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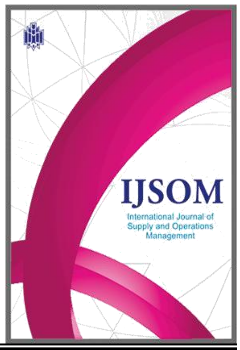

Aircraft Component Spare Parts Logistics and Operation Planning: A Case Study in FARSCO Aircraft MRO Center

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Abstract

In this research, spare parts logistics in the aviation industry has been investigated. Since each aircraft consists of several components such as landing gear, engines, fuselages, propeller, wings, etc., the availability, ordering, and delivery of them are important during aircraft repair and maintenance operations and delays in supplying component spare parts will have a direct impact on the delivery of aircraft. This paper aims to optimize a supply of component spare parts using a programming model considering minimize the holding and purchasing costs. Due to the shortage of spare parts plays a key role in increasing the turnaround time of the aircraft, penalties for delay in delivery of the parts have been considered. Moreover, two critical constraints including the purchase budget and repair capacity which are rarely mentioned in the previous papers have been noted in this research. FARSCO aviation maintenance & overhaul center as the biggest dedicated Maintenance, repair and overhaul center in the Middle East has been considered in this paper as the case study. Based on its capabilities, FARSCO provides various services to all Iranian airlines and almost 90% of domestic airlines send their aircraft to this maintenance center for performing light and heavy checks and maintenance. The proposed model was verified and solved by using CPLEX solver and is constructed for the case by considering the numerical data. The results are obtained in two average demand and pessimistic modes (worst case scenario). Finally, a sensitivity analysis of the model is carried out to investigate the applicability of the problem. Results demonstrate the optimal number of maintenance jobs that can be completed to deliver at each period, as well as the order quantity of spare parts and the shortages of spare parts which are important for managers to deliver aircraft to the customers on time.

Keywords: Aircraft; Maintenance, Repair and Overhaul center; Component; modules; Mathematical programming model.

1. Introduction

Efficient inventory management is one of the most crucial factors with a direct impact on providing timely services by airlines. One of the most important types of inventory in the aviation industry, which has a direct relation to the aircraft delivery time, is the inventory of modules. Modules that contain components are more expensive than other parts, which must get overhauled by MRO centers*. The repair and overhaul process of these modules is continuously repeated, and after each repair process, they are installed on the aircraft. Due to the importance of the availability of aircraft and its delivery according to the agreed schedule, delays in repair and delivery of required modules will increase the delivery time of the aircraft (aircraft turnaround time), delays in the delivery of aircraft and impose additional costs (Aviation week, 2009). Therefore, the maintenance and repair centers devote all their planning and efforts to reduce costs and time associated with modules repairs. To reduce TAT†, aircraft repair and overhaul companies send the serviceable modules that need repairs either to a repair center or replace that specific module with other modules in stock and run a so-called

* Maintenance Repair Overhaul (MRO)
† Turn Around Time(TAT)

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replacement program. In this case, the aircraft does not wait for that particular service component's supply, and the service time is simply for removing and replacing the aircraft modules with a similar service module in stock. At the same time, aircraft repair and overhaul companies repair unserviceable modules in their repair centers or send them or their components that need to be repaired to repair centers outside the company. These components will return to these centers after repairs and will be used as inventory of serviceable modules in future projects.

Because in this research a dedicated aviation MRO center has been considered as a case study, all the processes and procedures related to aircraft maintenance which has been executed in the case study are noted. So based on this MRO center procedures, after the modules are delivered, the company based on its repair capabilities test, supplying the requirements, Reassembly, and final testing of the modules gives the repair schedule and delivery time to the airlines. In presenting this schedule, the average time expected for spare items delivery to repair the modules or required components is considered according to the aircraft repair program and the preparation needs for aircraft release from repair hangars. In the case of delay in the delivery of required spare items, the aircraft repair center must pay a fee as a penalty for delay. These delays are mainly due to the delayed delivery of the spare items and the lack of manpower, equipment, etc. Because of the issues stated above and to model the problem, a mathematical programming model is presented in this paper considering definite demand to minimize the cost of purchasing spare items, inventory maintenance, and the penalty cost for late delivery of modules. Also, two critical constraints, including the budget for the purchase of spare parts and the repair capacity of the model, will be considered to become more realistic and closer to the real-world situation in aircraft repair and overhaul centers. The main difference between this modeling and previously proposed models is that in this case, the demand for serviceable modules that need repairing has transformed into a need for spare parts. Therefore, in this paper's objective function, due to the importance of supplying and ordering the required components and spare items, instead of considering the maintenance and delay cost for the modules, maintenance costs of purchased spare parts, and delay cost in the delivery of spare parts ordered from suppliers is considered.

Since the modeling of the problem has been considered the case study conditions, a description of the case study, FARSCO aviation maintenance center as the biggest MRO center with an area of 54,000 square meters, the operational hangar is the largest hangar in the Middle East, will be provided of this paper. FARSCO based on its capabilities provide various services to all Iranian airlines and almost 90% of domestic airlines send their aircraft to this maintenance center for performing light and heavy checks and maintenance. Moreover, FARSCO has become one of the leading companies among wide-body aircraft maintenance centers, especially in the area of the overhaul of Boeing 747. Recently and based on the market conditions, FARSCO has developed its capabilities in order to increase its market share in international aviation market. So, one of the main and biggest advantages of the present paper is to consider the real conditions in FARSCO as the case study. The remaining sections of this article, which will be organized as follows: Section 2 reviews the subject literature and related work. The third section describing the proposed model with model assumptions, parameters, model indices, and decision variables. In the fourth section, the mathematical model is presented with explanations for the objective function and constraints. In the rest of the section, a numerical example and sensitivity analysis for the model are given. Finally, in the fifth section, conclusions and suggestions for future research are stated.

2. Literature review

In this section, considering the topic in this study, some of the most important researches done in the field of provisioning of spare parts and components and inventory models in the aircraft MRO industry will be reviewed and the articles will be evaluated and analyzed. One of the first studies to discuss the serviceable components inventory was conducted (2000) by Rupp et al. In this study, they assumed that the demand entry rate follows a Poisson process. A simulation was the method used in this paper to solve the problem. This study focused on inventory management and did not consider demand management or production planning. LUH et al. (2005) proposed a mathematical scheduling model in which the issue of inventory control and replacement programs was considered in an integrated manner. As a solution method, the Lagrange release scheme was proposed. Delays are allowed in this approach, but there is a penalty. The main goal of this study was to minimize delays by considering alternative policies. In another study (2008) by Kumanakos titled "impact of inventory management on corporate performance", assumptions that led to inventory management efficiency and corporate financial performance improvement were tested and evaluated. This study's data were collected from large companies in Greece that operated in the food, textile, and chemical industries. Preliminary results of this study, analyzed by linear regression, showed that the higher the level of stored inventory, the lower the efficiency. Joo (2009) considered an alternative scheduling model for components. The study presented an alternative timeline for serviceable retables/components of a specific aircraft type (one of South Korea's military fleet). The expected repair and overhaul time was determined for the aircraft and the model was designed in a way so the components were sent to the repair center before the overhaul deadline, considering the limited number of components in stock. Therefore, the proposed model was developed to minimize this interval. A polynomial-time algorithm is used to solve the model, optimize the replacement times, and overhaul processes.

Kilpi (2009) specified cooperative strategies for the availability service of repairable aircraft components and finds out which factors contribute to the emergence of a particular cooperative strategy. A simulation model based on fair assumptions of the cost structure was constructed and the cooperative strategies were tested in a game-theoretic setting both from the viewpoint of total efficiency and from the perspective of each participant. Joo and Maine (2011) in another research developed the same issue of retables/ components with consideration of budget constraints. They also proposed a multi-objective programming model with a goal programming solution approach. Four hypotheses were considered in their research: (1) Due to changes in demand, the Repair schedule got divided into several periods. (2) The number of components to be sent for repairs in each period was determined at the beginning of the period. (3) Limits were set for the number of components sent to repair centers in each period. (4) Components were shipped for repairs before the due date.

In another study, Arts and Flapper (2015) provided an integrated production programming model that simultaneously focused on inventory and labor force planning in a long-term planning horizon. In this model, time limits were monthly and annually, and it was assumed that the level of manpower capacity and related costs can be changed only at the beginning of each year. The proposed model did not pay attention to the exact time request for serviceable components and instead focused on meeting the demands monthly through different levels of work. The goal defined in the proposed model was to minimize inventory, materials, parts, and labor costs and it was attempted to evaluate the level of manpower in each period to determine the total required capacity for repair operations. A recent study by Erkoc and Ertogel (2015) conducted a study on retables and alternative planning. They presented an integer programming model that could determine the best time to start overhauling component parts and the best time to replace them. The model's goal was to minimize the intervals between the time required to replace retables and the scheduled replacement date limit. The model considered only one type of component with a specific time for repair and overhaul. An exact algorithm was proposed to solve the model. Considering just one component type and not paying attention to the workforce capacity were among the shortcomings in this research. Other factors not considered in this model are the delay cost for late delivery and budget constraints. For this model's development, Erkoc and Ertogel (2016) considered component types in a limited planning horizon instead of a single component. Similar to the previous research, the goal was minimizing the interval between the time required to replace items and the scheduled replacement date. The proposed model was examined and tested with numerous numerical examples. Wijk et al (2017) presented a novel approach for cost-effective optimization of stop-maintenance strategies for a set of repairable items. The optimization method had two steps. First, the novel concept of matrix simulations was introduced to locate the solution space of the optimization problem in question. Second, a genetic algorithm was applied to find the minimum cost solution. Their proposed method was faster than the crude search and also located the optimum more often than the steepest descent search.

Mansik et al (2018) considered an inventory control problem of aircraft spare parts during the end-of-life (EOL) phase of fleet operations. In this research, they presented an algorithm that computes the optimal final order size of components under a budget constraint. By modeling the remaining part inventory as a continuous-time Markov chain, they developed analytical solutions using differential equations for single and two-item cases. In another study regarding provisioning spare parts by Katarzyna and et al (2019) concentrated on the provisioning of spare parts and its role in sustaining an anticipated operational competitiveness level via efficient and effective maintenance of machinery. In the paper, they have considered the factors related to the maintenance, logistics, and criticality levels. Also at the second part of their research, they have presented how to perform spare part prioritization within a selected group, via an analytic hierarchy process (AHP), to minimize ad hoc suboptimal assessments, together with sensitivity analyses. Auweraer and Boute (2019) developed a method to forecast the demand for critical spare parts by linking it to the service maintenance policy. By tracking the active installed base and estimating the part failure behavior, they provided a forecast of the distribution of the future spare parts demand during the upcoming lead time. Through a simulation experiment, they showed that their method has the potential to improve the inventory-service trade-off. In another research which has been done by Auweraer (2019) they reviewed the literature on the use of such installed base information for spare part demand forecasting to asses (1) what type of installed base information can be useful; (2) how this information can be used to derive forecasts; (3) the value of using installed base information to improve forecasting; and (4) the limits of the existing methods. In another research, Chen et al (2019) proposed the clustering of MRO parts into different groups and discuss the potential strategy to improve inventory management efficiency by leveraging emerging technologies for each MRO part group. Al-Momani et al (2020) aimed to establish a local, affordable, high quality, reliable, and adaptive inventory management system which manages and improves inventory in the military aviation industry (Air forces). The aim of the new system was to improved aircraft fleet serviceability, reliability, and readiness to enhance the operational status and level of readiness at the least possible costs. Results showed improved components, increased serviceability, availability, and reliability, decreased costs, and decreased Aircraft on Ground (A.O.G.).

Wakiru et al (2021) developed an integrated methodology to optimize maintenance, remanufacturing, and multiple spare strategies (new and remanufactured exchange) jointly, for life extension of an aging multi-component system with dependencies. The model inculcated the asymmetric relationship to assist the end-user to derive decision support on optimal maintenance and remanufacturing strategies while minimizing the costs. The study showed that the approach offers robust decision support, and further demonstrates the significance of the maintenance function and end-user influence in the remanufacturing decision making. Ramaganesh et al (2021) provided a multi-objective model for spare parts optimization. Spare parts which were critical were categorized in condition based replacement method, for those critical equipment remaining useful life (RUL) (i.e. Decision variable) was determined to find the actual degradation state level. Spare parts which were non-critical & having longer life time were categorized under age based replacement method. By taking case studies in the pharmacy industry, the model and technique were demonstrated by a numerical illustration.

Summarizing the review presented above, it could be said that the papers were mainly on the optimization of retables/ modules problem with considering types of costs and solution problems. Thus, the main difference between the modeling proposed in this study and previous problems is that in this case, the demand for serviceable modules/components that need repairing has transformed into a need for spare parts. Therefore, in this paper's objective function, due to the importance of supplying and ordering the required components and spare items, instead of considering the maintenance and delay cost for the modules, maintenance costs of purchased spare parts, and delay cost in the delivery of spare parts ordered from suppliers is considered.

3. Problem Setup

Since the modeling of the problem has been considered the case study conditions, a description of the case study, FARSCO aviation maintenance center is provided first. FARSCO is responsible for providing various services to the country's aviation fleet in the field of major repair (overhaul) and other periodic and maintenance services in compliance with international standards at the level of leading and advanced companies. With an area of 54,000 square meters, the operational hangar is the largest hangar in the Middle East, which includes 40,000 square meters of hangar space and 14,000 square meters of support workshops, and can accommodate 4 Boeing 747s and 2 Airbus 300s at the same time. Due to its extensive activity in the field of aircraft maintenance, this company has become one of the leading companies among wide-body aircraft maintenance centers, especially in the area of the overhaul of Boeing 747, as well as modernization and optimization of some sensitive aircraft systems such as optimization of avionic systems of Boeing 747.

As the largest specialized center for maintenance, repair, and overhaul in the country based on available facilities and equipment as well as approvals obtained from Iran Civil Aviation Organization, FARSCO can provide services to all aircraft in the domestic fleet and all airline companies are among its main customers. Presently, up to 90% of the market share in the field of maintenance, repair, and overhaul of commercial aircraft belongs to this company. Recently and based on market conditions, FARSCO has developed its capabilities on aircraft components and modules. Due to this capability and offer competitive prices compared to the competitors, all airlines prefer to send their components such as landing gear, heat exchangers, hydraulic modules, avionic components to FARSCO. When an aircraft of each airline enter the operational hangar, in addition to light and heavy checks which consist of inspections of the interior, exterior, fuselage, engine, accessories, and other equipment's of aircraft, maintenance services and repairs (for example, aircraft landing gear) are also provided for that aircraft.

The serviceable module consists of a significant number of components and parts. When the repair shop (FARSCO repair shops) receives serviceable modules for repair, open it and check the components (parts) in it, and case of failure, request parts supply. In this case, there are two cases as the following: first, the parts are available in the warehouse. In this case and after submitting the request by the relevant shop, those parts are received from the warehouse and the components are repaired in the shortest possible time. Second, if the required parts are not available in the warehouse, a request to purchase and order the parts will be issued to suppliers outside the company. Finally, after supplying the required parts (which may be specified in the schedule and without delay or due to late delivery of the required items, lead to delays in repair and delivery), the components are repaired. Since each module has a large number of non-identical components, MRO center may encounter significant volumes of non-identical demands of components at different times. Therefore, when various requests are submitted by customers (airlines), a significant amount of repair requests for various types of modules and their internal components is created. Within this condition, The MRO repair centers should place an order on the spare parts needed to repair the components and put them on the modules.

Due to the importance of inventory of spare items for serviceable components and module repair, planning for spare items has been considered in this study. Based on the factors mentioned above and to model the problem, a mathematical planning model considering definite demand to minimize the cost of purchasing spare items, inventory maintenance, and the cost of fines for late delivery will be presented. Also, two critical constraints, including the budget for the purchase of spare items and the repair capacity of the model, will be considered to become more realistic and closer to the real-world situation in aircraft repair and overhaul centers. Therefore, in this paper's objective function, due to the importance of supplying and ordering the required components and spare items, instead of considering the maintenance and delay cost for the modules, maintenance costs of purchased spare parts, and delay cost in the delivery of spare parts ordered from suppliers is considered. In short, the remaining assumptions of our model are described as follows:

- It is assumed that FARSCO as MRO center receives a specific type of serviceable module (for example, landing gear) to carry out repairs in its repair shops during the designated planning horizon.
- The modules assigned to FARSCO for repair consist of several independent components, and their conditions do not affect each other.
- Planning horizon (for example, one year) and the number of intervals (for example, 12 months) are considered in the problem.
- After checking the module in repair shops, defective components are identified and removed from the module. After the initial inspection of the components, the required parts are identified, and requests are issued to either supply from the warehouse or to purchase from suppliers.
- Defective components are repaired after supplying the required parts, and finally, components are assembled on the serviceable module for installation on the aircraft. The failure rate of each component is assumed specific and independent of the failure rate in other components of the modules.
- It is assumed that if, for example, FARSCO receives ten modules in the first planning period, with a delivery date of three months, the airline's demand at the end of the third month is equal to ten serviceable modules.
- The number of modules that FARSCO is obligated to deliver in each period is interpreted as the sales number. Any delay in the delivery of modules is considered a shortage. It is worth mentioning that the serviceable module, which is not repaired in the planned period due to the lack of items, will be delivered to customers (airlines) in the next period, with the delay cost.
- The time required to repair the serviceable module agreed with the customer is based on the time required to replace the defective parts with working ones and the assembly time.
- Delay in each period depends on the components with the highest delay rate. For example, if in a planning period two parts are needed for the first component, four parts for the second component, and six parts for the repair of the third component; FARSCO as a repair center will face a delivery delay of six parts.

To model the discussed problem, we first define the following notations. The indices are shown in table 1, the parameters are shown in table 2.

Table 1. Indices

Index	definition
$t \in T$	Symbol of the time period
$c \in C$	Symbol of components

Table 2. Indices

Parameter	Definition
l_c^p	Time set for purchasing the component c
h_c	Holding cost of component c
SS_c	Safety stock of component c
b	Unit of penalty cost for late delivery of serviceable modules
d_{ct}	Demand for component c in period t
p_c	Purchase price of component c
M_{ct}	Maximum supply capacity to prepare component c in period t
L_t	The amount of budget available in period t
α_c	Consumption factor (Manpower/ machine) for performing the repair on component c
E_c	The amount of resource available (Manpower/machine) to replace component c in period t

Table 3. Decision variables

Decision variables	Definition
Q_{ct}^{P}	Number of component c to be ordered in period t
l_{ct}	Number of components available on the stock in period t
Q_{ct}^{d}	Number of component c that can be delivered for assembly on the modules in period t
B_{ct}^{d}	Shortage of component c that should be delivered in period t
δ_{t}	Variable indicating the maximum amount of shortage among all components need to repair the module Shortage of component c that should be delivered in period t

4. Mathematical Model

Since we described all problem notifications in the previous section, we provide the mathematical programming formulation of the problem in this section.

$$Min \sum_{t\in T/1,\ldots l_c^p} \sum_{c\in C} P_C Q_{ct}^{p} + \sum_{t\in T}\sum_{c\in C} h_c l_{ct} + b\sum_{t=1}^{T}\delta_t \tag{1}$$

Subject to $Q_{ct}^{d} - B_{c,t-1}^{d} + B_{ct}^{d} = d_{ct}$ (2)

$$Q_{c,(t-l_c^p)}^{p} + l_{c,t-1} - l_{c,t} = Q_{ct}^{d} \tag{3}$$

$$\delta_t \geq B_{ct}^{d} \tag{4}$$

$$Q_{ct}^{p} \leq M_{ct} \tag{5}$$

$$l_{ct} \geq SS_c \tag{6}$$

$$\sum_{c\in C} P_c Q_{ct}^{p} \leq L_t \tag{7}$$

$$\alpha_c Q_{ct}^{d} \leq E_c \tag{8}$$

$$Q_{ct}^{p}, l_{ct}, Q_{ct}^{d}, B_{ct}^{d}, \delta_t \geq 0 \tag{9}$$

$$\forall t \in T, c \in C$$

In the proposed model, the objective function is formulated by minimizing the cost of purchasing the required parts and the cost of inventory (storage in the warehouse). The fines for delay in delivery of modules to customers are considered as well. As explained in the text, in this modeling the δ_t the variable represents the longest delay among the components required to repair the serviceable module.

The first constraint guarantees that the MRO repair center will replace all the components needed to repair the module according to the set schedule. Also, with the help of this constraint, it is possible to calculate the shortage of components/parts that need replacing, and their shortage will cause delays in the repair process and reassembly of components on the module and installing them on aircraft. The second one determines the balance at the inventory level for the required components. It is formulated so that the number of components/parts that must be purchased is gained from the difference between the number of components that must be sent to repair shops and the inventory from previous periods. Constraint 3 indicates that is the variable that represents the most delay among the total number of deficiencies and delays in the required component/parts. Constraint 4 indicates the limit of capacity to supply the required components/parts from suppliers. The fifth constraint ensures that the assurance level of inventory of components/parts required in each period is considered. The purpose of presenting constraint 6 in the proposed modeling is that the total number of purchases of components/parts for repair of the serviceable module should be proportionate to the total budget available and available (L_t) in each period. Finally, the proposed constraint 7 indicates the capacity limit in manpower/machinery for each component/part required for "c" in period t.

4.1. Numerical Example

In this section, the proposed mathematical programming models are solved by considering numerical examples and validation purposes. The results of the model will be compared in two modes of mean demand value for required spare items and maximum demand (worst demand scenario). The planning period consists of four sections (each period can include a month or season-for example, four-section of 3-months) to solve the model. It is assumed in each period that FARSCO receives ten modules to repair and provide services. It is assumed that each serviceable module consists of four components, each of which may fail. The probability of failure of components 1 to 4 is considered as 0.6, 0.4, 0.5, 0.7, respectively. It is assumed that the delivery time of spare items needed to repair the components in the module is in one period, and also the amount of safety inventory for all components is considered one unit (SSC=1). The maintenance cost of the required spare items is 5% of the item price. The initial inventory of all components is considered four (4) units. The cost of delay in delivery of serviceable modules is 600 and the total budget to provide the required parts is 10,000 per period. Demand for spare items (required components) is obtained by multiplying the probability of each component's failure in demand at the serviceable module level. The maximum capacity of the supplier to supply the components in each period is considered nine units and it is assumed that the repair center (FARSCO) can repair a maximum of 10 serviceable modules in each period. Definitive Mathematical Programming of the problem is modeled by Python 3.9 code using pulp library, and this model is solved by CPLEX solver and COID-CMD solving engines, and its results are presented in the form of Tables 5 and 6 as follows. The specification of the computer system is an I7-7500u processor, 4MB of memory cache, and 12 GB of RAM.

Table 4. Numerical example quantities

Parameter	Quantities
l_c^p	Four section- 3 months- Totally one year
h_c	6,4,8,10 (for components 1-4)
SS_c	1(for each period)
b	600
d_{ct}	6,4,8,10 (for components 1-4)
p_c	120,80,160,200 (for components 1-4)
M_{ct}	9(for each period)
L_t	10,000
α_c	10,7,6,9 (for components 1-4)
E_c	10(for each component)

Based on the given numerical example, Table 5 shows the results related to each component considering four time periods. The table is arranged in such a way that based on each component and in each time period, the results related to the values of the number of components must be ordered, the number of components to be delivered, and the number of components that are faced with the shortage. From a managerial point of view, by considering these values and based on the actual results, the commercial, logistics, and aircraft maintenance and repair units will be able to plan to reduce delivery time and make the necessary forecasts to prepare the aircraft according to the agreed schedule. Based on the analysis and the results, managers will be able to make the necessary decisions to prevent additional costs on the maintenance procedures.

Table 5. Computational Results

component	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4
period	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Q_{ct}^p	6	5	7	0	3	6	4	0	4	6	5	0	7	4	5	0
l_{ct}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Q_{ct}^d	3	6	5	0	3	3	6	4	3	4	6	5	3	7	4	5
B_{ct}^d	3	3	4	3	1	2	0	0	2	3	2	2	4	4	7	9

The amounts of purchasing, holding and shortage costs are presented in Table 6 based on the numerical example considering the two cases. In the first case, the average failure rate for each component is considered overtime. In this case, the probability of failure for the first to fourth components is 6, 4, 5, and 7 components, respectively. In the second case, the maximum number of failures for each of the four components is considered as the worst-case scenario. Based on the above, each cost is calculated and finally, the total cost is shown in Table 6.

Table 6. Cost values Results based on the programming model

Types of the programming model	Purchasing cost	Holding cost	Shortage cost	Total cost
Mean of demands	9,560	112	27,800	37,472
Maximum demands (worst scenarios)	10,640	112	46,160	56,912

Sensitivity analysis is one of the most essential topics in operational research that identifies the impression of the parameters on the optimal solution and examines the optimal value of the objective function and the optimal solution of the problem under the influence of the parameters. In the next section, we will examine the sensitivity of the optimal solution considering changes of parameters.

4.2. Sensitivity Analysis

4.2.1 Change in objective function coefficients

Three fixed amounts of late payment penalty, purchase cost, and component maintenance cost is considered in the objective function. Given the type of minimization objective function, it is obvious that increasing the values of constants will increase the value of the objective function, or in other words, the total costs will increase. The values in table 7 are obtained via the studies performed on the "fixed penalty for delay". Three options are considered for calculating the values of objective functions in Figure 1. The optimal value is considered to be only 2 components failures per period, and the actual value is equal to the number mentioned in the default problem. It is worth mentioning that the pessimistic value is considered equal to the failure of all components of a module (10 components in each period).

Table 7. Cost values Results based on the programming model

Row	"b" parameter values	Objective function values
1	300$	19,472$
2	600$	37,472$
3	900$	55,472$

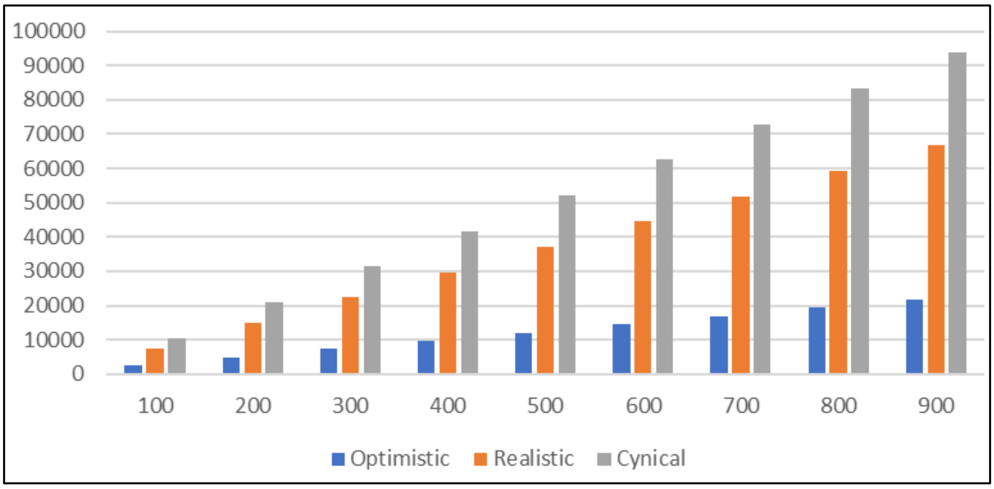

Figure 1. Sensitivity of the objective function in three cases to changes in late penalty values

In the study of changes in price constants, the effect of quantities can be seen in two parts of the objective function. Because by changing the purchase cost values in two parts, the total cost of purchasing the component due to the parameter of the purchase cost (P_c) and the cost of maintaining components in the warehouse (h_c) causes direct changes in the value of the objective function. These values can be examined in Table 8 (changes are obtained only through changing the cost of purchasing Component 3).

Table 8. Cost values Results based on the programming model

Row	"p_{C3}" parameter values	"h_{C3}" parameter values	Objective function values
1	100$	5$	37,400$
2	160$	8$	37,472$
3	180$	9$	37,496$

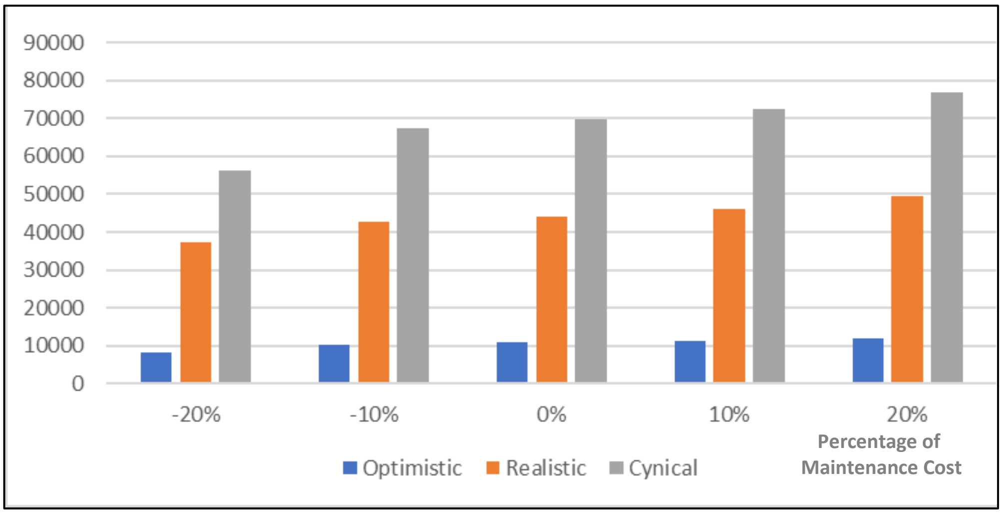

Figure 2. Sensitivity of the objective function to changes in maintenance cost

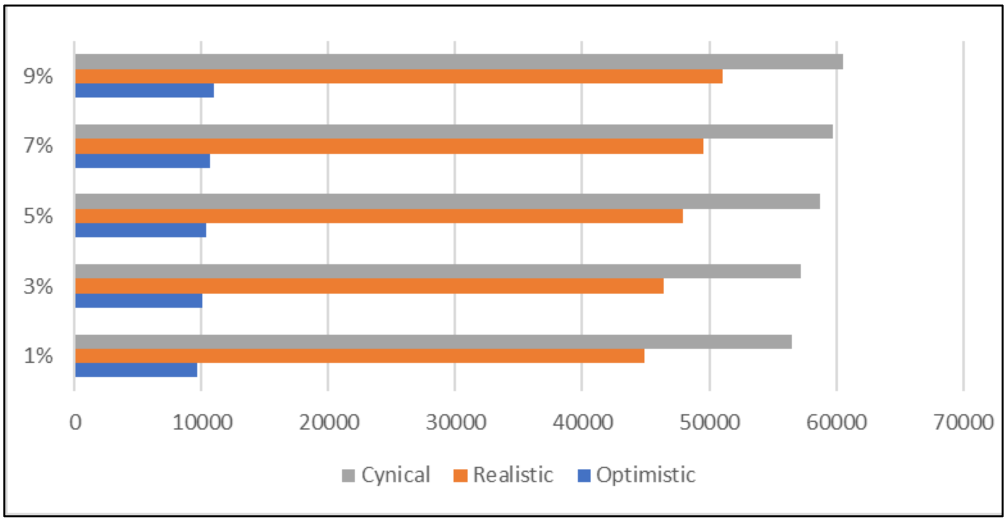

Figure 3. Sensitivity of the objective function to changes in purchasing cost

4.2.2 Change in the values of the right-side

In the budget discussion, like the objective function, it is not possible to comment definitively because the maintenance cost also plays a role in the objective function, which in some scenarios prevents us from ordering too much. Therefore, without considering this assumption, if only the desired values are changed, we will be able to provide more components by increasing the budget, resulting in fewer shortages and lower costs for delay penalties. By changing the existing safety stock, the minimum number of inventories in stock increases or decreases, which increases or decreases the maintenance cost and thus changes the number of new orders, which increases the total cost.

Table 9. Change in safety stock values

Row	**"SS_c" parameter values**	**Objective function values**
1	0	36,800$
2	1	37,472$
3	5	40,160$

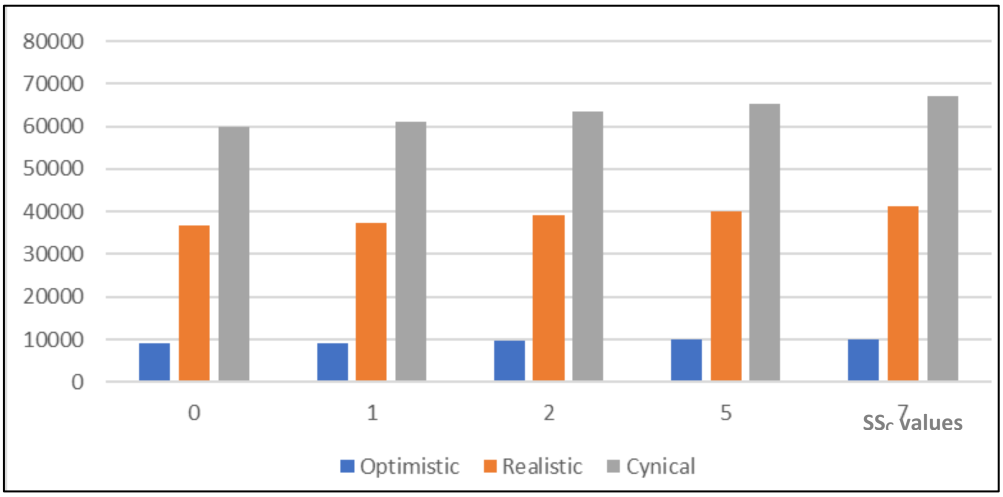

Figure 4. Sensitivity of the objective function to changes in safety stock values

With the reduction of the manpower and machinery for each period, it is obvious that the total costs will decrease. Because there may be delays in the repair of components which will cause more delay penalties. On the contrary, it can also be interpreted that the repairs are done faster due to the greater manpower and machinery, and we have to pay lesser penalties. By increasing the supplier capacity, it is obvious that the number of orders can be higher to compensate for the shortage (the better interpretation is that we will not see the situation worsen) and thus reduce the total cost.

Table 10. Change in manpower and machinery

Row	**"E_c" parameter values**	**Objective function values**
1	4	42,672$
2	6	40,334$
3	10	37,472$

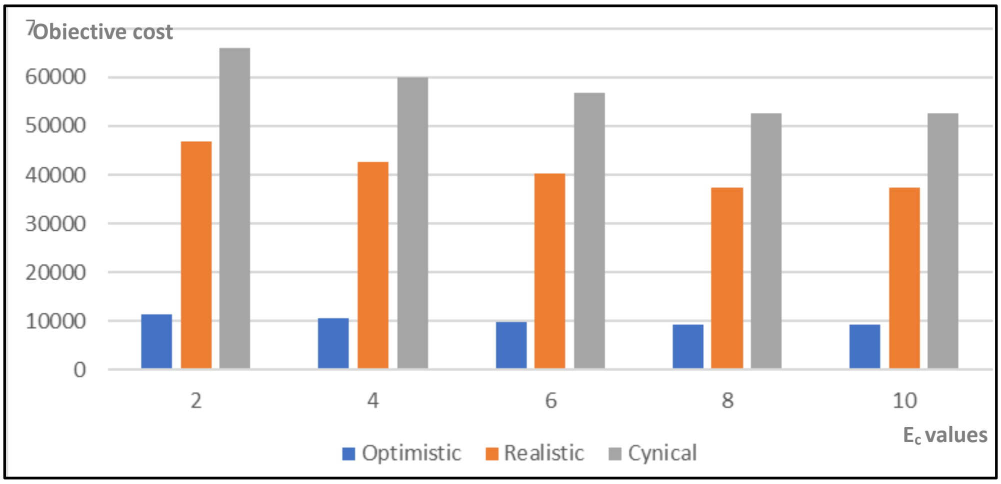

Figure 5. Sensitivity of the objective function to changes in the amount of the machine

5. Conclusion and recommendation for future research

In this paper, considering the importance of inventory management and scheduling of serviceable modules and supply of components and parts needed to perform repairs on them, modeling of spare parts and components scheduling to reduce the maintenance cost of holding components, their ordering for purchase, and supply and penalties for delay in delivery of required parts were presented. In this regard, a mathematical programming model is presented by considering the definite demand and minimizing the costs of purchasing spare items, inventory maintenance, and the cost of fines for late delivery of spare items for repair and delivery of serviceable modules. Also, two important constraints that have been less addressed in similar studies include budget constraints on the purchase of spare parts, as well as constraints on the repair capacity to be more realistic and closer to the actual conditions of aviation repair and overhaul centers, were considered.

The mathematical model is solved by considering numerical examples, and the results are solved in average demand and maximum component failure modes (worst case scenario). Sensitivity analysis was also performed on the proposed model by changing the parameter values.

To further develop the article, and according to the real-life conditions in the repairs of serviceable modules, when a module is given to FARSCO, the number of components/parts required in each serviceable module that needs to be repaired or replaced, is not definite, and it is very unpredictable. In other words, the type of spare parts/components required to repair a module is random, and therefore forecasting demand is a challenging task. Therefore, due to the uncertainties, especially concerning the demand for the required components/parts, modeling in the presence of uncertainties in the form of demand for components needed to repair the serviceable module to make it more realistic and closer to the real-life situation in aircraft repair and overhaul service centers can be considered in future research.

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