operational criteria group includes five different criteria: on-time delivery, geographical location, product quality, quality of service, and product price. The predesign related criteria group includes two criteria: dynamic viscosity and kinematic viscosity.

4.3.2 Experts' identification

In order to perform suppliers' pairwise comparison as explained in Sect. 3.1, a group of experts was selected which includes the supply chain manager, the quality manager, the finance manager, the warehouse supervisor, the product development manager and the marketing manager. The reason to select members from each department is to make sure that the experts' judgment is consistent and to include opinions from both the operational departments and the departments related to the development of the product.

4.3.3 Relative weights calculation

In order to rank the criteria, we performed pairwise comparison for each of the identified criteria with respect to the goal of selecting the best supplier(s), and each supplier with respect to each of the criteria. We used then the software Expert Choice™ which calculates the relative weights based on the equations explained in Sect. 3.1. Two scenarios were tested. In the first scenario, the predesign related criteria were not included in the comparison, whereas in the second scenario, they were included. Table 3 summarizes the criteria as well as their relative weights with respect to the goal of selecting suppliers. Table 4 summarizes the supplier's relative weights, $w_i, i = 1, \ldots, 5$, with respect to the goal.

The consistency ratio for Scenario 1 and Scenario 2 was equal to 0.07 and 0.08 respectively, which means that the expert judgments are consistent.

It is worth noting that in the first scenario the most important criterion with respect to the experts is the quality of service of the supplier, whereas in the second scenario the most important criterion is the dynamic viscosity. In general, the design criteria were given higher importance by the experts in the second scenario. On the other hand, the best supplier to contract with in both scenarios is the first supplier. However, the second rank goes to Supplier 4 in the first scenario and to Supplier 5 in the second scenario.

Table 3 Criteria relative weights with respect to the goal

	On-time delivery (%)	Geographical location (%)	Product quality (%)	Quality of service (%)	Product price (%)	Dynamic viscosity (%)	Kinematic viscosity (%)
Scenario 1	27.2	8.2	15.8	40.7	8.1	–	–
Scenario 2	8.4	3.7	5.5	11.4	3.2	34.6	33.1

Table 4 Suppliers' relative weights, w_i, with respect to the goal

Supplier i	$i = 1$ (%)	$i = 2$ (%)	$i = 3$ (%)	$i = 4$ (%)	$i = 5$ (%)
Scenario 1 (w_i)	29.1	11.8	22.1	27	10
Scenario 2 (w_i)	28.6	9.1	20.5	16.6	25.2

Table 5 Optimal solution of the first stage MILP

	Supplier i	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$
Scenario 1	Q_i^G	3200.000	0	0	840.8900	0
	y_i	1	0	0	1	0
Scenario 2	Q_i^G	3200.000	0	0	0	840.8900
	y_i	1	0	0	0	1

The suppliers' relative weights are used as inputs to solve the MILP problem defined in Sect. 3.2.1.

4.4 Solution of the first stage optimization model: utility function maximization

The model defined in Sect. 3.2.1 was implemented using the numerical data mentioned in Sect. 4.2 and the relative weights obtained in Sect. 4.3. The MILP was solved using the optimization software Lingo 11.0 on a Microsoft Windows 7 Enterprise (32 bit) platform and a computer equipped with Intel(R) Core (TM) i5-2410M CPU and 4.00 GB RAM. The results are summarized in Table 5 for both scenarios.

The objective function value in the first scenario is equal to 115,824 and in the second scenario to 112,710.4. The results are logical. In both scenarios, Supplier 1 is the preferred one in terms of relative weight. However, because of the capacity limitation, Supplier 1 cannot satisfy all the required demand. Therefore, in the first scenario, the second preferred supplier is used, namely Supplier 4 and the same occurs in the second scenario with Supplier 5. The results provided in Table 5 become constraints in the second stage MILP as detailed in Sect. 3.2.2. This MILP was also implemented and solved using the same platform as for the previous MILP. The results are given in Table 6.

The total optimal cost of the first scenario is equal to 508,072 USD, and for the second scenario is equal to 508,270.5 USD. Even if the followed policies are the same, the difference in cost comes from the difference in the unit purchasing cost between Supplier 4 and Supplier 5.

Table 6 Optimal solution of the second stage MILP

Period t	$t = 1$	$t = 2$	$t = 3$	$t = 4$
Scenario 1				
Supplier 1				
Q_t^1	800	800	800	800
y_t^1	1	1	1	1
Supplier 4				
Q_t^4	80.71	340.55	419.63	0.00
y_t^4	1	1	1	0
Inventory level				
I_t	0	0	−223.42	0
Scenario 2				
Supplier 1				
Q_t^1	800	800	800	800
y_t^1	1	1	1	1
Supplier 5				
Q_t^5	80.71	340.55	419.63	0.00
y_t^5	1	1	1	0
Inventory level				
I_t	0	0	−223.42	0

5 Conclusion

In this paper, we introduced an integrated approach to help decision makers in to select the best suppliers for their organization based on two different aspects of the business: a MCDM aspect and a cost based aspect. Experts can rank the potential suppliers based on different criteria, including operational criteria, such as quality and on-time delivery, and design related criteria, such as end customer requirements satisfaction or product technical specifications. An MILP model chooses the suppliers and the amounts of products to be purchased from each selected supplier, over a planning horizon, so that a total preference function, based on the expert's ranking, is maximized. In order to minimize the total operating cost, related to the purchasing process, a second MILP chooses the amounts to be purchased in every planning period of the planning horizon from the selected suppliers. An application on the selection of the suppliers of base oil for the redesign of a lubricant manufactured by a major oil company was used to show the applicability and effectiveness of the proposed approach. Five operational criteria, tow design related criteria, five potential suppliers and four quarters planning horizon were considered. The results show that the fact that considering predesign criteria may change the ranks of the suppliers and consequently the set of selected suppliers to be used in the procurement process, as well as the total cost related. One of the limitations of this work is the fact that only AHP was used among all the MCDM tools. Another limitation is the assumption that future demand is deterministic. Therefore, the consideration and the comparison of other MCDM tools as well as stochastic demand may constitute future research avenue.

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