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RELIABILITY PAPER

Supplier selection considering product structure and product life cycle cost

Vahid Ebrahimipour
University of McGill, Montreal, Canada
Babak Maleki Shoja
Department of Industrial Engineering, University of Tehran, Hamadan, Iran, and
Shanling Li
Desautels Faculty of Management, University of McGill, Montreal, Canada

Abstract

Purpose – Supplier selection is a complex decision that involves not only the consideration of unit purchasing cost but also product life cycle cost (LCC), which affects the company's after-sale costs over the life cycles of their products. Product structure and its impact on the supplier selection evaluation process are rarely investigated in the literature. Therefore, product structure for a multi-criteria multi-product supplier selection problem with uncertainty is considered. In the model, the authors address product structure, the competitive supply environment, diverse criteria, and standard requirements. The purpose of this paper is to choose suppliers that minimize LCC and maximize the reliability of the finished products.

Design/methodology/approach – The model provides straightforward representation of interrelationships among multi-objectives and analysis of tradeoffs among conflicting objectives affected by product structure. The authors illustrate the model by using real life data from lubrication systems in the offshore reliability data (*OREDA*) handbook. Sensitivity analysis is provided for the case study in which various scenarios that describe product structure, the uncertainties in purchasing prices, reliabilities of purchased components, machine downtime due to poor quality components, suppliers' capacity and delivery times. Different priority ranking among objectives is also tested to examine the impact of each objective on the overall objective.

Findings – The computational results are based on real data and would provide useful guidelines for the management in OEM to choose right suppliers.

Originality/value – Product structure and its impact on the supplier selection evaluation process are rarely investigated in the literature. Therefore, product structure for a multi-criteria multi-product supplier selection problem with uncertainty is considered.

Keywords Life cycle cost, Reliability, Supplier selection, Warranty policy, Product structure

Paper type Research paper

Nomenclature

i	the index for supplier i, $i=1, 2, \ldots, I$
j	the index for product j, $j=1, 2, \ldots, J$
k	the index for component k, $k=1, 2, \ldots, K$
w	the index for warranty policy w, $w=1, 2, \ldots, W$
$\tilde{C}^{0}_{ijkw}$	the unit purchasing cost for component k required for assembling product j from supplier i under wth warranty policies, which is a fuzzy parameter to reflect the uncertainty of the purchasing cost

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z'_{ijkw} the expected warranty cost under the wth policy for component k to assemble product j from supplier i

NR_{ijkw} the number of possible repairs for component k to assemble product j from supplier i under the wth warranty policy, which is an average number

$MTTR_{ijkw}$ the mean time to repair component k for semi product j from supplier i under the wth warranty policy

C_{ijkw} the unit repair cost of component k for semi product j from supplier i under the wth warranty policy

R the reliability of the assembled product

$\tilde{C}ap_i$ the capacity of supplier i under uncertain conditions, which is a fuzzy parameter to reflect the uncertainty of the suppliers' capacities

$\tilde{Q}_{jk}$ the demand of component k to assemble product j under uncertain conditions, which is a fuzzy parameter

$\tilde{d}t_{jk}$ the delivery time of component k of product j under uncertain conditions, which is a fuzzy parameter

$\tilde{D}T_{jk}$ the minimum accepted delivery time of component k for product j required by the manufacturer under uncertain conditions, which is a fuzzy parameter

$\tilde{t}d_{jk}$ the downtime due to a defective component k to assemble product j under uncertain conditions, which is a fuzzy parameter

$\tilde{T}D_{jk}$ the minimum accepted downtime due to defective component k to assemble product j required by the manufacturer under uncertain conditions, which is a fuzzy parameter.

Decision variables

q_{ijkw} the purchasing quantity of component k required to assemble product j from supplier i under the wth warranty policy

X_{ijkw} a binary variable. If $q_{ijkw} > 0$ for $i, j, k,$ and w, then $X_{ijkw} = 1$. Otherwise, $X_{ijkw} = 0$. Note if $X_{ijkw.} = 1$, it indicates supplier i will be chosen to produce component k for product j under the warranty policy of w

Y_{ijk} A binary variable. If $\sum_w q_{ijkw} > 0$ for all $i, j,$ and k, then $Y_{ijk} = 1$. Otherwise, $Y_{ijk} = 0$. Note if $Y_{ijk} = 1$, this indicates that supplier i will be chosen to produce component k for product j

1. Introduction

Despite the anti-outsourcing backlash of recent years, the benefits from outsourcing have been very tangibly felt across the North American economy. In the current fiercely competitive environment, which is characterized by thin profit margins and high consumer expectations regarding quality of products and short lead-times, companies are forced to increase their global dependency through outsourcing, supply base reduction, partnerships, privileged suppliers, and long-term agreements (Rezaei and Davoodi, 2008). For instance, part shortages contributed to long production delays for Boeing's 747 and 737 airplanes, and a resulting loss of over US$1 billion (Park *et al.*, 2001). Outsourcing in manufacturing began in the 1970s when the steel and textile industries in North America began to decline (Wadhaw and Ravi Ravindran, 2007). Today, large manufacturing companies are spending millions of dollars in outsourcing, which makes selecting and evaluating the right suppliers a crucial strategic decision that affects competitiveness in the global market. Indeed, decision makers are facing complex purchasing situations and need to understand suppliers' capabilities and performance potentials to make the right supplier choices. A supplier who can supply an item for the lowest per unit price may not have the best quality or service performance. Therefore, the purchasing department should determine exactly what they want to achieve by selecting a supplier. Choosing the right suppliers leads to a significant reduction in purchasing costs, an enhancement of downstream customer satisfaction, and an improvement of competitiveness. Weber *et al.* (1991) categorized 74 papers and divided the papers on supplier selection into the following groups: papers focussing on particular criteria; papers addressing the manufacturing environment (e.g. JIT, MRP, and general industrial settings); and papers focussing on particular methodologies. Interestingly, more than 60 percent of articles recommend multiple criteria for the process of supplier evaluation. Among the popular criteria considered in the papers, warranty is an important factor in marketing products because a better warranty policy usually signals a higher product quality and provides greater assurance to customers (Wu *et al.*, 2010). Some recent research studies that consider multi-criteria supplier selection problem are Saen (2010), Kokangul and Susuz (2009), Deng *et al.* (2014), Chen and Wu (2013), and Lima Junior *et al.* (2013). Suppliers offer different warranty policies having different prices; the better warranty policy, the more expensive. Proper warranty policy makes a good compromise between the cost of selecting the warranty policy and product life cycle cost (LCC). The major criteria proposed to address the selection problem are warranty and reliability due to the risk and uncertainty that exist in the overall design, product development, production, and delivery of products and services over the product life cycles (Thomas and Rao, 1999). For example, Japanese automobiles gained large market shares in the 1970s primarily because of their high reliability. Moreover, numerous recalls by GM, Chrysler, and Lexus over the last few years have cost the automobile industry billions of dollars (Teng and Jaramillo, 2005). Another important consideration when selecting suppliers is the real possibility of machine downtimes caused by defective parts or a lack of good quality parts. Over 50 percent of all quality defects can be traced back to outsources parts or materials (Gencer and Gurpinar, 2007). If a component or a batch of components to be assembled into a product is defective, the assembly process might have to stop. Then, the manufacturer will incur the costs associated with the machine downtime, which could be estimated based on the components' reliability. For example, Johnson & Johnson shutdown a manufacturing facility and recalled 136 million bottles of children's medicine due to contamination and dosage-level issues.

As mentioned above, reliability of products is a vital criterion in customer satisfaction and inevitably determines products' quality. When the product is an assembly of semi-finished parts, the reliability of these parts and more importantly the structure of parts in the final product significantly affect the reliability of products. The impact of semi-finished parts' reliability on the manufacturing product is evident. Poor reliability of a part decreases the overall reliability of the product. On the other hand, structure of parts in assembled product establishes that the reliability of some parts is critical for the quality of the product while others have slighter impacts. Consequently, in the supplier selection evaluation process, decision maker should select suppliers that offer parts with the level of reliability that provides better quality for the final product based on the semi-finished parts configuration in the product.

In this research, LCC of the product is investigated for the supplier selection problem for a manufacturer that assembles semi-finished parts supplied through outsourcing in an uncertain environment. Our model incorporates process-based and performance-based criteria, including reliability (i.e. quality), cost of warranties, unit purchasing cost of components (i.e. semi-finished parts), and the revenue loss due to machine downtime caused by defective components from suppliers. We believe our research will make important contributions towards the supplier selection literature from both the modeling and managerial insights perspective. Considering product structure in evaluating the reliability of the final product and its influence on the supplier selection evaluation process is one of the major contributions of this study. Products are assumed to have *M*-out-of-*N* series-parallel structure. In addition, our model provides a more realistic presentation of the supplier selection problem by considering uncertain parameters and conflicting multi-objectives. Uncertainty in supplier selection problem is addressed in the literature (Xiao *et al.*, 2012; Kilich, 2013; Kuo *et al.*, 2010). Parameters which are not in the control of the manufacturer and exist outside its boundary considered to be uncertain because in order to regulate them for supplier selection evaluation process, required data on these sorts of parameters are hardly available or accessible for the decision maker. Unit purchasing cost, suppliers' capacity and delivery times are instances of such parameters. In order to deal with these ambiguous parameters, a fuzzy approach proposed by Jimenez *et al.* (2007) is utilized. Furthermore, a goal programming approach proposed by Akoz and Petrovic (2007) is incorporated to handle multi-criteria decision-making model. The advantage of this approach is that the decision maker is able to put on his/her opinion on the relative importance of each criterion in comparison to others. Therefore, solutions are more compatible to company's strategies. Since the research that examines LCC based on the complex product structure is sparse, we believe that our research will provide additional value to the current literature on supplier selection.

2. Literature review

In this section, we provide an overview of previous research on supplier selection criteria and methodologies. We first review the papers that have focussed on certain supplier selection criteria and then evaluate the papers that have developed multiple objective models for the selection of suppliers.

2.1 Supplier selection criteria

The problems associated with selecting suitable suppliers are not new, and a great number of conceptual and empirical works on this subject have been published. In fact, even before supply chain management became a research topic, numerous publications addressed supply/vendor selection issues. The earliest publications on supplier selection can be traced back to the 1960s, and these studies have been summarized in Weber *et al.* (1991) in fact, of the 23 criteria surveyed, price, delivery, quality, and productive capability were the most used in the supplier selection process. Additionally, the product LCC is the most significant factor in the supplier selection process in the semi-conductor industry (Dance *et al.*, 1996). Some researchers have proposed the criteria of warranty and reliability as the most significant due to the risk and uncertainty that exists in product design, development, production, and delivery of products and services (Thomas and Rao, 1999). In an interesting overview of the literature on supplier selection models, the literature was reviewed based on different stages of supplier selection and corresponding problems and decision-making models and concluded that the process of generating criteria as well as evaluating the relevance of existing decision criteria in supplier selection have not gained much attention in the purchasing literature (Boer *et al.*, 2001). Quality risk and product reliability of the parts provided by suppliers in the supplier selection process have also been studied (Fernandez, 2001). Yet, among all the papers on the subject, very few papers related the supplier selection to product structures (Wong and Lai, 2011). Moreover, as previously indicated warranty is an important factor in marketing products because a better warranty policy usually signals a higher product quality and provides greater assurance to customers (Wu *et al.*, 2010). Also, reliability is a significant variable not only in manufacturing processes but also in the design stage (Kleyner and Sandborn, 2008). More recently, a review of 78 papers published between 2000 and 2008 revealed that 68 papers (i.e. 87.18 percent) considered quality in the supplier selection process; the next most popular criterion was delivery (i.e. 64 papers or 82.05 percent), and the third most popular criterion was purchasing price or cost (i.e. 63 papers or 80.77 percent) (Ho *et al.*, 2010). Recently, many studies have used the fuzzy programming method to address supplier selection problems. This method is popular because a decision maker often does not have sufficient information related to the different criteria; indeed, most data are fuzzy in nature. A review of 420 articles recently published in the areas of operation management and business concluded that the number of applications of fuzzy set theory had increased in those areas (Wong and Lai, 2011; Amid *et al.*, 2011). Therefore, supplier selection is an inherent multiple objective decision problem that involves tradeoffs among multiple criteria and the presence of both quantitative and qualitative data to concurrently minimize procurement cost and maximize quality and service performance. In other words, supplier selection is a process that involves uncertain and subjective preferences.

2.2 Supplier selection focus on reliability (quality), warranty, purchasing costs, and machine downtime

Previous work in this area is mostly operation research oriented, and little consideration has been given to manufacturing aspects. Recently, researchers have begun to realize that the decision and integration efforts in supply chain design should be driven by the manufactured product, specifically the product characteristics and product life cycle. In addition, decision-making processes should be guided by a comprehensive set of performance metrics. Generally, products can be categorized into three types, namely, functional, innovative, and hybrid (Akoz *et al.*, 2002). Hybrid products can consist of either: different combinations of functional components; or a mix of functional and innovative components. All products are typically depicted by general and technical attributes within a given life cycle time to meet the mission profile. A product mission profile is defined by main attributes, which include reliability, maintainability, availability, usability, and warranty; these attributes have the most impact on LCC (i.e. the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life) (Woodward, 1997; Wu *et al.*, 2010). For a majority of repairable products, the lifetime operation, maintenance, and repair costs make up the majority of the LCC (Yun *et al.*, 2008). Moreover, reliability is a significant variable not only in the manufacturing process but also in the design stage (Amid *et al.*, 2011). Furthermore, the reliability of a product depends on the reliability of the semi-finished parts from the suppliers (Levitin, 2005). Each semi-finished part can be in one of only two possible states, namely, working or failing to work, and each final product can be considered a *M*-out-of-*N* series-parallel system (i.e. binary *M*-out-of-*N* system). Warranty is defined as a contractual obligation connected to the sale of a final product or part incurred by the manufacturer or supplier. This contract assures product performance. When a purchased product or part fails, the warranty ensures that the failed item is repaired or replaced by a new item for a reasonable cost or sometimes free of charge. A study that proposed the taxonomy of 15 warranty types concluded that warranties play an important role when the product is complex and the buyer cannot evaluate the performance of the product prior to purchase due to a lack of knowledge or resources (Blischke and Murthy, 1992; Murthy *et al.*, 2004). Obviously, a better warranty policy lowers the risk for the consumer. On the other hand, since suppliers charge more for better warranty policies, a tradeoff must be identified in order to find the right warranty policy (Bhagwat and Sharma, 2007). Early research on purchasing cost is abundant because finding right suppliers may significantly reduce material purchasing costs and improve corporate competitiveness (Wong and Lai, 2011). (Perotti *et al.*, 2003) studied a case where a supplier offers a quantity discount if the order quantity increases. Indeed, the problem of finding best order quantities with price breaks combined with capacity or rationing the constraints of the suppliers, the quality, and the delivery requirements of the buyer can be complex (Tsai and Wang, 2010). When the product fails in the field, the cost is not limited to the cost of repair or replacement but may also include money lost because the product is out of service for repair or replacement. Downtime cost is related to the value of lost production and addressed as a part of LCC in the literature. When a semi-finished product is defective, downtime cost is incurred by the manufacturer in addition to the cost incurred due to the need to repair or replace the item. Each supplier may deliver different batches of semi-finished parts, and each batch may have a different number of defective parts related to the quality of the production technologies and quality control systems, both of which clearly affect the supplier selection problem. Moreover, downtime cost plays is important when attempting to find the best supplier (Flynn *et al.*, 2009).

2.3 Differences between previous studies and current research

In the present study, we first consider product structure that has multiple components, and some components are assembled in parallel. The components are provided by different suppliers who offer different warranty policies, charge different unit prices, and offer different component reliabilities. In physics, we know that if *N* identical components are assembled in parallel, the product may perform if and only if at least *M* out of *N* elements are operational status (i.e. the so-called *M* out of *N* rule). Due to possible complex product structures, we, therefore, developed a supplier selection problem characterized by a final product whose components are arranged as *M*-out-of-*N* series-parallel systems. The reliability of the final product depends on the reliabilities of each of the critical components. Thus, our problem differs from the existing literature that focusses on the quality or reliability of one product or component. Moreover, our research estimates the final product's LCC based on the unit purchasing cost, the cost of the warranty policies, and the machine downtime costs, and the final product's reliability based on the reliabilities of its components. The problem is modeled as a fuzzy multiple objective program that consists of four criteria to minimize purchasing, warranty, and machine downtime costs and to maximize the final product's reliability. The sum of the first three objectives is to minimize the final product's LLC. Since the research that examines LCC based on the complex product structure is sparse, we believe that our research will provide additional value to the current literature on supplier selection.

3. The proposed synergetic method

Recently, researchers have started to realize that supplier selection should be driven by product characteristics and product LCC. Product characteristics typically include functional attributes (e.g. power, throughput, and fuel consumption), reliability attributes (e.g. mean time to failure), and business attributes (e.g. rate of return). The functional and business attributes of a product entirely depend on how many times its components will fail over its lifespan. Component failure during assembly may also cause the abrupt shutdown of a process. Thus, minimizing the number of times the components fail during assembly decreases the machine breakdown cost. Similarly, maximizing how quickly a component can be restored to its working condition when it fails also reduces replacement and repair costs. To better understand product characteristics, we must study the product structure. Each component of the product plays a primary, auxiliary, informative, or safety roles. For example, in a centrifugal compressor comprised of a rotor, a lubricating system unit, and an anti-surge valve provides information that provides primary, auxiliary, informative, and safety roles, respectively. In general, only a few components are critical for a product and thus dominate the final product's reliability and LCC. The information related to the criticality of key components of a product help the managers choose appropriate suppliers. Therefore, in this research, we focus on a product whose critical part is in a parallel N-arrangement that explains below.

For a parallel N-component arrangement, if at least M out of N components work normally, the assembled product will function well. Such a system is called an M out of N system. For a lubrication system, the M out of N systems are applied to filters, pumps, and valves, which means that each lubrication system requires multiple components of the same type. As a result, the reliability of the final product is quite complex and really depends on the reliability of the components that are arranged as serial-parallel systems. Now, we present a general model in which we assume a manufacturer assembles multiple products by using the components purchased from suppliers. The major criteria that the manufacturer considers in choosing suppliers are as follows: reliability, warranty policies, unit purchasing cost, and machine downtime due to defective components provided by the suppliers.

3.1 Four objectives in the model

In what follows, we now present four objective functions in the model.

3.1.1 Objective 1: minimize purchasing cost. In the supplier selection process, the purchasing cost has always been an important criterion. Thus, the first objective, Z_1, is to minimize the total purchasing cost as follows:

$$\text{Min} Z_1 = \sum_i \sum_j \sum_k \sum_w \tilde{C}^0_{ijkw} \cdot q_{ijkw} \tag{1}$$

where i, k, j, and w represent the supplier, component, product, and warranty, respectively, and $\tilde{C}^0_{ijkw}$ is the unit purchasing cost and a fuzzy parameter.

3.1.2 Objective 2: minimize warranty costs. Warranty is a contractual obligation assuring the purchaser of the component's performance. When a component fails, the warranty states that the failed item will be repaired or replaced with a new item for a reasonable cost or sometimes free of charge. A good warranty policy may lower risks associated with the malfunction of the final product. Usually the suppliers develop various warranty policies for the manufacturer to consider, and the manufacturer then evaluates the trade-off between the warranty cost and the life cycle of the component/product when they purchase components from suppliers. Warranty policies are quite varied and depend on time periods, usages, or a combination of both. Usually, a final product fails for several reasons, including issues with component reliability, usage of the product, environments where failure rates assume a bath curve during the product's lifetime, and failure rates grow exponentially with use. Therefore, the warranty becomes a critical issue in a supplier selection problem. As such, the actual selection of warranty policies and the respective costs associated with such policies become critical when purchasing components from suppliers. The second objective, i.e., to minimize the total expected warranty cost, can be expressed as follows (Chattopadhyay and Rahman, 2008):

$$\mathrm{Min}Z_2 = \sum_i \sum_j \sum_k \sum_w z'_{ijkw}$$

$$z' = E(C(l,u)) = \bar{c}\left[\int_l^u \left\{\int_0^a \Lambda(t)dt\right\} h(a)da\right] \quad (2)$$

where a is a condition of coverage, l and u are lower and upper limits of a, respectively, $\Lambda(t)$ is the component failure intensity function, $h(a)$ represents the density function of the component lifetime coverage, and z' is the expected warranty cost over the product life cycle. Moreover, z' and $E(C(l, u))$ represent the general function to compute the expected warranty cost of any warranty policy, and z'_{ijkw} represents the warranty cost of component k under warranty w from supplier i to be assembled in product j.

3.1.3 Objective 3: minimize machine downtime cost. If a component or a batch of components to be assembled into a product is defective, the assembly process might have to stop. Then, the manufacturer will incur the costs associated with the machine downtime, which could be estimated based on the components' reliability. Thus, the third objective, i.e., Z_3 – to minimize machine downtime cost, can be calculated as follows:

$$\mathrm{Min}Z_3 = \sum_i \sum_j \sum_k \sum_w E\left(NR_{ijkw}\right) \cdot MTTR_{ijkw} \cdot E\left(C_{ijkw}\right) \cdot q_{ijkw} \quad (3)$$

where $E(NR_{ijkw})$ is the expected number of repairs/replacements for component k under the warranty policy w from supplier i for assembling product j. $MTTR_{ijkw}$ is the mean machine downtime, and $E(C_{ijkw})$ is the expected cost per time unit due to the halt of production.

3.2 Minimize LCC of products

The combination of the previously presented three objectives, i.e., Z_1, Z_2, and Z_3, is considered the LCC of the final product, which is represented by the following equation:

$$\mathrm{LCC} = Z_1 + Z_2 + Z_3 = \text{Purchasing Cost} + \text{Downtime Cost} + \text{Warranty Cost} \quad (4)$$

3.2.1 Objective 4: maximize product reliability. As previously mentioned, we assume the manufacturer purchases components from suppliers to assemble them into products. Usually, the components in a product are arranged either serially or in parallel, and the final product's reliability depends on the normal functioning of some critical components inside the product. After assembly, each component can either be in a normal or failed state, and the assembled product will function only when a certain number of components arranged in parallel are in the normal state (Levitin, 2005). We can use a structure function to represent a complex series/parallel system, and the function is composed of statistically independent subsystems in which components are possibly in binary states so that the reliabilities of the components can be represented by binomial probability distributions.

For example, we may denote a vector of $(X_{j1}, \ldots, X_{jk})$ as the state of K components, and X_{jk} indicates the state of the kth component in the jth product. Then, the state of product j can be expressed by a structure function, $X_j \underset{\varphi}{\otimes} (X_{j1}, \ldots, X_{jk})$, and $\underset{\varphi}{\otimes}$ is the composition operator that links all of the components' states together. The universal generating function (UGF) is the most effective method in the field of system reliability and is widely used to evaluate the reliability of complex binary systems based on using the z-transform. To obtain the reliability of a product in a series-parallel structure, we only need to apply the composition operator $\underset{\varphi}{\otimes}$ recursively following the sequence of the serial or parallel arrangements of the components. Through some transformations, we may express X_{jk} as $u_{jk}(z)$, and similarly $X_j \underset{\varphi}{\otimes} (X_{j1}, \ldots, X_{jk})$ as $U_j(z)$. This means $u_{jk}(z)$ represents the reliability of component k in product j, and $U_j(z)$ represents the reliability of the final product. Therefore, $U'(z=1)$ (first derivative of U at the point $z=1$) is the reliability of the final product in the normal state. For additional details, please refer to Levitin (2005). Hence, the reliability of product j can be expressed as follows:

$$U_j(z) = \underset{\varphi}{\otimes} \left(u_{j1}(z), \ \ldots, \ u_{jk}(z)\right) \tag{5}$$

where $u_{\mathrm{jk}}(z)$ z-transform represents the performance distribution of individual component jk, and $U_j(z)$ z-transform represents the performance distribution of the entire product. Based on the UGF, the manufacturer can estimate the reliability of product j if component k from supplier i is used and selects the suppliers whose components could maximize the reliability of the final product. Therefore, the fourth objective in our model becomes:

$$\mathrm{Max}Z_4 = R = \sum_{\text{All Product}} U'(z=1) \tag{6}$$

In order to find the reliability of the product, the reliability of each component should be considered. However, a specific component for a product may be purchased from different suppliers with different reliabilities. For example, assume that the manufacturer plans to product 1,000 units of product A for which 2,000 units of component B (based on product structure) are required and these components are purchase from two different suppliers who provide them with different reliabilities (failure probabilities). In order to find the reliability of the product A, both compoents' reliabilities should be considered. To deal with this problem, a weighted reliability (failure probability) for each component is developed. The weighted reliability of a component is calculated as follows:

$$P_{jk} = \sum_{\forall i,w} Pr_{ijkw} \cdot q_{ijkw} / Q_{jk} \tag{7}$$

where Pr_{ijkw} is the reliability of the kth component of the jth product from the ith supplier with the wth warranty policy and P_{jk} is the weighted reliability of the component k of product j. Instead of using the reliability of a component from different suppliers with different warranty policies, this weighted reliability will be used to calculate the final product's reliability.

3.3 The model: fuzzy multi-criteria goal programming

In this section, we propose a fuzzy goal programming model to solve the problem described in the previous section. A fuzzy model can be used to describe the vague information facing the manufacturer might at the stage when he (she) assesses suppliers; this vague information may include purchasing costs, supplier capacity, and delivery time. The manufacturer cannot provide special probability distributions to describe this uncertain information but the information that is obtained can be expressed as fuzzy parameters that might vary within certain ranges. The advantage of the goal programing model is that it can address multiple objectives. Hence, we believe that the development of an additive fuzzy multi-objective goal programming model with specified relative importance among the objectives is the best way to regulate the conflicts among multiple criteria. The following is the fuzzy goal programming model that contains both fuzzy parameters and soft constraints that are bounded by fuzzy parameters.

Objective functions:

$$\min Z_1 = \sum_i \sum_j \sum_k \sum_w \tilde{C}^0_{ijkw} \cdot q_{ijkw} \tag{8}$$

$$\min Z_2 = \sum_i \sum_j \sum_k \sum_w q_{ijkw} \cdot z'_{ijkw} \tag{9}$$

$$\min Z_3 = \sum_i \sum_j \sum_k \sum_w E(NR_{ijkw}) \cdot MTTR_{ijkw} \cdot E(C_{ijkw}) \cdot q_{ijkw} \tag{10}$$

$$\max Z_4 = R \tag{11}$$

Subject to:

$$\sum_j \sum_k \sum_w q_{ijkw} \lesssim \tilde{C}ap_{S_i} \quad \forall i \tag{12}$$

$$\sum_i \sum_w q_{ijkw} \gtrsim \tilde{Q}_{jk} \quad \forall j, k \tag{13}$$

$$\tilde{d}t_{ijk} \cdot Y_{ijk} \leqslant \tilde{D}T_{jk} \quad \forall i,j,k \tag{14}$$

$$\sum_i \sum_k \sum_w \tilde{t}d_{ijk} \cdot X_{ijkw} \lesssim \tilde{T}D_j \quad \forall j \tag{15}$$

$$M \cdot X_{ijkw} \geqslant q_{ijkw} \quad \forall i,j,k,w \tag{16}$$

$$M \cdot Y_{ijk} \geqslant \sum_w q_{ijkw} \quad \forall i,j,k \tag{17}$$

$$\sum_w X_{ijkw} \leqslant 1 \quad \forall i,j,k \tag{18}$$

$$X_{ijkw} \in \{0,1\} \quad \forall i,j,k,w \tag{19}$$

$$Y_{ijk} \in \{0,1\} \quad \forall i,j,k \tag{20}$$

$$q_{ijkw} \geqslant 0 \quad \forall i,j,k,w \tag{21}$$

Equations (8)-(11) are the objective functions of the model that minimize the total purchasing cost, warranty cost, machine downtime cost and maximize the ultimate reliability of the assembled product. Constraint (12) ensures that the amount of the ordered components does not exceed the capacity of each supplier. Constraint (13) requires that the demand for each component should be met in order to assemble multi-component products. Constraint (14) states that if a component is purchased from a supplier, its delivery time should be less than the minimum accepted delivery time. In Constraint (15), the total machine downtimes should be less than the minimum accepted downtime. Note that Constraints (12)-(15) are soft constraints since the values on the right are fuzzy parameters. In Constraint (16), X_{ijkw} is 1 if $q_{ijkw} > 0$; otherwise, X_{ijkw} is 0. In Constraint (17), Y_{ijk} is 1 if $\sum_w q_{ijkw} > 0$; otherwise, Y_{ijk} is 0. Constraint (18) ensures that only one warranty policy can be chosen for each component from each supplier. Constraints (19)-(21) are integrality and non-negativity constraints. We then used the technique discussed in additive fuzzy multi-objective models with relative importance of commensurable goals for the regulation of conflicts to solve the fuzzy goal programming model developed in this research (Jimenez *et al.*, 2007; Akoz and Petrovic, 2007). In this research, we assumed that the information of costs, demands, supplier capacity, delivery time, and downtime are vague. Also, the constraints correspond to supplier capacity and delivery time in which demand and downtime are treated as soft constraints. The model is a fuzzy mathematical model that can incorporate both uncertain parameters and soft constraints (for details see Jimenez *et al.*, 2007).

4. Case study

4.1 Preparing and solving the model

To illustrate the practical application of the fuzzy goal programming model developed in this paper, we use the real data for lubrication systems from *OREDA* handbook.

As previously mentioned, the lubrication system consists of a few critical components that are serially arranged, and some components are arranged in M-out-of-N systems. Assume the manufacturer needs three critical components, i.e., filters, valves, and a pump, to assemble three different models of lubrication systems. We labeled the components, i.e., the filters, valves, and pump, as units 1, 2, and 3, respectively. Assume if two out three filters (unit 1), one out of two valves (unit 2), and one pump (unit 3) function normally, the assembled lubrication will operate in steady state. Thus, following the UGF technique and based on the product structure in Figure 1, the reliability of the lubrication system can be calculated as follows:

$$R = \left(\sum_{j=1}^{3} P_{j1} \cdot \left(P_{j2}^2 + 2P_{j2} \cdot (1 - P_{j2}) \right) \cdot \left(P_{j3}^3 + 3(1 - P_{j3}) \cdot P_{j3}^2 + 3(1 - P_{j3})^2 \cdot P_{j3} \right) \right) \Big/ 3 \tag{22}$$

where P_{jk} is the weighted reliability of the kth component of jth product. As mentioned before, weighted reliability of components is used in Equation (21) as stated in Equation (7).

We also assume that three suppliers can provide all of the components for three models of the lubrication systems that have different structures and require different number of components. The components from different suppliers vary according to initial purchasing costs, warranties, downtime, and reliability. Among the 20 warranty policies available, we chose 11 widely used policies in the metal industry, namely, 1-8, 13, 15, and 19 that vary with coverage periods, repair/replacement policies or a combination of both (due to the space limit, we do not present the details of the warranty policies in this paper). To solve the model, the fuzzy goal programming model is coded by GAMS software. For the solution procedure, each of the four objectives is solved separately, and the optimal value for each objective is considered as the aspiration level of that objective. For example, the aspiration (minimal) level for the total purchasing cost is \$424,700, which is obtained by minimizing the total purchasing cost without considering other objectives. Second, we set upper tolerance limits for Z_1 (i.e. the purchasing cost), Z_2 (i.e. the warranty cost), and Z_3 (i.e. the machine downtime cost) at \$1,000,000, \$300,000, and \$1,500,000, respectively. The upper tolerance limits are estimated well above the ideal aspiration levels. The minimum accepted reliability for Z_4 is set at 0.85 since the aspiration level for the reliability is 0.989. The allowable tolerance for capacity, delivery time, and downtime constraints is equal to 0.5. As mentioned previously, only a few critical components dominate the reliability and LCC of a finished product. For example, failure, mode, effect and criticality analysis (see page 62 in *OREDA* handbook) shows the most frequent failure modes that crucially affect the filters, valves, and pump with failure rates of 8.95, 7.03, and 6.57 percent, respectively. This reflects the impact of defective filters, valves, and the pump because the failure rates related to machine downtime are very small. Thus, the reliability of the components and final products and the machine downtime costs are slightly preferable as compared to the purchase cost. Following similar logic, we defined the relative importance among the four goals of

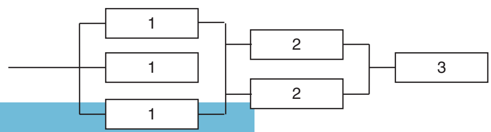


Figure 1.
The structure of the lubrication system

objectives as follows: Goal 1 is slightly preferred to Goals 2-4; Goal 2 is slightly preferred to Goals 3-4; and Goal 3 is slightly preferred to Goal 4. Note that Goals 1-3 are minimizing Z_1, Z_2, and Z_3, respectively and Goal 4 is to maximize the reliability. The results of the fuzzy multi-objective model are presented in Tables I and II. Table I details the purchasing quantities, and Table II illustrates supplier and warranty choices. For example, as indicated in the second column of Table II, supplier 1 is chosen to provide 600 units of component 1 for product 3 and 700 and 100 units of component 2 for products 2 and 3, respectively. All of these components will be purchased under warranty 1. Supplier 1 is also chosen to provide other components under different warranty policies. Supplier 3 is chosen to provide 31:100 that means K=100 units of component J = 3. Obviously, supplier 3 is not a potential long-term contract partner, whereas supplier 1 could be considered for long-term contracts in order to further improve component reliabilities and reduce all costs.

4.2 Sensitivity analysis

Considering that the results of the model depend on the parameters, we discuss the results derived from the sensitivity analyses by varying three parameters,

Objective decision variables	Optimum value
FGP	3.633
Z_1	804,140
Z_2	265,560
Z_3	1,233,300
Z_4	0.964
$q_{1,115}$	1,000
$q_{1,116}$	650
$q_{1,117}$	150
$q_{1,131}$	600
$q_{1,215}$	1,200
$q_{1,221}$	700
$q_{1,314}$	600
$q_{1,321}$	100
$q_{2,125}$	1,200
$q_{2,221}$	100
q_{2231}	400
$q_{3,331}$	200

Table I.
Results of the fuzzy goal programming model

	Warranty policy										
Supplier	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}	W_{11}
S_1	13:600			31:600	11:1000	11:650	11:150				
	22:700				21:1200						
	32:100										
S_2	22:100				12:1200						
	23:400										
S_3	33:200										

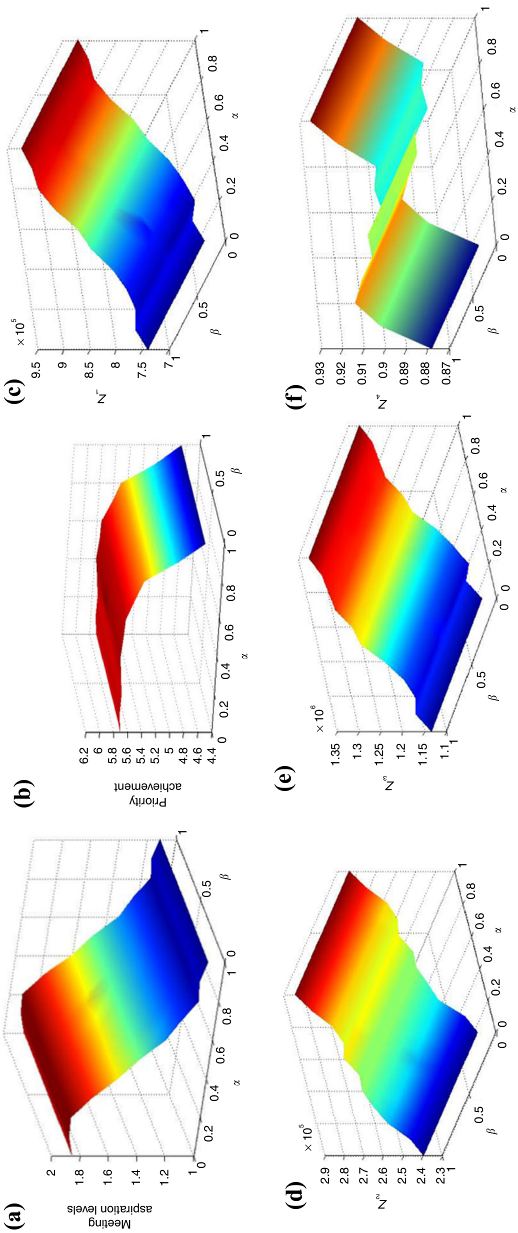
Note: [a]*JK*:*Q* means that the *k*th component of *j*th product with the quantity of *Q* is purchased for its specified warranty policy from a specified supplier

Table II.
Another representation of the solution for the fuzzy goal programming model

i.e., α, β, and λ. Akoz and Petrovic (2007) provides the reformulation of the multi-objective goal programming model where the three parameters appear. For simplicity, we will explain the parameters as follows. α represents the vagueness of the fuzzy parameters. When α approaches 1, all parameters are certain or constants. Otherwise, all the parameters are quite uncertain. β provides the minimal acceptable satisfaction level of soft constraints, and when β approaches 1, the acceptable satisfaction level becomes certain. λ is the value used to balance the relationship between achieving the aspiration levels of the four objectives and satisfying the pair-wise relative importance among objectives. When λ approaches 1, achieving the aspiration levels is the only criterion, and when λ approaches 0, the relative importance of the pair-wise objectives is the only criterion. When $0 < \lambda < 1$, achieving aspiration levels and the pair-wise relative importance of the objectives are weighted by λ and $(1-\lambda)$, respectively. All three parameters are in the range of 0 to 1. In the initial solution, we set $\alpha = \beta = \lambda = 0.5$. The sensitivity analysis is performed in the following direction: vary α, β, and λ values; (ii) change the pair-wise priorities between every two objectives; and increase unit purchasing prices.

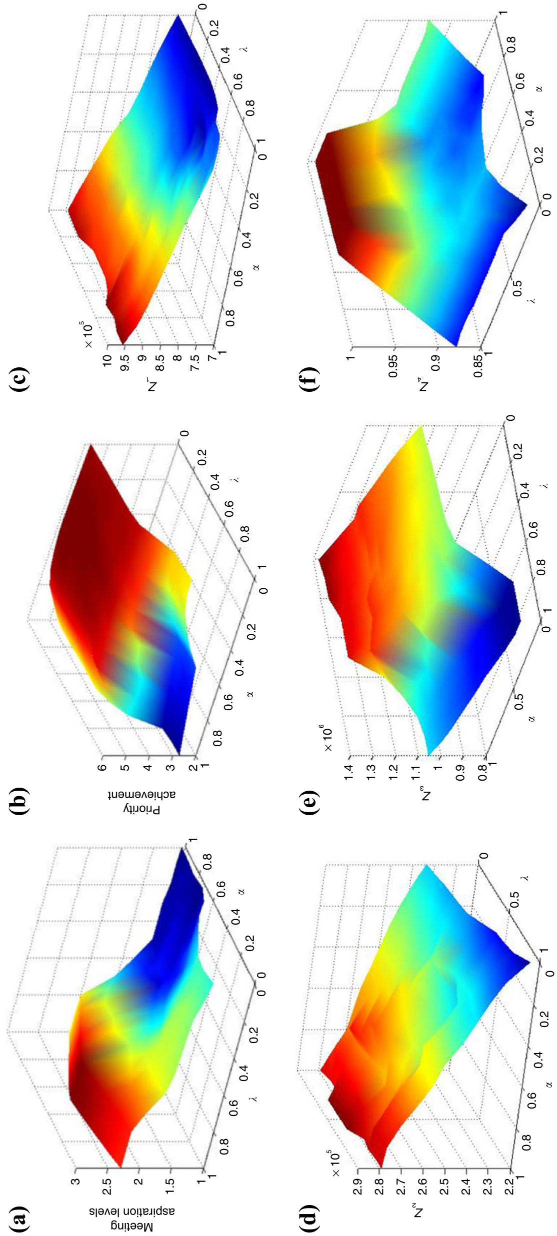
4.2.1 α-cut level vs β-cut level. To examine the impact of the α and β values, we evaluate 11 levels of α and β ranging from 0 to 1 with 0.1 as an increment, and we solved the model for a total of 121 possible combinations of α and β values. Figure 2 provides the sensitivity results. Figure 2(a) provides the impact of α and β levels on achieving the aspiration levels of four objectives. As the value in the vertical axis increase, the achievement of the four aspiration levels increases as well. Figure 2(b) provides the impact of α and β levels on meeting the relative importance of the pair-wise objectives. Figure 2(c)-(f) provide the impact on each of the four objectives. As Figure 2(a) indicates, when α approaches 0 (i.e. the fuzzy parameters are quite uncertain), the achievement of all objective values increase towards the maximum (i.e. when α is equal to 0). Indeed, when the fuzzy parameters are very vague, the model is more flexible. We also note in Figure 2(a) that when the α level is in the range of 0 to 0.2, the achievement of all four objectives is constant, and the achievement drops sharply only after α goes beyond 0.2. Similarly, in Figure 2(b), when α is in the range of 0 to 0.6, satisfying the relative importance of the pair-wise objectives is relatively constant, but when α is beyond 0.6, the satisfaction level decreases significantly. Our results suggest that the choice of α is important and must be made carefully in order to get meaningful results in the fuzzy goal programming model. The level of parameters vagueness can be easily determined by decision maker based on the current situation of the market and suppliers. Figure 2(c)-(f) illustrate the impact of α level on each of the four individual objective values. Similarly, Figure 3(a)-(e) show that when the α level approaches 1, the first three objective values are the highest because the parameters do not have any flexibility. Figure 2(f) does not provide meaningful results because the reliability is set as the lowest priority among all objectives in the model. In the next section, we discuss the sensitivity analysis by varying the importance among the four objectives. In contrast, Figure 3(a)-(f) show that β level changes create no impact on achieving aspiration levels and meeting the importance of objectives. Recall that the β represents the uncertain degree to which the minimum satisfaction level is met in the constraints. In situations with no impact, the minimum satisfaction levels do not create tight constraints in solving the model.

4.2.2 Vary α-cut level vs λ-cut levels. The results of solving the model with respect to different levels of α-cut and λ-cut are shown in Figure 3. As with Figure 3, Z_1 (i.e. total



Notes: (a) Achieving aspiration levels of objectives; (b) achieving relative importance of objectives; (c) Z_1; (d) Z_2; (e) Z_3; (f) Z_4

Figure 2.
α vs β levels



Notes: (a) Left side of the fuzzy goal programming objective; (b) right side of the fuzzy goal programming objective; (c) Z_1; (d) Z_2; (e) Z_3; and (f) Z_4

Figure 3.
α-cut vs λ-cut

purchasing cost), Z_2 (i.e. expected warranty cost), and Z_3 (i.e. expected machine downtime costs) are decreasing with respect to the decreasing α-cut. However, the reliability of the products is not affected due to the priority structure of the goals. Reliability in the structure of the priorities has the least importance, and all other goals are more important in this case. Therefore, the model tries to optimize the other goals first, and the reliability of the products is optimized via the other goals. This imples that the decision maker should evaluate the importance of the objectives when constructing his/her priority structure. Recall that λ balances the relationship between meeting aspiration levels and the pair-wise relative importance among objectives. When $0 < \lambda < 1$, achieving aspiration levels and the pair-wise relative importance of the objectives are weighted by λ and $(1-\lambda)$, respectively. Figure 3 shows that meeting the aspiration levels and priorities of the objectives do not change when the level of λ-cut changes are in the range of 0.8-1 and 0-0.6, respectively. When the λ changes from 0.8 to 1, meeting aspiration levels remains almost constant, and achieving priorities among objectives gets worse. Similarly, when λ changes from 0 to 0.6, satisfying objective priorities remains almost constant, and meeting aspiration levels gets worse. This implies to evaluate the trade-off between achieving aspiration levels and priorities, λ should be set in the range of 0.6 and 0.8. In Figure 3, we noticed that when λ is equal to 0.5, both the aspiration levels and the priority satisfaction level are the highest, and since the first objective (i.e. Z_1) is set as the most important, the solution is the best when λ is equal to 0.5. The other objectives have their best values when λ increases because the importance of the priority structure of the goals decreases for greater values of λ; therefore, the objectives with less importance can obtain better solutions.

4.2.3 Changing the pair-wise priorities between every two objectives. We introduced ten scenarios to evaluate the effect of changing pair-wise priorities between objectives. Table III shows pair-wise priorities between objectives in each scenario. In Table III, superscript "-1" indicates that the priority between goals is reversed. For example in Scenario no. 4, G2 is slightly preferred to G1. Table IV demonstrates the results.

In first, three scenarios, the relationships only differ in the level of priorities. Scenario No. 1 has the least level of priority and Scenario No. 3 has the highest level. As illustrated in Table IV, this leads to make Z_4 to become as small as possible which is the lower tolerance limit for reliability. In contrast, Z_1 and Z_2 become better. Second, three scenarios are like first three ones which have reversed relationships. In other

Scenario	G1-G2	G1-G3	G1-G4	G2-G3	G2-G4	G3-G4
No. 1	Sli.	Sli.	Sli.	Sli.	Sli.	Sli.
No. 2	Mod.	Mod.	Mod.	Mod.	Mod.	Mod.
No. 3	Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
No. 4	Sli.$^{-1}$	Sli.$^{-1}$	Sli.$^{-1}$	Sli.$^{-1}$	Sli.$^{-1}$	Sli.$^{-1}$
No. 5	Mod.$^{-1}$	Mod.$^{-1}$	Mod.$^{-1}$	Mod.$^{-1}$	Mod.$^{-1}$	Mod.$^{-1}$
No. 6	Sig.$^{-1}$	Sig.$^{-1}$	Sig.$^{-1}$	Sig.$^{-1}$	Sig.$^{-1}$	Sig.$^{-1}$
No. 7	Mod.	Mod.$^{-1}$	Sig.	Sig.$^{-1}$	Sig.	Sig.
No. 8	Mod.$^{-1}$	Sli.	Sli.$^{-1}$	Sig.	Sli.	Mod.$^{-1}$
No. 9	Mod.	Sli.	Sli.$^{-1}$	Sli.$^{-1}$	Sig.$^{-1}$	Mod.$^{-1}$
No. 10	Mod.	Sig.	Sli.	Sli.	Sli.$^{-1}$	Mod.$^{-1}$

Notes: Sli., slightly; Mod., moderately; Sig., significantly

Table III.
Pair-wise priorities scenarios

Table IV. Results for different scenarios

Scenario	FGP	Z_1	Z_2	Z_3	Z_4
1	3.633	804,410	265,610	1,235,300	0.931
2	2.355	861,860	254,030	976,210	0.9
3	0.408	833,420	270,710	1,290,700	0.9
4	4.268	871,420	255,170	960,830	0.989
5	3.459	886,820	251,990	968,780	0.989
6	2.664	915,120	252,730	992,550	0.989
7	2.531	800,660	282,500	92,660	0.9
8	3.632	1,000,000	218,150	1,500,000	0.978
9	3.411	786,900	282,010	1,199,500	0.989
10	2.618	898,190	244,060	1,391,800	0.977

words, instead of having a priority level for Goal 1 over Goal 2, there is a priority level for Goal 2 over Goal 1. This change forces Z_4 to reach to its aspiration level as much as possible. In other scenarios, the results are consistent with the defined priority relationships. Consequently, it is important for the decision maker to intelligently select proper priority relationships based on the company's strategy and also check the reversed scenarios. For example, in second three scenarios, the reliability is approximately reached to the aspiration level while other objectives are changed a little. Considering the aforementioned discussion in this section, it should be a good investigation between possible scenarios to find the most appropriate results. To sum up, it is recommended to decision maker to construct its priority structure based on his/her company strategies and the importance of each goal. Then, the reverse structure should be check and the differences between objective values should be evaluated.

4.2.4 Impact of purchasing price on objective price (Z_i). In real world situations, managers often encounter a sudden rise in the purchasing price due to several reasons that are related to market instability. Here, the effects of a rise in purchasing price are investigated. In this regard, purchasing price is increased, and the consequences of this growth on the selected warranty policies and total cost (i.e. purchasing cost, warranty cost, and downtime cost) is explored. Increases of 0, 5, 10, 15, 20, 25, and 30 percent in initial cost are considered. FGP, Z_1, Z_2, Z_3, Z_4, and total cost (i.e. $Z_1+Z_2+Z_3$) are shown in Table V. As shown in Table V, increasing unit purchasing costs results in consequent changes on total cost. Increasing unit purchasing costs also impacts the selection of appropriate warranty policies. In other words, the proposed model tries to

Table V. Objective function values vs growth amount of purchasing costs

	0%	5%	10%	15%	20%	25%	30%
FGP	3.762	3.633	3.505	3.377	3.249	3.121	2.995
Z_1	722,650	789,290	820,310	843,940	880,570	915,050	951,440
Z_2	258,260	262,950	265,440	271,220	271,220	272,090	272,090
Z_3	1,170,200	1,153,800	1,144,900	1,123,100	1,123,100	1,118,200	1,118,200
Z_4	0.908	0.901	0.897	0.89	0.89	0.889	0.889
Total cost	2,151,110	2,206,040	2,230,650	2,238,260	2,274,890	2,305,340	2,341,730

Notes: Z_1, initial costs; Z_2, warranty cost; Z_3; downtime cost; Z_4, product reliability. Total cost $= Z_1 + Z_2 + Z_3$

ease the impacts of ripple changes by considering different warranty policies when a sudden leap in unit purchasing price takes place. As shown in Figure 4, the decision maker should decrease the quantity of parts bought with the fifth warranty policy and should order more parts with the first warranty policy. He/she could also order a small number with the fourth warranty policy.

Ultimately, when the decision maker encounters a sudden rise in initial prices, the selection of better warranty policies, which lead to lower warranty costs, is more beneficial. In other words, reliable products provided by suppliers with a longer warranty period should be selected by the decision maker in order to decrease the re-buying and replacement costs. Note that optimal orders do not change significantly for situations beyond a 15 percent increase in unit purchase price. In such a case, the decision maker should change the priority structure/scenario and increase the importance of reliability (Z_4) to handle this sudden rise in cost.

5. Conclusion

This paper presents the study of a multi-criteria supplier selection problem for a manufacturer that purchases and assembles components to produce different products and the effect of product structure in supplier selection evaluation process. Optimal order quantities are obtained from available suppliers offering different warranty policies. Our objective is to analytically investigate the following: how a manager in such situations selects the proper supplier with products having appropriate warranty policies; and how a manager determines the order quantities from selected suppliers in order to optimize LCC and the ultimate quality of his/her product to align with his/her business environment. Moreover, a modified UGF, a known technique in evaluating the reliability of the products considered as binary series/parallel systems, was employed to evaluate the reliability of the products when different components from different suppliers were used to produce such products. In order to deal with the uncertainty that exists in real world situations, fuzzy mathematical programming was used, and a fuzzy multi-objective mathematical model was prepared. This approach enables the manager to simply apply his or her opinions about the importance of each goal in comparison to other goals. The manager can determine the importance of observing a particular priority structure instead of optimizing each goal separately and to what extent one should take precedence over the other. This was presented as the right and left side of the fuzzy goal programming objective function, respectively. To do so, the manager should cautiously select a small range of λ-cut to demonstrate his or her opinion via

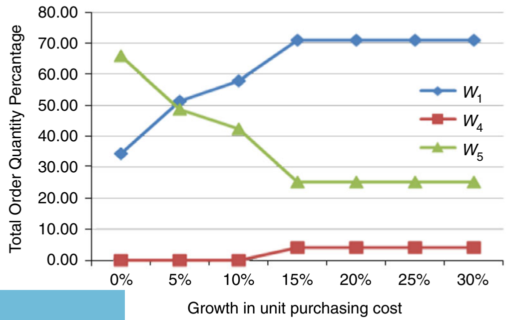


Figure 4.
Effects of the growth in purchase price on the selections of proper warranty policies

the satisfaction and aspiration levels. We also explored the impacts of chaos changes in the purchase price of parts in the supplier selection problem. These changes drive the decision maker to increase their dependency on privileged suppliers with long-term agreements for critical components. In summary, a constant rise in initial prices encourages the decision maker to adopt a specific policy (policy 11 (RIW)) with the longer lifetime. In this situation, he/she should alter the priority structure and enhance the importance of reliability (Z_4) to handle the radical rise in prices.

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