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RESEARCH PAPER

Maintenance Supplier Selection: Evaluating the Effect of Maintenance and Sourcing Strategies

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Abstract

The advent of globalization and outsourcing of products and services has resulted in more networked, highly dependent firms in supply chains; so supply chains' vulnerability to several risks such as equipment breakdown is increased. Although optimizing maintenance supplier selection has a vital role in supply chain performance, it has not received enough attention in the literature. Due to the effect of maintenance strategies and supplier selection approaches, in this paper, three scenarios are considered based on various strategies as follows: 1-Preventive Maintenance with single supplier selection (PM_s), 2- Preventive Maintenance with multiple supplier selection (PM_m), and 3-Condition Based Maintenance with multiple supplier selection (CBM_m). A fuzzy goal programming approach is applied to make trade-offs between several objectives. The efficacy of the model is validated through numerical examples, and results are compared to investigate the effect of implementing each scenario. The results show that in situations that reducing unreliability cost has higher priority for a decision-maker, CBM_m is more efficient than other scenarios.

Keywords:
Supplier Selection;
Maintenance;
Risk Management;
Life Cycle Costing;
Fuzzy Goal Programming

Introduction

With the advent of globalization and the emergence of interdependent organizations, the importance of supplier evaluation and selection has been increased [1]. Therefore, in this competitive environment optimizing supplier partner selection, which has a significant effect on firms' success, is inevitable. Supply chain management (SCM) aims to minimize overall costs across the system by controlling transaction flows through the whole supply chain [2]. Both academics and professionals have dealt with supplier selection as a theoretical and practical issue [3] and have emphasized the importance of the supplier selection process [4]–[7]. Moreover, the advantages of using a systematic approach to select the suppliers are emphasized in some researches [8], [9].

Despite all the advantages cited, the implementation of SCM's principles results in more networked, highly dependent organizations. In other words, organizations are vulnerable to risks that arise from the problems of coordinating supply and demand, and risks that arise from disruptions to normal activities [10]–[12]. Disruption events can affect the performance of the supply chain, and enterprises should be able to deal with such events. Accordingly, dealing with supply chain risks considerably take into consideration in recent years. Supplier selection and

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evaluation models mainly use acquisition costs as the primary criterion for solving problems, but this approach to decision-making only attempts to save money in a short time. Life Cycle Costing (LCC) is an approach that includes the cost of acquisition, ownership, and disposal of the product/service [13]. LCC is usually defined as all the costs associated with a product through its operational life [14]. Operating and Maintenance costs (i.e., the ownership cost) have a significant effect on the supplier selection problem. Subsequently, the decisions about supplier selection may affect the performance of an organization.

Furthermore, maintenance strategy selection plays a significant role in the maintenance supplier selection process [15]. The applied maintenance strategy may affect several factors in manufacturing systems, such as demand for parts, system reliability, and total costs. So, it is essential to select the proper maintenance strategy and supplier selection process to have a successful system. There are different maintenance strategies which are explained in short as follows [16]. Corrective maintenance is unscheduled maintenance used for equipment after equipment breaks down or malfunctions. Preventive Maintenance (PM), on the other hand, is scheduled maintenance carried out routinely at pre-determined intervals. Conditioned-Based Maintenance (CBM) is proposed to increase the effectiveness of preventive maintenance. CBM decisions are based upon measures of the condition of a system that is obtained over time [17], [18]. In other words, CBM is a maintenance strategy where maintenance activities are performed in response to a significant deterioration observed by a change in a monitored parameter of the machine condition. With technological advancement, maintenance sensors such as vibration sensors, flow sensors, and photoelectric sensors are becoming more accurate and reliable. Furthermore, data collection, data analysis, and decision support capabilities for large datasets are possible with the advent of emerging Information Communication Technologies [19]. For advantages such as cost reduction by unnecessary maintenance elimination and more efficient maintenance, CBM implementation in industries has been increased. Studies have proven that the CBM strategy can be useful in reducing the costs associated with maintenance, thereby minimizing the occurrence of serious faults [20]. Recent studies in this area attempt to present SCM models that consider different SCM's criteria simultaneously, such as purchasing, production, and distribution [21]. Ristono et al. [22] used statistical multi-criteria decision making (S-MCDM) methods to propose criteria design methods for the selection of suppliers, which provide ongoing guidance and avenues for further researches.

Numerous investigations have focused on the number of simultaneous suppliers for the same product. Some maintenance managers prefer a single supplier strategy. This strategy is popular among managers who prefer a lower initial prices and ongoing costs to disruption risks [23]. Moreover, it forms long term-relationship, a significant commitment of the supplier for maintaining equipment, and lower wholesale price. As the total life cycle costs play a significant role in SCM, this study intends to examine the effects of various maintenance and supply selection strategies upon the total life cycle costs. To do so, we define three scenarios and compare total LCC. All in all, these scenarios are composed of 1. Preventive Maintenance with single supplier selection (PM_s), 2. Preventive Maintenance with multiple supplier selection (PM_m), and 3. Condition Based Maintenance with multi-supplier selection (CBM_m).

This study aims to deal with two general concepts in (SCM), including supplier chain risks and partner selection. In the following subsections, these two concepts are reviewed.

Supply chain and risk

Several studies have investigated supply chain disruption risks and their impact using different approaches such as risk modeling [24]–[27] and risk mitigation [28]–[32]. Fagundes et al. [33] classified risk decision support models into three groups and determined six current clusters of researches. Supply chain disruption literature is divided into quantitative and qualitative researches [34]. Recent studies of supply chain management focused on coordination schemes. Revenue-sharing contracts among supply chain participants have become popular [35]. Song and Gao [36] proposed two green supply chain game models under revenue-sharing contracts to improve the greening level of the products and the overall profitability of the supply chain.

Disruption management is a new field in the study of supply chain management. For the first time, Clausen et al. [37] introduced the concept of disruption management and applied it successfully in airline operations. Qi et al. [38] investigated demand disruption's impact on supply chain coordination. They introduced a quantity discount contract to coordinate a two-stage supply chain with one manufacturer and one retailer. Yu and Goh [39] explored the effects of Supply Chain Visibility (SCV) and Supply Chain Risk (SCR) on supply chain performance. SCV is related to the capability of sharing timely and accurate information on demand, inventory, transportation cost, and other activities through the supply chain. SCR can be defined as the probability of an event and its consequences during a specific period through a supply chain. They used a fuzzy multi-objective decision-making approach to model SCV and SCR to maximize SCV and Minimize SCR and costs. DuHadway et al. [40] provided a framework for the detection of disruption sources such as intentional or inadvertent acts. Finally, they proposed corrective actions for mitigating disruption consequences based on the intent and the source of the disruption. Lee and Michael [41] presented strategies for reducing vulnerability to security losses that may cause disruptions. Kleindorfer and Saad [10] proposed a model to estimate and reduce the outcomes of disruptions, which may arise from natural disasters, strikes, and economic disruptions. Some studies have developed frameworks to test the threat of potential disruption on the supply chain process [42]–[44]. They focused on potential mitigation and supply chain design strategies that can mitigate these disruptions and consequences.

Partner selection

Partner selection is a vital step in the formation of any supply chain [45]. Supplier selection has received particular attention due to its critical effect on successful supply chain management. Jain et al. [46] reviewed the main approaches to supplier-related issues based on a summary of existing research before 2007. Glock et al. [47] conducted a systematic literature review with a focus on decision support models for partner selection problem. Ho et al. [48] analyzed multi-criteria decision making (MCDM) approaches for supplier selection based on journal articles from 2000 to 2008. Ocampo et al. [49] reviewed different partner selection methods in the supply chain such as multi-criteria decision-making, fuzzy decision-making, artificial intelligence, mathematical programming, and statistical models from 2006 to 2016. Lin and Kuo [50] introduces a method named MCB (Multiple Comparisons with the Best), which uses suppliers' capabilities such as precision, loss, and accuracy to identify the best supplier and measure its superiority over other suppliers. Huang et al. [51] developed a two-stage selection framework based on the factors affecting the partner selection process. They defined practical factors in the partner selection process as hard and soft factors. In the first stage, they determined potential partner candidates. Then, in the second stage, they assess candidate partners' cooperation ability. Çebi and Otay [52] also presented a two-stage framework for partner selection. The first stage is evaluating and selecting suppliers, and the second is determining the number of orders allocated to selected suppliers.

Supplier selection techniques have a different amount of complexity and accuracy. There are three different groups of techniques [3]. The first consists of supplier selection techniques with low complexity and accuracy, including the Scoring Model (SM) and the Categorical Methods (CMs). The second group encompasses supplier selection techniques with medium accuracy and complexity, including the Analytic Network Process (ANP), Analytic Hierarchy Process

(AHP), and Data Envelopment Analysis (DEA). The third one consists of supplier selection techniques with high complexity and accuracy, including the Fuzzy Set Theory (FST), Mathematical Programming (MP), and Total Cost of Ownership (TCO) models. Chai and Ngai [53] reviewed decision-making techniques in supplier selection problem and categorized them into three main groups: Multi-Criteria Decision Making (MCDM) techniques, Mathematical Programming (MP) techniques, Data Mining, and Artificial Intelligence (DMAI) techniques.

Although there are many studies in the literature on supplier selection and order allocation problems, they generally focused on purchasing parts that are used in the manufacturing system to create final products, not on those used for maintenance of production machinery. Therefore, it could be deduced that maintenance supplier selection has not received considerable attention yet. Also, the effect of maintenance strategy and sourcing policy on supplier selection has not been considered. To fill these gaps, this study aims to make a comparison between PM_s, PM_m, and CBM_m as a variety of maintenance strategies in the supplier selection process by considering single and multiple sourcing l6 options.

Problem description

The maintenance supplier selection and order allocation models aim to assist the decision-maker in choosing the best maintenance supplier and determining the quantity order of each part. In order to compare mentioned scenarios, identical objective functions are defined for each of them, while the objective functions aim to minimize purchasing cost, risk measure, downtime cost, and unreliability cost of the production system simultaneously. Since CBM scenario bears a time dimension, it is necessary for PM scenarios to consider the demand of each period equal to that of the first period. In the following sections, three scenarios are explained covering two maintenance policies (PM and CBM) and two sourcing strategies (single and multiple). For CBM policy, multiple sourcing is more applicable, and therefore, single sourcing is not considered.

Scenario 1 (PM_s)

The following assumptions are considered:

- Each procured part has a deterministic demand rate (i.e., a given demand per period) and regularly replace in a pre-defined time interval.
- Because of the unusual situation of manufacturers (such as economic sanctions impact), lead times are considerable.
- There are several pre-qualified suppliers for each part.
- A multi-period time horizon is considered.
- Because of the nature of the PM strategy, equal demand is considered for each period.
- Medium/long-term contracts are taken into account, and the choice of the supplier is fixed for a reasonable period.
- Historical data for suppliers, parts, and criteria are available.
- It is assumed that the cost associated with each unit of uncertainty is constant. Therefore, the cost coefficients are not incorporated in the formulation of uncertainty cost.
- Manufacturing, disposal, discount rate, and information costs are assumed to be the same for all suppliers and consequently have no significant effect on the supplier selection problem.
- Stocking cost is also not considered in the model because it is assumed that the total number of parts is ordered according to pre-determined demand, and it is

independent of the suppliers. In other words, stocking cost is equal for all of the suppliers.

- Operation and maintenance costs include the cost of installation and costs associated with the reliability and maintainability of the equipment.
- Uncertainty cost is defined as the summation of those costs related to the risks of different phases of the supply chain.
- Each equipment's part in each period must be purchased from only one supplier.

The following notations have been used for the model formulations:

Table 1. Indices and parameters of the basic model

Indices	
i	Index of suppliers, $i = 1, \dots, I$
j	Index of equipment, $j = 1, \dots, J$
k	Index of each part of equipment, $k = 1, \dots, K$
Input parameters	
C_{ijk}^{0}	Purchasing cost for part k of equipment j supplied by supplier i
NR_{ijkt}	The number of repairs for part k of equipment j supplied by supplier i in period t
$MTTR_{ijk}$	Mean time of repair for part k of equipment j supplied by supplier i
C_{ijk}	Repair cost for part k of equipment j supplied by supplier i
R_t	System reliability in period t
Cap_i	Capacity of the supplier i
D_{jkt}	Demand rate for part k of equipment j in period t
dt_{ijk}	Delivery time of part k of equipment j supplied by supplier i
DT_{jk}	Maximum accepted lead time for part k of equipment j
td_{ijk}	Downtime of part k of equipment j supplied by supplier i
TD_j	Maximum accepted downtime of equipment j
RI_i	The risk value of selecting ith supplier
C_{UR}	Cost of unreliability

Basic problem variables are denoted in Table 2:

Table 2. Variables of the basic model

Decision Variables	
q_{ijkt}	Purchasing quantity of part k of equipment j supplied by supplier i in period t
x_{ijkt}	1, if $q_{ijk} > 0$, 0 otherwise

According to the above notations, the basic model are as follows:

Objective functions:

$$\min Z_1 = \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} C_{ijk}^{0}.q_{ijkt} \tag{1}$$

$$\min Z_2 = \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} q_{ijkt}.RI_i \tag{2}$$

$$\min Z_3 = \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} E(NR_{ijkt}).MTTR_{ijk}.E(C_{ijk}).q_{ijkt} \tag{3}$$

$$\min Z_4 = \sum_{t=1}^{T} (1 - R_t).C_{UR} \tag{4}$$

Subject to:

$$\sum_{j=1}^{J}\sum_{k=1}^{K} q_{ijkt} \leq Cap_i \qquad \forall\, i, t \tag{5}$$

$$\sum_{i=1}^{I} q_{ijkt} \geq D_{jkt} \qquad \forall\, j, k, t \tag{6}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} td_{ijk}.x_{ijkt} \leq TD_j \qquad \forall\, j\,, t \tag{7}$$

$$dt_{ijk}.x_{ijkt} \leq DT_{jk} \qquad \forall\, i, j, k, t \tag{8}$$

$$x_{ijkt} \leq q_{ijkt} \qquad \forall\, i, j, k, t \tag{9}$$

$$M.x_{ijkt} \geq q_{ijkt} \qquad \forall\, i, j, k, t \tag{10}$$

$$\sum\nolimits_{i=0}^{I} x_{ijkt} = 1 \qquad \forall\, j, k, t \tag{11}$$

$$x_{ijkt} \in \{0,1\} \qquad \forall\, i, j, k, t \tag{12}$$

$$q_{ijkt} \geq 0 \qquad \forall\, i, j, k, t \tag{13}$$

Eqs. 1 to 4 are the objective functions that minimize purchasing cost, risk measure, downtime cost, and unreliability cost of the production system, respectively. Constraint (5) guarantees that the quantity of products ordered from each supplier does not exceed its capacity. Constraint (6) ensures that the demand for each part is satisfied by suppliers. Constraint (7) assures that the total downtime of each part should be less than the maximum accepted downtime of that part. In constraint (8), if a part is purchased from a supplier, its delivery time should be less than the maximum accepted delivery time. Constraints (9) and (10) present the relation between x_{ijkt} and q_{ijkt}. Constraint (11) demonstrates each part must be provided by only one specific supplier. Finally, Eqs. 12 and 13 are non-negativity and integrality formulas.

Scenario 2 (PM$_m$)

This scenario is identical to PM$_s$, but then again, in PM$_m$ supply managers are allowed to divide purchasing quantity order between different maintenance suppliers—that is—a multi-sourcing strategy is used to satisfy the demand of each part. Therefore, all constraints and assumptions of the PM$_s$ model are still valid apart from constraint (11) and the last assumption.

Scenario 3 ($\mathrm{CBM_m}$)

Since the issue of inventory management is very important in this scenario, storage cost must be added to the objective function. As mentioned before, because the amount of the order in each period is different according to the inspections, the cost of ordering for each period must also be considered. New required parameters and variables are defined as follows:

Table 3. New parameters and variables

Input parameters	
I_{ijkt}	Mean inventory for part k of equipment j supplied by supplier i in period t
S_{jk}	Ordering cost for part k of equipment j
β	storage cost coefficient
Problem Variables	
q_{ijkt}	Purchasing quantity of part k of equipment j supplied by supplier i in period t
X_{ijkt}	1, if q_{ijkt} > 0, 0 otherwise
NS_{jkt}	The number of the ordering of part k of equipment j in period t

The first term, storage cost, is calculated as follows:

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} I_{ijkt}.\beta.C_{ijk}^{0}$$

Where β is the identical storage cost coefficient for all parts of all equipment and then $\beta.C_{ijk}^{0}$ is the storage cost per unit in each period. The second term, ordering cost, is calculated as follows:

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} S_{jk}.NS_{jkt}$$

These two new objective functions are added to the first previous objective function (Z_1). According to the aforementioned expressions, the new model is developed as follows:
Objective functions:

$$\min Z_1 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}(C_{ijk}^{0}.q_{ijkt}) + \left(I_{ijkt}.\beta.C_{ijk}^{0}\right) + (S_{jk}.NS_{jkt}) \tag{14}$$

$$\min Z_2 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} q_{ijkt}.RI_i \tag{15}$$

$$\min Z_3 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} E(NR_{ijkt}).MTTR_{ijk}.E(C_{ijk}).q_{ijkt} \tag{16}$$

$$\min Z_4 = \sum_{t=1}^{T}(1-R_t).C_{UR} \tag{17}$$

S.t constraints (5-10, 12, 13), and:

$$NS_{jkt} = \sum_{i=1}^{I} x_{ijkt} \qquad \forall\, j,k,t \tag{18}$$

$$I_{ijkt} = \frac{q_{ijkt}}{2} \qquad \forall\, i, j, k, t \tag{19}$$

Eqs. 14 to 17 are the objective functions and total purchasing cost—including storage and ordering cost—risk measure, downtime cost, unreliability cost of the production system, respectively. In constraint (18), the number of ordering each part to the suppliers is calculated. Constraint (19) denotes that the average amount of inventory is equal to the number of corresponding parts divided by 2. It should be noted that ordering and storage costs are also incorporated in two other scenarios, but for them the cost values are constant. It is assumed that whenever the condition of the equipment is degraded, and therefore we have to replace it, the replacement action will be delayed to the end of the current period.

Illustrative examples

To demonstrate the validity and reliability of the proposed model, a petrochemical case study is considered. Due to the fact that some required data is missed, some parameters are randomly generated. In this example, the system of production has three main sub-systems or more specific equipment. Each piece of equipment involves three parts that could be supplied by three suppliers. The planning horizon is a multi-period, so $t \in \{1,2,3\}$. The system works correctly if at least one piece of equipment of each type (1, 2, or 3) works flawlessly. Therefore, by applying the Universal Generating Function (UGF) technique [54], the total reliability of the system is calculated as follows:

$$R_t = \left(\sum_{j=1}^{3} P_{j1t}.\left(P_{j2t}^2 + 2P_{j2t}.\left(1 - P_{j2t}\right)\right).\left(P_{j3t}^3 + 3\left(1 - P_{j3t}\right).P_{j3t}^2 + 3\left(1 - P_{j3t}\right)^2.P_{j3t}\right)\right)/3 \tag{20}$$

Which, P_{jkt} indicates the weighted reliability of the k^{th} part of the j^{th} equipment in period t. The reliability of each part is dependent on the respective suppliers, so it is computed as a weighted average:

$$P_{jkt} = \sum_{n_j} Pr_{ijk}.q_{ijkt}/D_{jkt} \tag{21}$$

Where, Pr_{ijk} denotes the reliability of the k^{th} part of the j^{th} equipment supplied by i^{th} supplier. In this section, numerical examples are proposed to demonstrate the validity and applicability of the developed model. Three examples are presented in the next section. The first one belongs to the PM_s, the second one is concerned with PM_m, and the last one is about the CBM_m scenario. Finally, the results of each scenario are presented to have a comparative study among them.

Example one: PM$_s$

Because of using PM as a maintenance strategy in this scenario, the demands are the same in each period. It is worth noting that $C_{UR} = 15$. Moreover, only one supplier could be selected to provide the demand for each part.

Table 4. Demand of products in periods

D_{jkt}		Period 1, Parts			Period 2, Parts			Period 3, Parts		
		1	2	3	1	2	3	1	2	3
Equipment	1	80	120	60	80	120	60	80	120	60
	2	120	60	40	120	60	40	120	60	40
	3	80	40	120	80	40	120	80	40	120

Example two: PM$_m$

In the PM$_m$ scenario, the demand for products in all periods is precisely as identical as the ones in PM$_s$. The other parameters of both PM$_s$ and PM$_m$, including suppliers capacity, and Suppliers delivery time are presented in appendix I.

Example three: CBM

In the previous scenario, all parameters and assumptions are the same as the basic model except for the planning horizon. In the CBM strategy, the demands are different in each period. Besides, in this scenario, the ordering cost for part k of equipment j is added and $\beta = 0.2$. Table 5 shows the demand for each part for different periods.

Table 5. Demand of products in periods

D_{jkt}		Period 1, parts			Period 2, parts			Period 3, parts		
		1	2	3	1	2	3	1	2	3
Equipment	1	80	120	60	85	115	60	84	120	53
	2	120	60	40	117	53	47	124	53	41
	3	80	40	120	83	34	121	84	41	120

The ordering cost of each equipment parts is shown in Table 6.

Table 6. Ordering cost of products

S_{jk}		Parts		
		1	2	3
Equipment	1	50	45	40
	2	55	50	45
	3	60	55	50

As mentioned, these values are the constants for other scenarios. The other parameters are presented in Appendix.

Results and discussion

The Fuzzy Goal Programming (FGP) approach can be applied in order for supply chain management to attain a compromise solution for multi-objective problems. In order to apply FGP to solve the models, aspiration levels of each objective are calculated. Then, considering 300000, 5000, 300000, and 10—respectively—as Upper tolerance limit for Z_1 to Z_4 and $\lambda = 0.5$, the amounts of the objective function for FGP and also order quantities are calculated. The models are coded in GAMS software, and the results for the examples are shown in the following tables. Table 7 indicates the aspiration level of each objective.

Table 7. Aspiration levels of objective functions

Objective		Aspiration Level		
		PM$_s$	PM$_m$	CBM$_m$
Purchasing, ordering and storage cost	Z_1	287566.2	257742	288514.15
Risk of purchasing cost	Z_2	469.998	469.798	468.609
Downtime cost	Z_3	266104.92	268144.8	268133.7
Unreliability cost of the system	Z_4	0.881	0.909	0.901

For calculating the aspiration level of each objective, the corresponding single-objective model subject to all constraints was solved separately. Table 8 shows the objective function values of the FGP model.

Table 8. Results of the fuzzy goal programming model

Objective	Optimum Value		
	PM$_s$	PM$_m$	CBM$_m$
FGP	4.212	4.754	3.355
μ_{z1}	0.606	0.985	0.472
μ_{z2}	0.956	0.992	0.974
μ_{z3}	0.606	0.952	0.023
μ_{z4}	0.606	0.585	0.753

Table 8 denotes the value of the fuzzy goal programming model objective functions. It is noted that the fuzzy goal programming model aims to maximize the FGP value, which leads to minimizing Z_1, Z_2, Z_3, and Z_4 values. The results show the capability of the proposed model for solving the maintenance supplier selection problem while considering the LCC and supply chain risks. Order quantities for each scenario are presented in Tables 9 to 11 for PMs, PMm, and CBMm scenarios, respectively.

In line with Table 9, as expected, each part purchased from only one maintenance supplier, and demands in all periods are satisfied.

Table 9. Order quantities for PMs

		Supplier 1			Supplier 2			Supplier 3		
		q_{j1}	q_{j2}	q_{j3}	q_{j1}	q_{j2}	q_{j3}	q_{j1}	q_{j2}	q_{j3}
Period 1	q_{1k}	80	-	-	-	120	60	-	-	-
	q_{2k}	-	-	-	120	60	-	-	-	40
	q_{3k}	-	-	120	80	-	-	-	40	-
Period 2	q_{1k}	85	-	-	-	-	60	-	115	-
	q_{2k}	-	-	-	117	53	-	-	-	47
	q_{3k}	83	-	121	-	34	-	-	-	-
Period 3	q_{1k}	84	-	53	-	-	-	-	120	-
	q_{2k}	124	-	-	-	53	-	-	-	41
	q_{3k}	84	-	120	-	41	-	-	-	-

Table 10. Order quantities for PM_m

		Supplier 1			Supplier 2			Supplier 3		
		q_{j1}	q_{j2}	q_{j3}	q_{j1}	q_{j2}	q_{j3}	q_{j1}	q_{j2}	q_{j3}
Period 1	q_{1k}	80	20	-	-	100	60	-	-	-
	q_{2k}	100	-	-	20	60	-	-	-	40
	q_{3k}	80	-	20	-	40	-	-	-	100
Period 2	q_{1k}	60	20	-	20	100	60	-	-	-
	q_{2k}	90	-	-	30	60	10	-	-	40
	q_{3k}	80	-	30	-	40	-	-	-	90
Period 3	q_{1k}	80	20	20	-	100	40	-	-	-
	q_{2k}	100	20	-	20	40	-	-	-	40
	q_{3k}	80	-	40	-	40	-	-	-	80

According to Table 10, all demands are satisfied, and some of them, such as D_{121} and D_{211}, are provided from different suppliers.

Table 11. Order quantities for CBM_m

		Supplier 1			Supplier 2			Supplier 3		
		q_{j1}	q_{j2}	q_{j3}	q_{j1}	q_{j2}	q_{j3}	q_{j1}	q_{j2}	q_{j3}
Period 1	q_{1k}	80	20	-	-	100	60	-	-	-
	q_{2k}	100	-	-	20	60	-	-	-	40
	q_{3k}	80	-	20	-	40	-	-	-	100
Period 2	q_{1k}	85	15	-	-	100	60	-	-	-
	q_{2k}	100	-	-	17	53	-	-	-	47
	q_{3k}	83	-	21	-	34	-	-	-	100
Period 3	q_{1k}	84	20	-	-	100	53	-	-	-
	q_{2k}	100	-	-	24	53	-	-	-	41
	q_{3k}	84	-	20	-	41	-	-	-	100

According to Table 11, demands in all periods are satisfied, and they are also provided from different suppliers, and suppliers contribute to providing demands.

Comparative results

The comparative results are shown in Table 12 and Figs. 1 to 6.

Table 12. Summary of results

Value	PM_s	PM_m	CBM_m
FGP	4.212	4.7535	3.3545
μ_{z1}	0.606	0.985	0.472
μ_{z2}	0.956	0.992	0.974
μ_{z3}	0.606	0.952	0.023
μ_{z1}	0.606	0.585	0.753

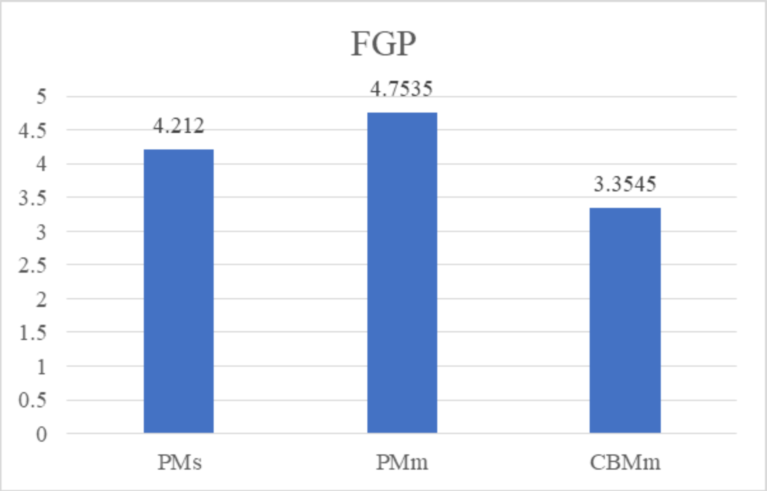

Fig. 1. Values for FGP

Since the FGP is a compromised value for multi objective models, it can be considered as a suitable criterion for organizations to choose proper maintenance strategy with multi-objective functions. According to Fig. 1, PM_m is the strategy which has the highest FGP value. Therefore, PM_m can be taken into account as an appropriate approach for the case study. Note that in different scenarios, other maintenance strategies may be selected as the preferred one.

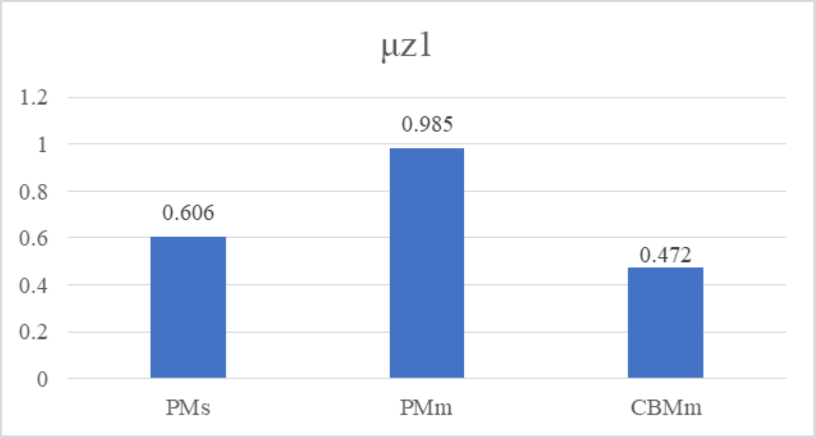

Fig 2. Values for purchasing, ordering and storage cost (μ_{Z1})

As Fig. 2 demonstrates, for companies where total purchasing cost (μ_{z1}) is more important than other measures, the PM_m strategy provides better results. PM_s and CBM_m are respectively in the next ranks.

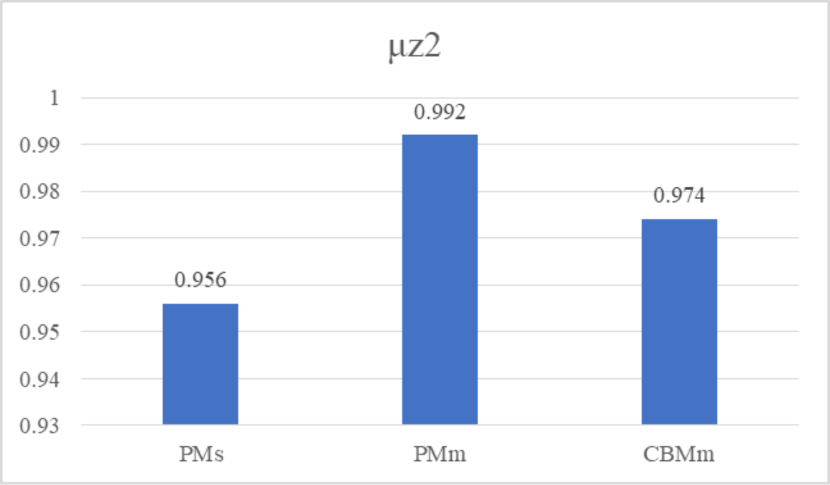

Fig. 3. Values for risk of purchasing cost (μ_{Z2})

On the other hand, Fig. 3 shows that, in preventive maintenance approach, by choosing multiple sourcing strategy rather than single sourcing, the risk measure criterion is improved by 0.046. Thus, referring to risk measure objective function, multiple sourcing strategy should be preferred instead of single sourcing strategy.

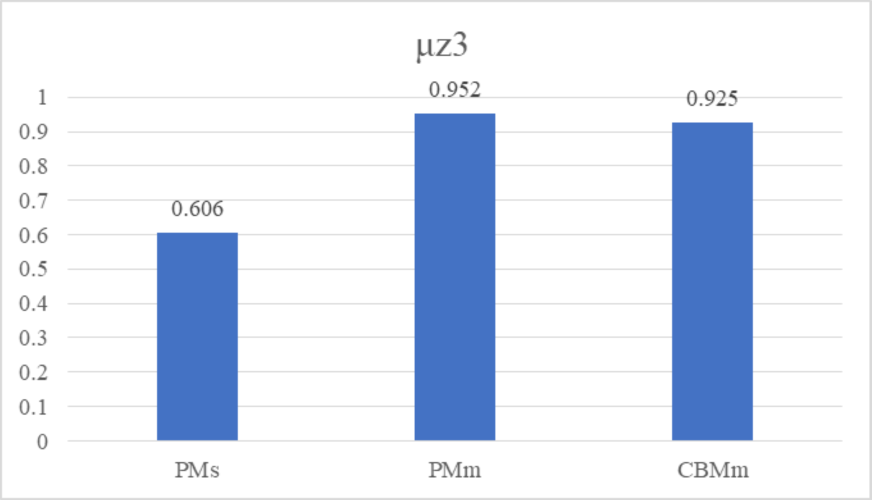

Fig. 4. Values for downtime cost (μ_{Z3})

Fig. 4 illustrates that multiple sourcing strategy also can bring about notable enhancement in terms of downtime cost.

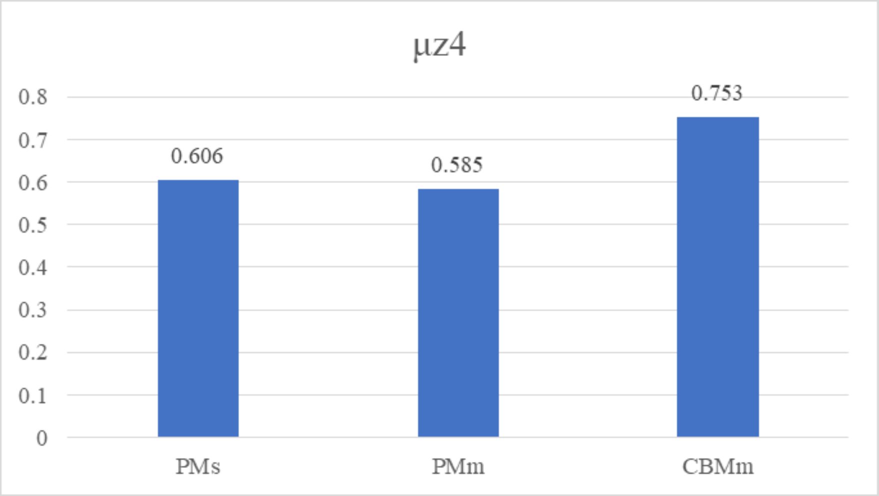

Fig. 5. Values for unreliability cost of the system (μ_{Z4})

According to Fig. 5, the fourth objective (unreliability costs) is the only criterion in which PM_m is not superior to other strategies. CBM_m is the preferable strategy to cope with the unreliability cost of the production system. Ultimately, in the industries in which the importance of unreliability risk of system outweighs other objective functions, supply chain managers may would rather CBM strategy with multiple sourcing policies.

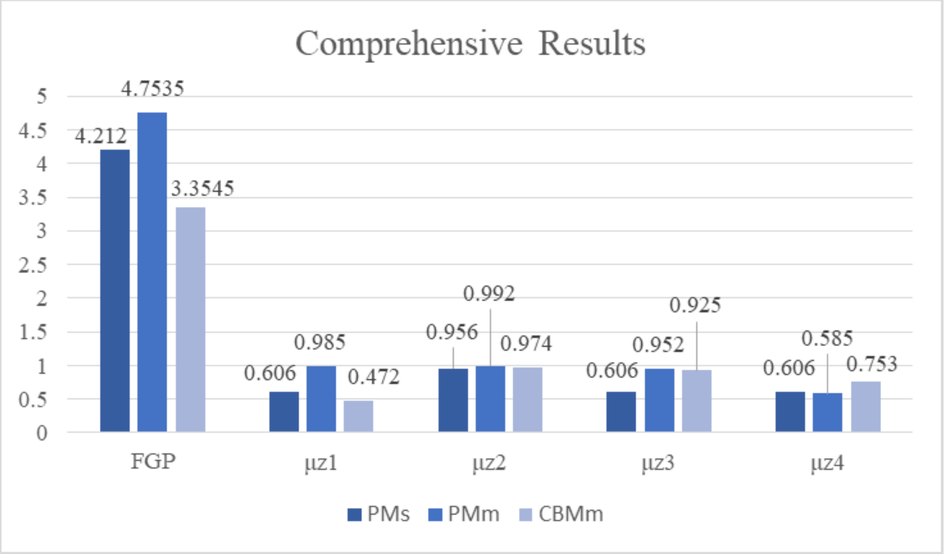

Fig. 6. Comparison of three scenarios

Altogether, we can conclude that for the proposed case study, PM_m is the preferred strategy. Noteworthy to mention if we consider various weights for objective functions, other maintenance strategies and sourcing policies may be selected as an optimum one.

Conclusion

In this paper, a maintenance supplier selection problem that considers total cost (including storage and ordering cost), risk measure, downtime cost, and unreliability cost of the production system is addressed. In the proposed model, the manufacturing system consists of some different multi-component (part) equipment, and a set of suppliers can provide the required parts. In order to compare different types of maintenance strategies and sourcing policies, three scenarios are considered: preventive maintenance with multiple and single supplier and condition-based maintenance. A multi-period mathematical model is formulated, and FGP is applied to handle four objective functions. The results show that apart from one of the objectives—that is unreliability costs—PM_m is the recommended strategy for the case study. It is worth noting that in some industries and plants– for instance, oil and gas, aviation, military and defense industries, and nuclear power plants – a failure in systems causes irreparable damage, which leads to considerable cost. This is why supply chain managers of these industries not only pay particular attention to the system reliability but also set that as the first priority among all the other objective functions. In the proposed model, the CMB strategy has the best performance according to the reliability measure. Thus, for future research and in case that one of the objective functions has higher priority, the weighted sum method can be applied. Also, uncertainty in determining some parameters, such as demand rate, delivery time, unreliability cost, and repair cost can be addressed in future studies.

References

[1] M. A. Nekooie, M. Sheikhalishahi, and R. Hosnavi, “Supplier selection considering strategic and operational risks: a combined qualitative and quantitative approach,” *Prod. Eng.*, vol. 9, no. 5–6, pp. 665–673, Dec. 2015, doi: 10.1007/s11740-015-0643-6.

[2] D. J. Thomas and P. M. Griffin, “Coordinated supply chain management,” *Eur. J. Oper. Res.*, vol. 94, no. 1, pp. 1–15, Oct. 1996, doi: 10.1016/0377-2217(96)00098-7.

[3] D. Masi, G. J. L. Micheli, and E. Cagno, “A meta-model for choosing a supplier selection technique within an EPC company,” *J. Purch. Supply Manag.*, vol. 19, no. 1, pp. 5–15, Mar. 2013, doi: 10.1016/j.pursup.2012.07.002.

[4] M. E. González, G. Quesada, and C. A. M. Monge, “Determining the importance of the supplier selection process in manufacturing: A case study,” *Int. J. Phys. Distrib. Logist. Manag.*, vol. 34, no. 6, pp. 492–504, 2004, doi: 10.1108/09600030410548550.

[5] M. A. Salam and S. A. Khan, “Achieving supply chain excellence through supplier management: A case study of fast moving consumer goods,” *Benchmarking*, vol. 25, no. 9, pp. 4084–4102, Nov. 2018, doi: 10.1108/BIJ-02-2018-0042.

[6] R. Verma and M. E. Pullman, “An analysis of the supplier selection process,” *Omega*, vol. 26, no. 6, pp. 739–750, Dec. 1998, doi: 10.1016/S0305-0483(98)00023-1.

[7] R. D. Banker and I. S. Khosla, “Economics of operations management: A research perspective,” *J. Oper. Manag.*, vol. 12, no. 3–4, pp. 423–435, Jun. 1995, doi: 10.1016/0272-6963(95)00022-K.

[8] M. A. Vonderembse and M. Tracey, “The Impact of Supplier Selection Criteria and Supplier Involvement on Manufacturing Performance,” *J. Supply Chain Manag.*, vol. 35, no. 3, pp. 33–39, Jun. 1999, doi: 10.1111/j.1745-493X.1999.tb00060.x.

[9] C. A. Weber, J. R. Current, and W. C. Benton, “Vendor selection criteria and methods,” *European Journal of Operational Research*, vol. 50, no. 1. North-Holland, pp. 2–18, Jan. 07, 1991, doi: 10.1016/0377-2217(91)90033-R.

[10] P. R. Kleindorfer and G. H. Saad, “Managing Disruption Risks in Supply Chains,” *Prod. Oper. Manag.*, vol. 14, no. 1, pp. 53–68, Jan. 2009, doi: 10.1111/j.1937-5956.2005.tb00009.x.

[11] A. Oke and M. Gopalakrishnan, “Managing disruptions in supply chains: A case study of a retail supply chain,” *Int. J. Prod. Econ.*, vol. 118, no. 1, pp. 168–174, Mar. 2009, doi: 10.1016/j.ijpe.2008.08.045.

[12] V. Babich, G. Aydin, P.-Y. Brunet, J. Keppo, and R. Saigal, “Risk, Financing and the Optimal Number of Suppliers,” *SSRN Electron. J.*, Dec. 2011, doi: 10.2139/ssrn.912679.

[13] D. G. Woodward, “Life cycle costing - Theory, information acquisition and application,” *Int. J. Proj. Manag.*, vol. 15, no. 6, pp. 335–344, Dec. 1997, doi: 10.1016/S0263-7863(96)00089-0.

[14] A. Kleyner and P. Sandborn, “Minimizing life cycle cost by managing product reliability via validation plan and warranty return cost,” *Int. J. Prod. Econ.*, vol. 112, no. 2, pp. 796–807, Apr. 2008, doi: 10.1016/j.ijpe.2007.07.001.

[15] M. Mathew, R. K. Chakrabortty, and M. J. Ryan, “Selection of an Optimal Maintenance Strategy Under Uncertain Conditions: An Interval Type-2 Fuzzy AHP-TOPSIS Method,” *IEEE Trans. Eng. Manag.*, pp. 1–14, Mar. 2020, doi: 10.1109/tem.2020.2977141.

[16] A. Rashidi Komeijan and M. Shabankareh, “Mathematical Model for Fleet Assignment with Maintenance and Aircraft Ramping Scheduling,” *Adv. Ind. Eng.*, vol. 52, no. 1, pp. 61–72, 2018.

[17] W. Wang and A. H. Christer, “Towards a general condition based maintenance model for a stochastic dynamic system,” *J. Oper. Res. Soc.*, vol. 51, no. 2, pp. 145–155, 2000, doi: 10.1057/palgrave.jors.2600863.

[18] S. Lu, Y.-C. Tu, and H. Lu, “Predictive condition-based maintenance for continuously deteriorating systems,” *Qual. Reliab. Eng. Int.*, vol. 23, no. 1, pp. 71–81, Feb. 2007, doi: 10.1002/qre.823.

[19] J. H. Shin and H. B. Jun, “On condition based maintenance policy,” *J. Comput. Des. Eng.*, vol. 2, no. 2, pp. 119–127, Apr. 2015, doi: 10.1016/j.jcde.2014.12.006.

[20] S. Alaswad and Y. Xiang, “A review on condition-based maintenance optimization models for stochastically deteriorating system,” *Reliab. Eng. Syst. Saf.*, vol. 157, pp. 54–63, Jan. 2017, doi:

10.1016/j.ress.2016.08.009.

[21] V. Veleva and M. Ellenbecker, “Indicators of sustainable production: Framework and methodology,” *J. Clean. Prod.*, vol. 9, no. 6, pp. 519–549, Dec. 2001, doi: 10.1016/S0959-6526(01)00010-5.

[22] A. Ristono, Pratikto, P. Budi Santoso, and I. Pambudi Tama, “A literature review of design of criteria for supplier selection,” *Journal of Industrial Engineering and Management*, vol. 11, no. 4. Universitat Politecnica de Catalunya, pp. 680–696, Oct. 10, 2018, doi: 10.3926/jiem.2203.

[23] N. Costantino and R. Pellegrino, “Choosing between single and multiple sourcing based on supplier default risk: A real options approach,” *J. Purch. Supply Manag.*, vol. 16, no. 1, pp. 27–40, Mar. 2010, doi: 10.1016/j.pursup.2009.08.001.

[24] W. Ho, T. Zheng, H. Yildiz, and S. Talluri, “Supply chain risk management: A literature review,” *International Journal of Production Research*, vol. 53, no. 16. Taylor and Francis Ltd., pp. 5031–5069, Aug. 18, 2015, doi: 10.1080/00207543.2015.1030467.

[25] I. Kilubi, “The strategies of supply chain risk management – a synthesis and classification,” *International Journal of Logistics Research and Applications*, vol. 19, no. 6. Taylor and Francis Ltd., pp. 604–629, Nov. 01, 2016, doi: 10.1080/13675567.2016.1150440.

[26] B. Fahimnia, C. S. Tang, H. Davarzani, and J. Sarkis, “Quantitative models for managing supply chain risks: A review,” *European Journal of Operational Research*, vol. 247, no. 1. Elsevier, pp. 1–15, Nov. 16, 2015, doi: 10.1016/j.ejor.2015.04.034.

[27] I. Heckmann, T. Comes, and S. Nickel, “A critical review on supply chain risk - Definition, measure and modeling,” *Omega (United Kingdom)*, vol. 52. Elsevier Ltd, pp. 119–132, Apr. 01, 2015, doi: 10.1016/j.omega.2014.10.004.

[28] D. Bandaly, L. Shanker, Y. Kahyaoglu, and A. Satir, “Supply chain risk management-II: A review of operational, financial and integrated approaches,” *Risk Management*, vol. 15, no. 1. Palgrave, pp. 1–31, Feb. 25, 2013, doi: 10.1057/rm.2012.8.

[29] I. Kilubi and H.-D. Haasis, “Supply chain risk management enablers-A framework development through systematic review of the literature from 2000 to 2015,” 2015. Accessed: Apr. 24, 2020. [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2728911.

[30] V. Rajagopal, S. Prasanna Venkatesan, and M. Goh, “Decision-making models for supply chain risk mitigation: A review,” *Computers and Industrial Engineering*, vol. 113. Elsevier Ltd, pp. 646–682, Nov. 01, 2017, doi: 10.1016/j.cie.2017.09.043.

[31] L. V. Snyder, Z. Atan, P. Peng, Y. Rong, A. J. Schmitt, and B. Sinsoysal, “OR/MS models for supply chain disruptions: A review,” *IIE Transactions (Institute of Industrial Engineers)*, vol. 48, no. 2. Taylor and Francis Ltd., pp. 89–109, Feb. 01, 2016, doi: 10.1080/0740817X.2015.1067735.

[32] C. Elock Son, “Supply Chain Risk Management: A Review of Thirteen Years of Research,” *Am. J. Ind. Bus. Manag.*, vol. 08, no. 12, pp. 2294–2320, Dec. 2018, doi: 10.4236/ajibm.2018.812154.

[33] M. V. C. Fagundes, E. O. Teles, S. A. B. Vieira de Melo, and F. G. M. Freires, “Decision-making models and support systems for supply chain risk: literature mapping and future research agenda,” *Eur. Res. Manag. Bus. Econ.*, Mar. 2020, doi: 10.1016/j.iedeen.2020.02.001.

[34] S. H. Zegordi and H. Davarzani, “Developing a supply chain disruption analysis model: Application of colored Petri-nets,” in *Expert Systems with Applications*, Feb. 2012, vol. 39, no. 2, pp. 2102–2111, doi: 10.1016/j.eswa.2011.07.137.

[35] G. P. Cachon and M. A. Lariviere, “Supply Chain Coordination With Revenue-Sharing Contracts: Strengths and Limitations,” *pubsonline.informs.org*, vol. 51, no. 1, pp. 30–44, Jan. 2005, doi: 10.1287/mnsc.1040.0215.

[36] H. Song and X. Gao, “Green supply chain game model and analysis under revenue-sharing contract,” *J. Clean. Prod.*, vol. 170, pp. 183–192, Jan. 2018, doi: 10.1016/j.jclepro.2017.09.138.

[37] J. Clausen, J. Larsen, A. Larsen, and J. Hansen, “Disruption management-operations research between planning and execution,” *Or/ms Today*, vol. 28, no. 5, pp. 40–43, 2001, Accessed: Apr. 24, 2020. [Online]. Available: https://www.academia.edu/download/30969045/404.pdf.

[38] X. Qi, Jonathan F. Bard, and Gang.Yu., “Supply chain coordination with demand disruptions,”

Omega, vol. 32, no. 4, pp. 301–312, 2004, Accessed: Apr. 24, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0305048303001658.

[39] M.-C. Yu and M. Goh, "A multi-objective approach to supply chain visibility and risk," *Eur. J. Oper. Res.* , vol. 233, no. 1, pp. 125–130, Feb. 2014, Accessed: Apr. 24, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0377221713007212.

[40] S. DuHadway, S. Carnovale, and B. Hazen, "Understanding risk management for intentional supply chain disruptions: risk detection, risk mitigation, and risk recovery," *Ann. Oper. Res.*, vol. 283, no. 1–2, pp. 179–198, Dec. 2019, doi: 10.1007/s10479-017-2452-0.

[41] H. L. Lee and W. Michael, "Supply Chain Security Without Tears," *SUPPLY Chain Manag. Rev.*, vol. 7, no. 3, pp. 12–120, Jan. 2003, Accessed: Apr. 24, 2020. [Online]. Available: https://trid.trb.org/view/623920.

[42] C. Speier, J. M. Whipple, D. J. Closs, and M. D. Voss, "Global supply chain design considerations: Mitigating product safety and security risks," *J. Oper. Manag.*, vol. 29, no. 7–8, pp. 721–736, Nov. 2011, doi: 10.1016/j.jom.2011.06.003.

[43] C. Colicchia, A. Creazza, C. Noè, and F. Strozzi, "Information sharing in supply chains: a review of risks and opportunities using the systematic literature network analysis (SLNA)," *Supply Chain Management*, vol. 24, no. 1. Emerald Group Publishing Ltd., pp. 5–21, Jan. 14, 2019, doi: 10.1108/SCM-01-2018-0003.

[44] G. Lu, X. Koufteros, S. Talluri, and G. T. M. Hult, "Deployment of Supply Chain Security Practices: Antecedents and Consequences," *Decis. Sci.*, vol. 50, no. 3, pp. 459–497, Jun. 2019, doi: 10.1111/deci.12336.

[45] L. Mikhailov, "Fuzzy analytical approach to partnership selection in formation of virtual enterprises," *Omega*, vol. 30, no. 5, pp. 393–401, Oct. 2002, doi: 10.1016/S0305-0483(02)00052-X.

[46] V. Jain, S. Wadhwa, and S. G. Deshmukh, "Select supplier-related issues in modelling a dynamic supply chain: Potential, challenges and direction for future research," *Int. J. Prod. Res.*, vol. 47, no. 11, pp. 3013–3039, Jan. 2009, doi: 10.1080/00207540701769958.

[47] C. H. Glock, E. H. Grosse, and J. M. Ries, "Reprint of 'Decision support models for supplier development: Systematic literature review and research agenda,'" *Int. J. Prod. Econ.*, vol. 194, pp. 246–260, Dec. 2017, doi: 10.1016/j.ijpe.2017.11.006.

[48] W. Ho, X. Xu, and P. K. Dey, "Multi-criteria decision making approaches for supplier evaluation and selection: A literature review," *Eur. J. Oper. Res.*, vol. 202, no. 1, pp. 16–24, Apr. 2010, doi: 10.1016/j.ejor.2009.05.009.

[49] L. A. Ocampo, G. K. M. Abad, K. G. L. Cabusas, M. L. A. Padon, and N. C. Sevilla, "Recent approaches to supplier selection: A review of literature within 2006–2016," *Int. J. Integr. Supply Manag.*, vol. 12, no. 1–2, pp. 22–68, 2018, doi: 10.1504/IJISM.2018.095683.

[50] C. Lin and H. Kuo, "Multiple Comparisons with the Best for Supplier Selection," *Qual. Reliab. Eng. Int.*, vol. 30, no. 7, pp. 1083–1092, Nov. 2014, doi: 10.1002/qre.1599.

[51] X. G. Huang, Y. S. Wong, and J. G. Wang, "A two-stage manufacturing partner selection framework for virtual enterprises," *Int. J. Comput. Integr. Manuf.*, vol. 17, no. 4, pp. 294–304, Jun. 2004, doi: 10.1080/09511920310001654292.

[52] F. Çebi and I. Otay, "A two-stage fuzzy approach for supplier evaluation and order allocation problem with quantity discounts and lead time," *Inf. Sci. (Ny).*, vol. 339, pp. 143–157, Apr. 2016, doi: 10.1016/j.ins.2015.12.032.

[53] J. Chai and E. W. T. Ngai, "Decision-making techniques in supplier selection: Recent accomplishments and what lies ahead," *Expert Systems with Applications*, vol. 140. Elsevier Ltd, p. 112903, Feb. 01, 2020, doi: 10.1016/j.eswa.2019.112903.

[54] Y. Ding and A. Lisnianski, "Fuzzy universal generating functions for multi-state system reliability assessment," *Fuzzy Sets Syst.*, vol. 159, no. 3, pp. 307–324, Feb. 2008, doi: 10.1016/j.fss.2007.06.004.

Appendix

Table A.1. Demand of products

D_{jk}		Parts		
		1	2	3
Equipment	1	80	120	60
	2	120	60	40
	3	80	40	120

Table A.2. Capacity of the suppliers

Supplier	Capacity
1	500
2	450
3	420

Table A.3. Supplier's delivery time (dt_{ijk})

dt_{jk}	Supplier 1			Supplier 2			Supplier 3		
	dt_{j1}	dt_{j2}	dt_{j3}	dt_{j1}	dt_{j2}	dt_{j3}	dt_{j1}	dt_{j2}	dt_{j3}
dt_{1k}	8	7	12	13	10	7	11	17	10
dt_{2k}	9	15	7	10	6	8	6	11	16
dt_{3k}	7	12	16	12	8	8	16	11	10

Maximum accepted delivery time= 16 for all parts

Table A.4. Downtimes (td_{ijk})

td_{jk}	Supplier 1			Supplier 2			Supplier 3		
	td_{j1}	td_{j2}	td_{j3}	td_{j1}	td_{j2}	td_{j3}	td_{j1}	td_{j2}	td_{j3}
td_{1k}	14	6	6	15	6	10	7	15	15
td_{2k}	11	7	8	8	12	9	9	11	6
td_{3k}	12	15	7	12	14	10	11	13	12

Maximum accepted downtime= (2880,5760, 3760) for equipment

Table A.5. Expected number of repairs ($E[NR_{ijkt}]$)

$E[NR_{jkt}]$		Supplier 1			Supplier 2			Supplier 3		
		NR_{j1}	NR_{j2}	NR_{j3}	NR_{j1}	NR_{j2}	NR_{j3}	NR_{j1}	NR_{j2}	NR_{j3}
Period 1	NR_{1k}	0.55	0.52	0.49	0.52	0.50	0.48	0.49	0.46	0.43
	NR_{2k}	0.51	0.48	0.46	0.49	0.46	0.45	0.46	0.43	0.40
	NR_{3k}	0.48	0.46	0.43	0.46	0.44	0.43	0.43	0.40	0.38
Period 2	NR_{1k}	0.54	0.49	0.52	0.50	0.51	0.48	0.43	0.49	0.46
	NR_{2k}	0.46	0.51	0.48	0.45	0.49	0.46	0.40	0.43	0.46
	NR_{3k}	0.43	0.48	0.46	0.43	0.46	0.44	0.38	0.43	0.40
Period 3	NR_{1k}	0.52	0.50	0.48	0.55	0.52	0.49	0.52	0.50	0.48
	NR_{2k}	0.49	0.46	0.45	0.51	0.48	0.46	0.49	0.46	0.45
	NR_{3k}	0.46	0.44	0.43	0.48	0.46	0.43	0.46	0.44	0.43

Table A.6. Mean time to repair ($MTTR_{ijk}$)

$MTTR_{jk}$	Supplier 1			Supplier 2			Supplier 3		
	$MTTR_{j1}$	$MTTR_{j2}$	$MTTR_{j3}$	$MTTR_{j1}$	$MTTR_{j2}$	$MTTR_{j3}$	$MTTR_{j1}$	$MTTR_{j2}$	$MTTR_{j3}$
$MTTR_{1k}$	5.00	4.75	4.50	4.80	4.56	4.42	4.51	4.20	3.90
$MTTR_{2k}$	4.65	4.42	4.19	4.46	4.24	4.11	4.20	3.90	3.63
$MTTR_{3k}$	4.40	4.18	3.96	4.22	4.01	3.89	3.97	3.69	3.43

Table A.7. Parts reliabilities (pr_{ijk})

pr_{jk}	Supplier 1			Supplier 2			Supplier 3		
	pr_{j1}	pr_{j2}	pr_{j3}	pr_{j1}	pr_{j2}	pr_{j3}	pr_{j1}	pr_{j2}	pr_{j3}
pr_{1k}	0.96	0.69	0.89	0.69	0.92	0.96	0.72	0.83	0.86
pr_{2k}	0.97	0.74	0.70	0.88	0.90	0.77	0.67	0.82	0.87
pr_{3k}	0.93	0.77	0.90	0.82	0.96	0.89	0.91	0.96	0.95

Table A.8. Expected value of the repair cost (C_{ijk})

C_{jk}	Supplier 1			Supplier 2			Supplier 3		
	C_{j1}	C_{j2}	C_{j3}	C_{j1}	C_{j2}	C_{j3}	C_{j1}	C_{j2}	C_{j3}
C_{1k}	79	65	53	80	66	57	79	63	50
C_{2k}	78	64	52	79	64	56	77	61	48
C_{3k}	78	63	51	78	64	55	76	60	47

Table A.9. Purchasing price (C_{ijk}^0)

C_{jk}^0	Supplier 1			Supplier 2			Supplier 3		
	C_{j1}^0	C_{j2}^0	C_{j3}^0	C_{j1}^0	C_{j2}^0	C_{j3}^0	C_{j1}^0	C_{j2}^0	C_{j3}^0
C_{1k}^0	115.9	104.3	93.9	127.5	114.7	103.2	139.0	125.1	112.6
C_{2k}^0	127.5	114.7	103.2	140.2	126.2	113.6	153.0	137.7	123.9
C_{3k}^0	140.2	126.2	113.6	154.2	138.8	124.9	168.2	151.4	136.3

Table A.10. Weights of risks for each supplier

Risks	Supplier 1	Supplier 2	Supplier 3
Supplier bankruptcy	0.06	0.014	0.0056
War and terrorism, man-made disasters	0.0245	0.069	0.02383
Excessive handling due to border crossing or to change in transportation modes	0.0040	0.022	0.0419
Cost uncertainty	0.0316	0.0128	0.0095
Exchange rate risk	0.0114	0.0577	0.0868
Data information security risks and legal risks	0.0159	0.0618	0.1283
Natural disasters	0.0437	0.0405	0.0206
Total	0.1911	0.2778	0.531