# MULTI-FACILITY INVENTORY SYSTEM MANAGEMENT FOR REPAIRABLE ITEMS

by

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## Abstract

Multi-Facility inventory system for repairable items is used for the management of critical spare parts for durable equipment where a repair facility is considered along with several operating facilities. This inventory system is very useful in industries in which there is a constant and huge demand for repaired and new spare parts from multiple operating facilities. It is exceptionally vital for maintenance, repair and overhaul organizations to enhance the spare parts inventory management by modeling the on-hand inventory of new and repaired spare parts. Nowadays, simulation methods have become promising methods to investigate and optimize real-world processes. It is anticipated that the appropriate development of simulation models for managing repaired and new spare parts of durable equipment in industry can result in healthy stocks of repaired and new spare parts and cost savings. This research describes the development of promising simulation models for multi-facility inventory system of repairable items in a centralized inventory environment considering the probabilistic nature of the system, with emphasis on the applicability of the models to different industries where multiple operating facilities in a region undergo spare parts repair whereby they send their faulty spare parts to a repair facility. Such models allow investigating the inventory systems for repairable items in a flexible and risk-free manner to effectively design the processes of repairing faulty spare parts and procuring new spare parts considering different ordering policies, and, furthermore, achieving sufficient fill rate and service level of spare parts with minimum inventory investment. A case study along with its results, sensitivity analysis, and managerial insights are presented in this research to illustrate the applicability and suitability of the proposed simulation models. The key results are the valuable managerial insights provided by the proposed simulation models into the complex inventory system of repairable items. These managerial insights are extremely important for achieving a maintenance, repair and overhaul organization's objectives such as minimizing inventory costs and maximizing service levels.

**Keywords:** ***Multi-Facility Inventory System; Repairable Items; Simulation; Spare Parts Management; Maintenance.***

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## List of Abbreviations

| | |
|---|---|
| AIT | Automated Identification Technologies |
| ARIS | Aircraft Repairable Item System |
| CDC | Central Distribution Centre |
| CM | Corrective Maintenance |
| CMSP1 | Corrective Maintenance Spare Part 1 |
| DEA | Data Envelopment Analysis |
| DEA | Data Envelopment Analysis |
| EOQ | Economic Order Quantity |
| IT | Inspection Time |
| JIT | Just In Time |
| L4L | Lot-Lot sizing |
| LT | Lead Time |
| METRIC | Multi Echelon Technique for Recoverable Item Control |
| MFIS | Multi-Facility Inventory System |
| MFIS-M | Multi-Facility Inventory System for Multi Repairable Items |
| MFIS-M-L4L | Multi-Facility Inventory System for Multiple Repairable Items, L4L Sizing |
| MFIS-M-QR | Multi-Facility Inventory System for Multiple Repairable Items, (Q, R) Sizing |
| MFIS-S | Multi-Facility Inventory System for a Single Repairable Item |
| MFIS-S-L4L | Multi-Facility Inventory System for a Single Repairable Item, L4L Sizing |
| MFIS-S-QR | Multi-Facility Inventory System for a Single Repairable Item, (Q, R) Sizing |
| MRO | Maintenance, Repair and Overhaul |

| | |
|---|---|
| M.U | Monetary Units |
| NOHSP1 | New On-Hand Inventory Spare Part 1 |
| PHM | Prognostics and Health Monitoring |
| PM | Preventive Maintenance |
| PMSP1 | Preventive Maintenance Spare Part 1 |
| (Q,R) | Reorder Quantity, Reorder Point |
| ROHSP1 | Repaired On-Hand Inventory Spare Part 1 |
| RT | Repair Time |
| SP | Spare Part |
| SP1 | Spare Part 1 |
| SP2 | Spare Part 2 |
| SP3 | Spare Part 3 |
| SFIS | Single-Facility Inventory System |
| SFIS-M | Single-Facility Inventory System for Multi Repairable Items |
| SFIS-M-L4L | Single-Facility Inventory System for a Multi Repairable Items, L4L Sizing |
| SFIS-M-QR | Single-Facility Inventory System for Multi Repairable Items, (Q, R) Sizing |
| SFIS-S | Single-Facility Inventory System for a Single Repairable Item |
| SFIS-S-L4L | Single-Facility Inventory System for a Single Repairable Item, L4L Sizing |
| SFIS-S-QR | Single-Facility Inventory System for a Single Repairable Item, (Q, R) Sizing |
| TBF | Time Between Failures |

## Chapter 1. Introduction

In this chapter, a background on inventory systems is provided. This is followed by stating the problem definition. Research objectives are then stated in order to overcome those problems. Finally, this chapter also describes the significance of this research and the thesis organization.

### 1.1. Background

Inventory systems of spare parts in this research work are divided into single-facility and multi-facility inventory systems. In a single-facility inventory system, one facility is involved from which a corrective maintenance (CM) or a preventive maintenance (PM) failed spare part reaches the inventory in order to be repaired or be replaced by a new spare part according to some conditions as shown in Figure 1.

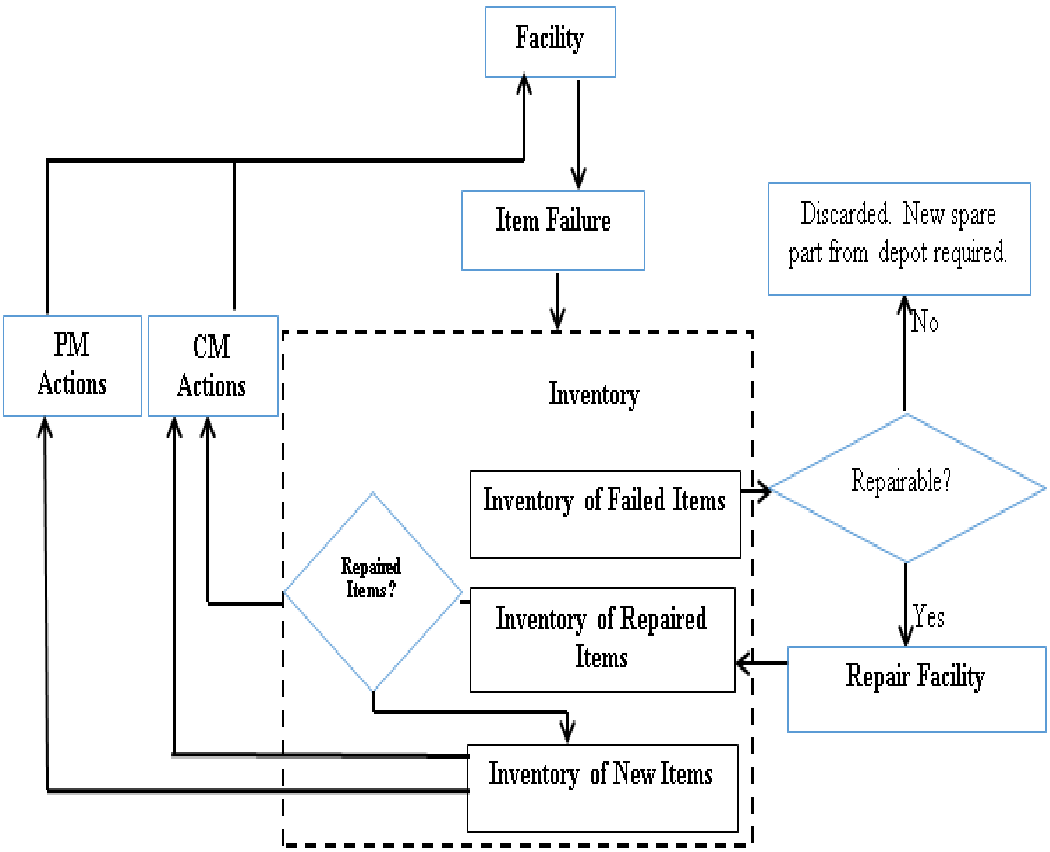


Figure 1: Single-Facility inventory system

A shown in Figure 1, in case of CM, if the number of on-hand inventory of new spare parts or repaired spare parts is equal to 0, then the spare parts are held in the inventory of PM and CM spare parts until either one of new or repaired spare parts become greater than 0 in the inventory. If the number of on-hand inventory of repaired spare parts is greater than 0 then repaired spare parts are used for CM. However, if the number of on-hand inventory of new spare parts reaches the Re-order Point (ROP), new spare parts are utilized from the inventory of new spare parts while at the same time new spare parts are ordered using Economic Order Quantity (EOQ) through an ordering process which are stored in the same inventory of new spare parts. If the number of on-hand inventory of new spare parts is between 0 and some number greater than ROP and the number of on-hand inventory of repaired spare parts is equal to 0, then new spare parts are utilized from the inventory of new spare parts for corrective maintenance.

In case of PM, if the number of on-hand inventory of new spare parts is equal to 0, then the PM spare parts are held in the inventory of PM and CM spare parts until the new spare parts become greater than 0 in the inventory. Nevertheless, if the number of on-hand inventory of new spare parts reaches the Re-order Point (ROP), new spare parts are utilized from the inventory of new spare parts while at the same time new spare parts are ordered using Economic Order Quantity (EOQ) through an ordering process which are stored in the same inventory of new spare parts. If the number of on-hand inventory of new spare parts is between 0 and some number greater than ROP, then new spare parts are utilized from the inventory of new spare parts for preventive maintenance.

Another scenario is when new spare parts are ordered based on Lot-Lot (L4L) case. In this case new spare parts are ordered based on exact quantities of spare parts required. When PM and CM spare parts come from the facility, they are stored in the inventory of PM and CM spare parts until new spare parts are ordered. When new spare parts are ordered, the PM and the CM spare parts reach the repair facility and the new spare parts are utilized for preventive and corrective maintenance. If there are already repaired and new spare parts available in the inventory of repaired and new spare parts respectively, then these spare parts are utilized first and then an order of new spare parts is made based on the number of PM and CM spare parts that are stored in the inventory of PM and CM spare parts.

All PM and CM spare parts must go through an inspection process where it is decided whether a spare part is repairable or not. If it is repairable then spare parts are sent to the repair facility, where the spare part is held in the inventory of repaired spare parts in order to be used for corrective maintenance. If these PM and CM spare parts are not repairable, then these spare parts are discarded.

There are number of issues to be addressed in a single-facility repairable item problem, for example the problem of the distribution of the arrival of failed items to the repair facility. This depends on the objects involved; their usage frequency and the maintenance policy on them. The second problem is of the repair capacity which determines the service rate of repair. Some parameters determine performance of a single-facility inventory system and this includes the average fill rate, which is the percentage of parts required for repair that are available from on the shelf inventory. Moreover, the determination of the number of new spare parts and repaired spare parts required to be stored in a multi-facility inventory system is an important factor to be addressed.

Multi-Facility Inventory Systems takes in to account the impact of inventories at any given facility on other facilities. For example, an inventory system with a single facility can have its faulty spare parts repaired and new spare parts procured more easily than an inventory system with multiple facilities. Hence, an inclusion of an extra facility will affect the service level offered to the other facilities. Multi-facility inventory system consists of a repair depot and many operating facilities. Three processes occur simultaneously in both the single-facility and multi-facility inventory systems. The first process is when a failed item is replaced with a spare item from the item's inventory. If a spare part is short then a replacement part arrives from the repair depot. The second process is when the failed item is sent to the repair depot for repair. The third process is when the repair depot ships a replacement part. If the replacement part is unavailable, then a new spare part is sent from the depot to the facility which requires it. In the meanwhile, the failed item gets repaired and fills up the depot's repaired spare parts inventory.

It is extremely vital for a Maintenance, Repair and Overhaul (MRO) organization, which is an independent organization to manage its spare parts demand and supply effectively and efficiently. An MRO is responsible for maintaining, repairing and overhauling mechanical spare parts for itself or for its customer's facility such as an aircraft as a whole. The MRO is also responsible for keeping a healthy stock of repaired and new spare parts in the inventory. The MRO must conduct timely procurement of new spare parts and the timely repair of repairable spare parts. The timely repair that an engineering system requires is vital before it gets delayed to deliver service to its customers. In addition to this, an MRO also has a repair facility, which takes care of all the maintenance of faulty spare parts of that facility. It is extremely vital to enhance the spare parts inventory management of a firm by overseeing its inventory level for both new and repaired spare parts, the time required to undergo various processes that are involved in the procurement of new spare parts and the repair of faulty spare parts in a single-facility and multi-facility inventory system. Figure 2 shows a multi-facility inventory system.

Same concept of handling preventive maintenance and corrective maintenance of spare parts is applied in Figure 2 by using the multi-facility inventory system. A centralized inventory system is considered in which all facilities are handled by one repair facility.

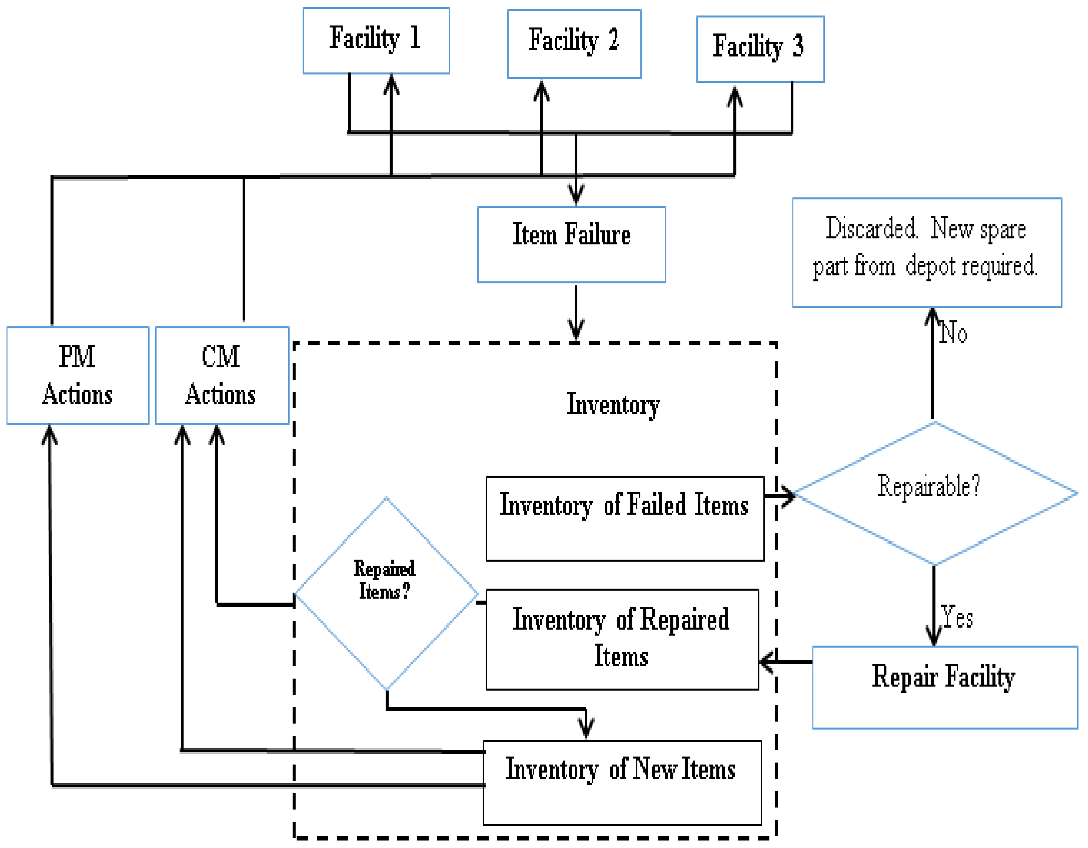


Figure 2: Multi-Facility inventory system

In [1], a scenario was presented whereby an airline repairs a spare part from its own repair facility, after which the repaired part reaches the airline's warehouse from where it is taken to the aircraft for installation. This warehouse also stores new spare parts as well. If for instance, the airline is not able to repair or procure a spare part from its own facility then it undergoes transshipments of spare parts from a competitor airline where it procures spare parts from the inventory of the competitor's airline. However, this research paper and the various other research papers did not consider the various time factors involved in the procuring of new spare parts and the various processes involved in procuring new spare parts, such as ordering of new spare parts, inspection and repairing of faulty spare parts etc.

### 1.2. Problem Definition

A Maintenance, Repair and Overhaul (MRO) organization faces problems of managing spare parts inventory levels and having the correct inventory levels of both repaired and new spare parts at a low cost in a centralized inventory environment. Apart from this, an MRO also faces problems in deciding the best ordering policy, in terms of total cost of repair and inspection processes, backorder cost and the total cost of the inventory system which includes the ordering cost and holding cost of spare parts. In addition to this, an MRO is under constant pressure of improving the inspection time, repair time and resource utilization of its inspection and repair processes which in turn will affect the service level and the fill rate of its spare parts. These problems are addressed here by simulating repaired and new spare parts in a depot and the operating facilities by taking into consideration process times and process costs of different spare parts.

### 1.3. Research Objectives

Driven by the problems faced by MROs, this research will achieve the following objectives: -

- Define the general spare parts inventory system problem.
- Survey the approaches that have been developed in the recent past for the spare parts inventory system problem.
- Use simulation to simulate inventory management of preventive maintenance, corrective maintenance, repaired and new spare parts in a centralized inventory

system environment using various time factors and probability distributions for various inventory system processes in order to determine the best ordering policy.

## 1.4. Significance of the Research

The significance of this research is to expand the existing research areas by working on the research gaps. This research will most importantly consider various process costs, time factors and probability distributions that are involved in various processes using a simulation software in a centralized inventory environment. This research work is major portion of this thesis which will significantly expand this research area.

## 1.5. Thesis Organization

The remainder of this thesis report is organized as follows. Chapter 2 reviews the literature related to various types of inventory systems. Later on, findings from the literature review are presented. Chapter 3 develops a single-facility inventory system in a centralized inventory environment for both single spare part and multiple spare parts using the (Q, R) and L4L inventory systems, This chapter also shows details of the simulation models and results. Similarly, Chapter 4 develops a multi-facility inventory system in a centralized inventory environment for both single spare part and multiple spare parts using the (Q, R) and L4L inventory systems. This chapter also shows details of the simulation models and results. Chapter 5 presents a case study based on the multi-facility inventory system in a centralized inventory system environment. Finally, Chapter 6 summarizes and concludes the report and briefly discusses some potential extensions to this research work.

# Chapter 2. Literature Review

This chapter of the report summarizes the relevant research conducted on various inventory management systems. This literature review is divided in to various sections which discusses various aspects of inventory systems.

## 2.1. Overview

Hu *et al.* [2] analyzed the problem of  reducing the consequences of equipment downtime, which plays a vital role in determining equipment availability at a minimum economic cost. In this paper, a framework for operational research in spare parts management was presented. Apart from this, Mobarakeh *et al.* [3] stated that the performance of supply chain depends on accurate demand forecasting. The authors used the Boot Strapping (BS) method for forecasting purposes and concluded that this method gives significant cost savings compared to other forecasting methods.

Saalmann [4] analyzed that the reliability of complex production systems is important for business environments. Downtimes of machines lead to production losses and high costs. This research studied the characteristics of spare parts supply chains, empirically investigated that how coordination in current spare parts supply chains can be improved. Additionally, Murino *et al.* [5] stated that the customer support in an aeronautical supply chain is a significant element which is present throughout the life cycle of the aircraft. Every customer order is different since each customer requires that their aircraft adhere to particular specifications, only then it is necessary to estimate the cost of spare parts service each time there is a certain customer request. The authors used Exact Estimation method for this research. Furthermore, Kilpi [6] used numerical values to determine the fleet composition of an airline in determining its costs and operational performance.

In addition to this, Ghobbar and Friend [7] researched that due to the irregular nature of demand for aircraft maintenance repair parts, airline operators perceive difficulties in forecasting Hence, this paper dealt with techniques applicable to predicting spare parts demand for airline fleets. Besides this, Ward *et al.* [8] presented the case that in order to improve a highly complex system such as aircraft maintenance, it is necessary to develop a comprehensive and economically valid model of the maintenance operational system. Moreover, Ghobbar and Friend [9] further worked on the sources of intermittent demand for aircraft spare parts within airline operations and researched on the problem by investigating the sources of demand unevenness which is a function of flying hours that may affect the spare parts demand rate.

## 2.2. Classification of Repairable Spare Parts

Jingjiang and Zhendong [10] researched that as demands for spare parts increase, inventory management of spare parts become more and more important. Inadequate management have severe consequences. This paper presented a classification application for spare parts based on Analytic Hierarchy Process (AHP). Five criterions were defined using AHP and for each criterion, four alternatives were defined. According to the authors this method is more effective than some old methods of classification. In addition to this, Rad *et al.* [11] stated that maintenance planning is a major aspect for airlines. This study focused on classifying spare parts into three groups by using the Analytic Hierarchy Process (AHP) and Data Envelopment Analysis (DEA) methods based on factors associated with spare parts: unit price, usage rate, lead time, and reliability.

Molenaers *et al.* [12] classified spare parts for industrial plants using the Analytic Hierarchy Process (AHP). The criteria that the authors used for this AHP method were equipment criticality, probability of failure of the item, replenishment time, number of potential suppliers, availability of technical specifications and maintenance type. Furthermore, Teixeira *et al.* [13] proposed spare parts classification using a computerized maintenance management system (CMMS) of a manufacturing company. The authors used three criticality categories, namely Vital, Essential and Desirable. Wongmongkolrit *et al.* [14] addressed the main aim of this paper to classify spare parts based on the ratio of production lost cost to inventory cost. If the ratio of production lost cost to inventory cost is over than one, then part is critical. Otherwise, it is non-critical. Besides this, Li and Wei [15] sugggested that supplier management is an important connection for efficient spare parts supply system. In this paper, firstly, various types of spare parts were analyzed and were divided into four categories and secondly supplier is classified according to spare parts it provides. Finally, Bevilacqua *et al.* [16] used Failure Mode, Effects and Criticality Analysis (FMECA) analysis and ABC method for classification of spare parts.

## 2.3. Approaches for Managing Spare Parts

Researchers have used different methodologies for managing spare parts. Two most commonly used methods that were used were mathematical programming approaches and simulation methods. In mathematical programming, researchers have used linear programming or optimization techniques to solve small and large spare parts management problems. Simulation methods included using some simulation software to deal with large number of spare parts in a specific industry. Simulation software was used to determine the inventory policy for a specific industry.

**2.3.1. Mathematical programming approaches**. Johansson and Olsson [17] determined the effect of emergency parts' replenishments from outside suppliers of a multi-echelon inventory system. They also determined the sustainability effects of this multi-echelon inventory system by calculating the amount of Carbon Dioxide ($CO_2$) emitted by using a faster mode of transportation for emergency supplies. Regarding the amount of $CO_2$ generated in the process the authors concluded that the use of a more polluting but faster replenishment can prevent a production batch being wasted, hence decreasing $CO_2$ emissions.

Humaira and Inalhan [18] used mathematical formulas to present a new model and analysis technique that can be used to calculate aircraft downtime cost due to maintenance. The authors concluded that this model will help operators not only to determine the best time to schedule maintenance but also to reduce the total maintenance cost and accordingly the aircraft's total operating cost. Furthermore, Fritzsche and Lasch [19] stated that unscheduled maintenance events and excessive spare parts deliveries are mostly caused by an incorrect choice of the maintenance strategy. The author used a dynamic prediction model and a prognostics-based preventive maintenance strategy to examine options for improving the logistics network. Similarly, Tracht *et al.* [20] calculated the optimal cost of inventory levels for warehouses in a two-echelon supply-chain for spare parts supply in the aviation industry. Many researchers followed similar approach for calculating various parameters of a multi-echelon inventory system through various methods. Some of them considered calculating the lead time of delivery of spare parts for the repairable item system while some considered incorporating transshipment costs and various other types of costs.

Fritzsche [1] developed an analytical model for cost estimation in a single-item, multi-hub inventory policy pooling model for high value spare parts in the aviation industry. By using mathematical models and by applying learning effect of the failure behavior of the used aircraft components, the research found out that the total costs can be decreased. Besides this, by using mathematical models, Osman [21] analyzed the problem that a need is to be addressed on optimizing maintenance data allocation to several repairable items. The author developed a general model for optimizing the use of Automated Identification Technologies (AIT) system for repairable equipment and items, and the allocation of preventive and corrective maintenance data on tags. Additionally, again by using mathematical formulas to take into account all the parameters that are related to the maintenance activities, Saltoğlu *et al.* [22] stated that aircraft maintenance has a cost and there are several factors that determine the magnitude of its cost. Similarly, Xie and Wang [23] compared having neighbor support or emergency lateral transshipment Using mathematical formulas and simulation algorithms in numerical experiments showed that neighbor support can lead to more cost saving in comparison with emergency lateral transshipment.

Sun and Zuo [24] observed that it is a problematic for airline companies to determine how to increase the aircraft's availability by the use of minimum spare cost. In this research, the relationship of availability of spare parts and backorder was proved. It was shown by computational methods that minimization of total backorders is approximately equivalent to maximization of availability. Likewise, Costantino *et al.* [25] prepared a state-of-the-art model of spare parts allocation for the Italian Air Force with the aim of minimizing back orders and simultaneously ensuring an availability of 99% depending on the actual flight plan.

On a different note, Kilpia and Veps.al.ainenb [26] discussed inventory pooling arrangements among various airlines and addressed the managerial implications of successful cooperation among airlines. Similarly, Rodrigues and Yoneyama [27] researched on the spare parts inventory control for non-repairable items based on Prognostics and Health Monitoring (PHM) Information. A comparison between two different inventory control policies in terms of service level achieved and average total cost required is made. The well-known [R,Q] (re-order point, economic order quantity) inventory model was used as a reference. This model was then compared with a model based on the information obtained from a PHM system. The authors concluded that for high service levels, the proposed model showed itself even more efficient. In addition to this, Tracht *et al.* [28] analyzed repairable items by varying repair capacity on a repairable item system. The authors used a mathematical model for varying the vacation times of workers (repair capacity) to see the effect on the backorders of unrepaired or broken parts. Lu and Yang [29] determined that repairable spares have particularly high unit price and low demand as compared to non-repairable spares. The authors emphasized that inventory optimizing of repairable spares is an important approach to improve operations. The authors used the conventional METRIC (Multi-Echelon Technique for Recoverable Item Control) like model for this approach and established a three-echelon inventory model of repairable spares. Similarly, Jiangsheng *et al.* [30] conducted a research that stressed on the fact that spare parts support is an important and difficult issue in weapon equipment support. This paper used the METRIC model and theory. Likewise, Haas and Verrijdt [31] worked on setting service level targets for the aircraft engine module, parts and module repair departments and their stock locations for an Aircraft Repairable Item System (ARIS). The authors used METRIC and MOD-METRIC models in this research. Wang *et al.* [32] formulated support policy with spares under the consideration of discarding unrepairable spare parts.

Song *et al.* [33] analyzed the aircraft spare parts inventory control problem by using minimum variance control by MATLAB. Furthermore, Xingfang and Juheng [34] took some constraints like cost, storehouse capacity, transport capacity and management ability into consideration when optimizing spare parts inventory. Additionally, Block *et al.* [35] produced a paper which proposed a methodology to determine the optimum time to repair repairable units to minimize the maintenance cost. Likewise, Gu *et al.* [36] addressed that in airline industries, the operating cost can be reduced by good planning. This paper presented two non-linear programming models, through which the optimal order time and order quantity was found by minimizing total cost.

**2.3.2. Simulation.** Lye *et al.* [37] developed an exact model which can be deployed for use in an airline's MRO inventory management. The authors stated that this simulation system allows an MRO operator to predetermine the optimum inventory level and placement. Furthermore, Nie and Sheng [38] researched that the models for multi-echelon inventory systems in existing literatures mainly address analytical models. The authors' experiments showed that the simulation model runs better than METRIC model. Besides this, the model can balance between cost and availability to withstand demands. Apart from this, Kilpi *et al.* [39] developed strategies of improvised cooperation, cooperative pooling and commercial pooling and compared it to the alternative of acting alone, i.e. solo strategy. A simulation model on the fair assumptions of the cost structure was used. Commercial pooling is more efficient than cooperative pooling in most of the cases. This was the conclusion given. Additionally, Peter Lendermann, *et al.* [40] focused on the problem of aviation spare parts provisioning. The authors used D-SIMSPAIR, simulation software package for their analysis. The authors came to a conclusion that the increase in logistics cost is minor compared to the decrease in inventory cost. Specifically, the authors showed that the prospective of pooling of inventory between inventory locations can be quantified. Finally, Li *et al.* [41] analyzed that the aviation industry generates large data every day. By analyzing this data, airlines can optimize the flight and operations of aircraft.

**2.3.3. Heuristics algorithm.** Kang and Kim [42] minimized the sum of warehouse operation costs, spare parts' holding costs in the warehouses and the transportation costs from the Central Distribution Centre (CDC) to warehouses as well as from warehouses to retailers. The authors used non-linear mixed integer programming model and developed a heuristic algorithm. In addition to this, Xiancun *et al.* [43] used a heuristic algorithm to solve the inventory allocation of spare parts' problem and to determine the correct quantity of each kind of spare part.

## 2.4. Sensitivity Analysis and Risk Analysis

Wang *et al.* [44] stated that lead time is one of the most important aspects in supply chain management. A short lead time reduces the spare parts stockout situation and it also reduces the holding cost, leading to reduced risk. Likewise, Radke and Tseng [45] addressed that manufacturers often have to meet difficult choices for meeting high service level without investing in expensive inventory, especially for long lead time items. By using mathematical formulas and based on fixed inventory budget, customer responsiveness was optimized by the authors. Furthermore, Jaarsveld and Dekker [46] studied the obsolescence of spare parts in order to enhance inventory control of those spare parts. The authors' objective was to estimate the risk of obsolescence of spare parts. The authors stressed that non-stationary demand of spare parts can cause unnecessary buildup of stock. The authors also therefore emphasized that minimizing Dead stock which are the non-moving parts is vital. In addition to this, Ko *et al.* [47] considered the transportation risk between the manufacturers, suppliers and retailers in a two-echelon inventory system and a transportation risk model was also generated. On a different note, Block *et al.* [48] used Monte Carlo Simulation to simulate operational requirements, spares inventories, failure rates and some other parameters to analyse the risk involved.

## 2.5. Key Findings from the Literature Review

Most of the researchers based their study on either reducing various types of costs or reducing the overall duration of supply of spare parts. In the research papers, many authors have considered optimizing various costs that were involved in the operation of inventory management systems. They have used several methodologies to identify, assess and optimize these costs. Some of the authors have also considered reducing transportation times, repair times, procurement times, scrap rate and procurement costs. However, after reviewing these papers in depth, certain gaps of research were identified. These gaps could be used to enhance the research on this area. The following paragraph summarizes the research papers.

After a thorough a literature review, it is determined that researchers have used various methods to classify spare parts based on their criticality. Moreover, researchers mostly have used optimization techniques to optimize either costs, time or inventory level which is an important aspect of inventory management systems but from the literature review it was observed that no researcher has considered applying various probabilities and time factors involved in each of the processes of spare parts inventory in a multi-facility inventory management system. Very few researchers have addressed the various time factors involved in the various processes of procuring new spare parts and repairing faulty spare parts. Finally, no researcher has considered preventive maintenance and corrective maintenance of spare parts along with procuring new spare parts and repairing old spare parts during preventive and corrective maintenance for a multi-facility inventory management system in a centralized inventory system environment.

## Chapter 3. Simulation Models of Inventory Systems for Repairable Items – Single Operating Facility

This chapter discusses the simulation that was developed for single-facility inventory system in a centralized inventory system environment using Arena simulation software. This chapter consists a detailed explanation of single-facility inventory systems for both single and multi-repairable items using Economic Order Quantity (Q, R) and Lot-Lot (L4L) ordering policy.

### 3.1. Single-Facility Inventory Systems for Repairable Items: Overview

Single-Facility Inventory System (SFIS) handles repairable spare parts from a single facility. This facility has both preventive and corrective maintenance spare parts. Preventive Maintenance (PM) spare parts are sent for overhauling in the repair facility and this is replaced by a new spare part which is taken from the inventory of new spare parts. On the other hand, Corrective Maintenance (CM) spare parts are sent to the repair facility. CM spare parts can either be repaired or discarded if not repairable. A CM spare part is replaced by either a repaired spare part which is taken from the inventory of repaired spare parts or a new spare part which is taken from the inventory of new spare parts. Figure 3 shows a schematic representation of the inventory system.

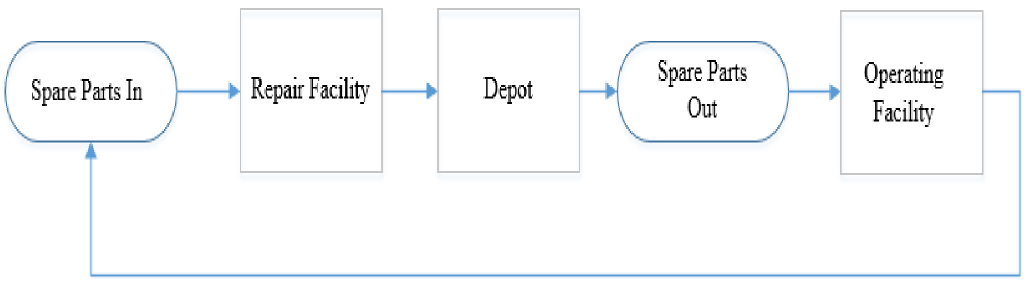


Figure 3: Schematic representation of the repairable inventory system

As shown in Figure 3 that initially spare parts enter the repair facility. These spare parts can be either PM or CM spare parts. After being repaired, these spare parts enter the depot where these repaired spare parts are stored until required for preventive or corrective maintenance. When these repaired spare parts are required for preventive or corrective maintenance, they are taken from the depot and transferred to the operating facility that requires these spare parts. This cycle continues when the operating facility sends the PM or CM spare parts again to the repair facility.

Figure 4 shows the (Q, R) inventory system. It shows that repairable spare parts arrive from the facility and are segregated into PM and CM spare parts. In case of PM, if the number of on-hand inventory of new spare parts is equal to 0, then the PM work order are held until the new spare parts become available in the inventory. Nevertheless, if the number of on-hand inventory of new spare parts reaches the Re-order Point (ROP), new spare parts are taken from the inventory of new spare parts while at the same time new spare parts are ordered through an ordering process which are stored in the same inventory of new spare parts upon arrival. If the number of on-hand inventory of new spare parts is not equal to ROP and greater than 0, then new spare parts are taken from the inventory of new spare parts for preventive maintenance.

In the case of CM, if the number of on-hand inventory of repaired spare parts is greater than 0 then a repaired spare part is used for CM. Otherwise, a new spare part is used for CM, if the number of on-hand inventory of new spare parts is greater than 0. If the If the number of on-hand inventory of new spare parts is equal to 0, then the CM work orders are held until either one of new or repaired spare parts become available in the inventory. However, if the number of on-hand inventory of new spare parts reaches the Re-order Point (ROP), a new spare part is taken from the inventory of new spare parts while at the same time new spare parts are ordered through an ordering process to replenish the same inventory of new spare parts. If the number of on-hand inventory of new spare parts is between 0 and a value greater than ROP and the number of on-hand inventory of repaired spare parts is equal to 0, then new spare parts are taken from the inventory of new spare parts for corrective maintenance.

All faulty spare parts go through an inspection process for repairability. If CM spare parts are repairable, then these spare parts are sent to the repair facility for repair after which the spare parts are held in the inventory of repaired spare parts in order to be reused for corrective maintenance. Some PM spare parts are overhauled so that they can be used for a prolonged amount of time. If the CM spare parts are not repairable, then these spare parts are discarded as shown in Figure 4. If PM spare parts reach the repair facility for repair, they are overhauled and stored in the inventory of repaired spare parts in order to be used for corrective maintenance. These repaired spare parts are stored until and unless repaired spare parts are required for corrective maintenance.

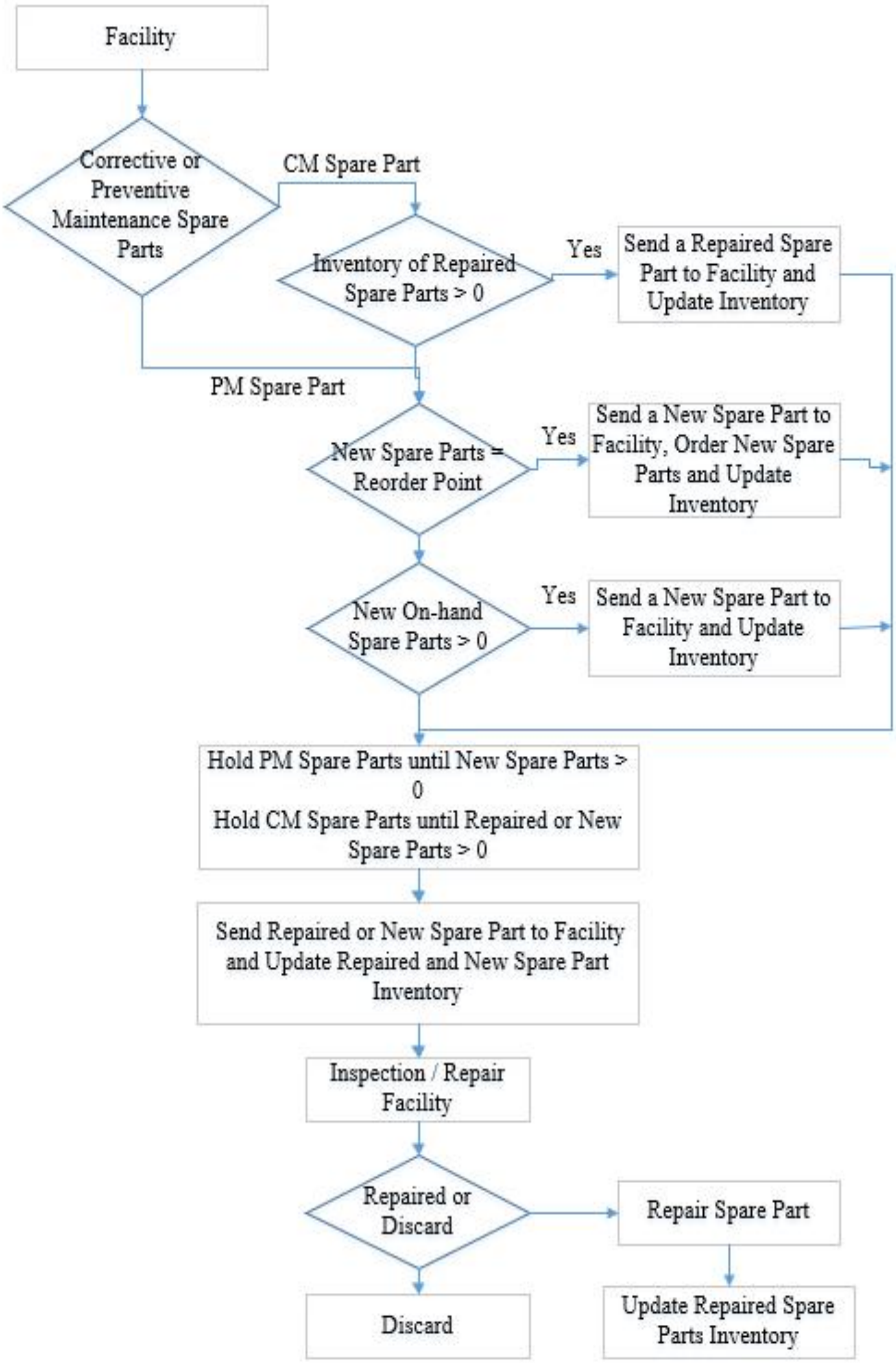


Figure 4: Flowchart of single-facility inventory system for the (Q, R) system

Moreover, the single-facility inventory system can either be for single repairable item (SFIS-S) in which just one type of spare part is involved or multiple repairable items (SFIS-M) in which many types of spare parts are involved. Inventory system for repairable items can either be (Q, R) or Lot-Lot (L4L), modeled using lot size / reorder point. Ordering policy (Q, R) is the policy of ordering a fixed number of new spare parts every time the number of new spare parts reaches the Re-Order Point (ROP) of new spare parts. On the other hand, L4L ordering policy is conducted based on the demand for new spare parts at a particular point in time.

## 3.2. Assumptions

Some assumptions were made when developing various inventory systems. Firstly, it was assumed that preventive maintenance require only new spare parts, whereas corrective maintenance require both repaired and new spare parts. Secondly, it was assumed that preventive maintenance spare parts can be overhauled in the repair facility and these overhauled spare parts can be reused for corrective maintenance.

## 3.3. SFIS Simulation Models for a Single Repairable Item

Single-Facility Inventory System for a single repairable item (SFIS-S) is the simplest inventory system for repairable items. It consists of a single facility with just one type of spare part.

**3.3.1. SFIS-S model using (Q, R) ordering policy.** The Single-Facility Inventory System for a single repairable item using (Q, R) ordering policy (SFIS-S-QR) handles the inventory system when a fixed number of new spare parts for that one type of spare part are ordered every time the number of new spare parts reaches the Re-Order Point (ROP) of new spare parts.

**3.3.1.1. *SFIS-S-QR model development.*** SFIS-S-QR model was developed using the Arena simulation software. Initially some new spare parts are generated using a submodel in order for those spare parts to be stored in inventory of new spare parts section. This initial number of new spare parts is the economic order quantity for that spare part. Figure 5 shows the second step of faulty spare parts entering the system from the facility having one type of faulty spare part. Corrective and preventive maintenance spare parts are created using the ‘Create’ modules and these spare parts are then connected to ‘Process’ modules of material handling process to transfer materials from the facilities to the different points in the inventory system. It is important to note here that both corrective maintenance and preventive maintenance spare parts have different arrival rate from the facility to the inventory system. Corrective maintenance can occur at any time and it depends when the equipment is going to break down. On the other hand, preventive maintenance is periodic and occurs based on a fixed schedule.

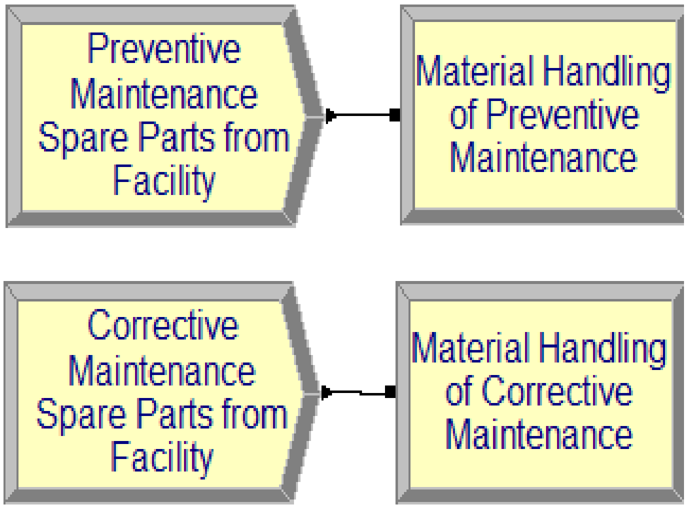


Figure 5: Creation of spare parts and their assignments

These material handling processes are followed by 'Assign' modules for preventive and corrective maintenance. The purpose of adding these 'Assign' modules is to assign some attributes to the spare parts. These attributes include maintenance type, SP type, no. of operating hours, maximum no. of operating hours, no. of repairs, maximum no. of repairs, inspection time, repair time, repairability or physical damage, spare part price, book value and lead time as shown in Figure 6.

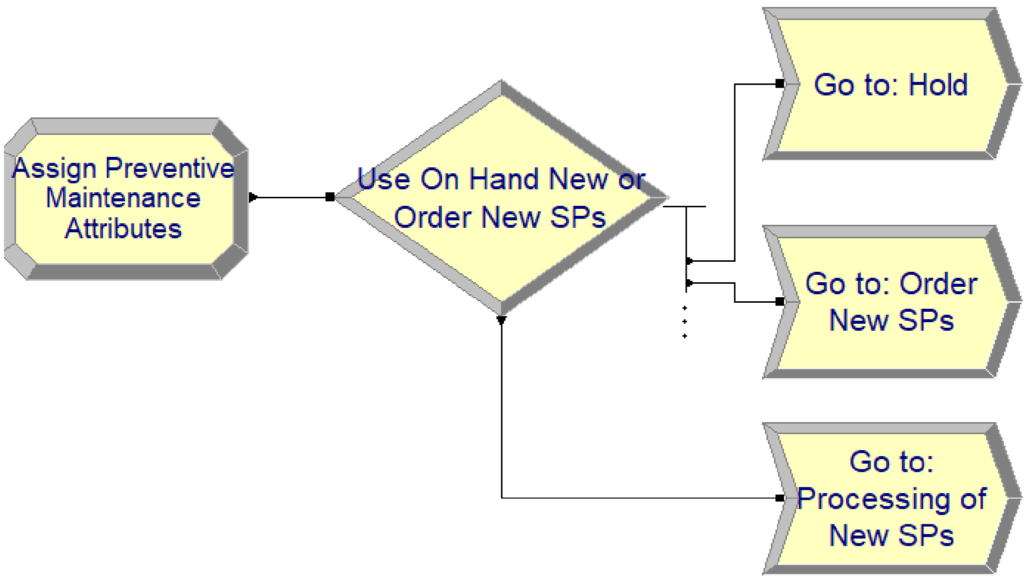


Figure 6: Preventive maintenance of spare parts

After the PM spare parts are assigned with entity types and attributes, the next step is to decide whether to use on-hand inventory of new spare parts or to hold the preventive maintenance until new spare parts become available. This is also demonstrated in Figure 6. For this, some conditions are used. Under the first condition, when the number of on-hand inventory of new spare parts is equal to 0, the PM spare parts are held until a new spare part becomes available. Under the second condition, when the number of on-hand inventory of new spare parts is equal to the reorder point, then these faulty spare parts are replaced by new ones from the on-hand inventory. Lastly, when the number of new spare parts are anywhere between 0 and ROP, then these faulty spare parts are replaced by new ones from the inventory of new spare parts.

The economic order quantity or lot size is determined by developing a simple and distinct simulation model that incorporates uncertainty in demand and lead time. At first, this model is run to determine the demand of the spare part and compute the economic lot size, and then the model is run for the probabilistic lead time to determine the demand of the spare parts during lead time, which will be set as reorder point.

Almost the same procedure is followed when handling corrective maintenance spare parts as shown in Figure 7. Here, 'Decide' module is used to satisfy three conditions of the corrective maintenance. Under the first condition, when the on-hand inventory of repaired spare parts is greater than 0, an 'Assign' module is then used to update and decrease the quantity of on-hand inventory of repaired spare parts as shown in Figure 7. A 'Signal' module is used to send a signal to release the repaired spare part that is held in the inventory of repaired spare parts. Under the second condition when the number of on-hand inventory of new spare parts is 0, the CM spare part is held until either of the repaired or new spare parts becomes available. Under the third condition, when the number of on-hand inventory of new spare parts is equal to the reorder point, then these spare parts are replaced with new ones while new spare parts are ordered using the ordering process. Finally, when the number of on-hand inventory of new spare parts is not equal to ROP and greater than zero then the faulty spare part are replaced from the inventory of new spare parts. For the first condition, the faulty spare part of CM goes to the repair facility through the 'Go to Inspection Label'. When the CM spare part reaches the repair facility it goes through the inspection and repair process. If it is repairable, then the CM spare part is repaired and stored in the inventory of repaired spare parts until and unless it is required, otherwise it is discarded.

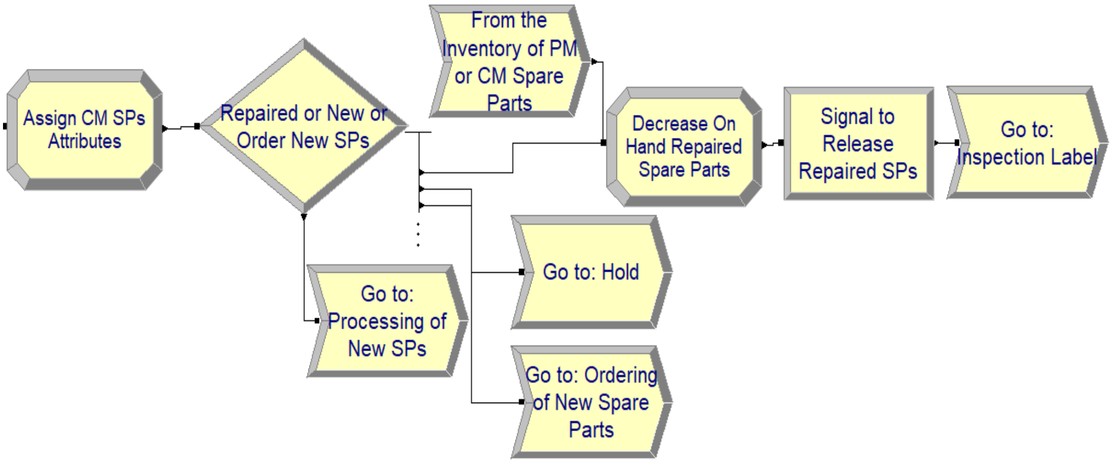


Figure 7: Corrective maintenance of spare parts

As shown in Figure 8, the faulty PM and CM spare parts reach ‘Processing of New Spare Parts’ module. These spare parts will always release the new spare parts from the inventory of new spare parts by using the ‘Signal’ module. A ‘Decide’ module with two conditions is then used. If a spare part is required for a corrective maintenance, this spare part is sent to a ‘Clone’ module after which the faulty CM spare part is sent for inspection in the repair facility and the cloned spare part is sent to the inventory of new spare parts for modeling purposes to be stored in the ‘Hold’ module of new spare parts in order to be released when a signal is sent to release the next new spare parts and when enough new spare parts are available in the inventory of new spare parts. However, if the faulty spare part is from preventive maintenance, this spare part is sent to another ‘Decide’ module to decide whether to overhaul this PM spare part or to discard it. The condition used in this ‘Decide’ module is No. of operating hours < Max. operating hours. If this condition is satisfied, then this PM spare part is overhauled and its maximum operating hours increases using an 'Assign’ module. After this ‘Assign’ module, it is then sent to the same ‘Clone’ module from where the faulty PM spare part is sent for inspection in the repair facility and the cloned PM spare part is sent in the inventory of new spare parts to be stored in the ‘Hold’ module for the same modeling purpose. It is assumed in this simulation that the spare parts that come from different facilities for preventive maintenance can be overhauled in the repair facility. This overhauling of spare parts increases the number of operating hours and repair time of those PM spare parts. After the PM spare parts are overhauled, they are stored in the inventory of repaired spare parts.

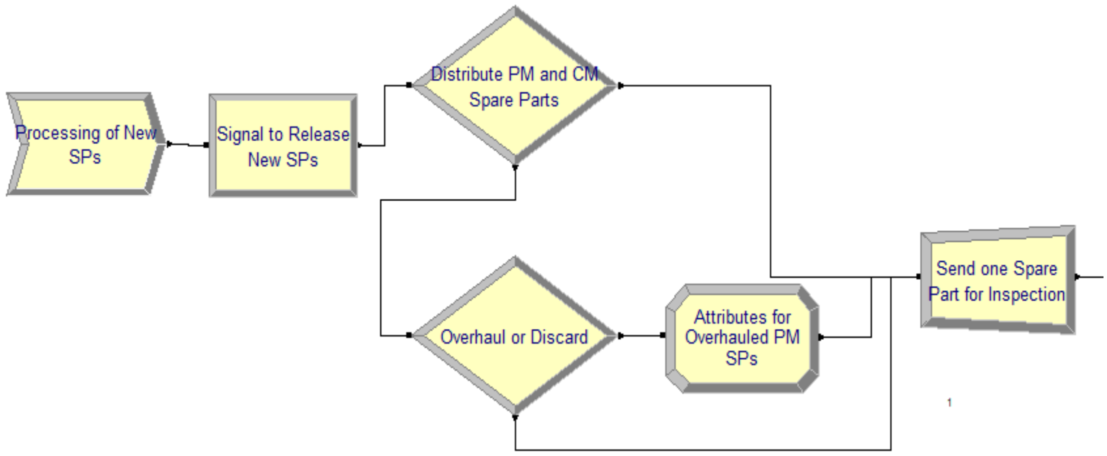


Figure 8: Overhauling and using new spare parts

After the cloned spare parts leave the 'Clone' module in Figure 8, the next step is that these spare parts enter the inventory of new spare parts section as shown in Figure 9. The cloned spare parts entering this section of inventory of new spare parts are just used to be held in the 'Hold' module in order to be released when a signal is sent to release new spare parts. Each spare part that is entered in the inventory of new spare parts section is assigned a book value for that spare part which is always equal to the spare parts' price without taking into consideration any depreciation as new spare parts are new and do not undergo any depreciation until they are used. A 'Hold' module is then linked to the 'Signal' module in Figure 8. A new spare part is held in this 'Hold' module until a signal is received to release the new spare part. Consequently, an 'Assign' module is used to decrease the quantity of new spare parts after the 'Hold' module.

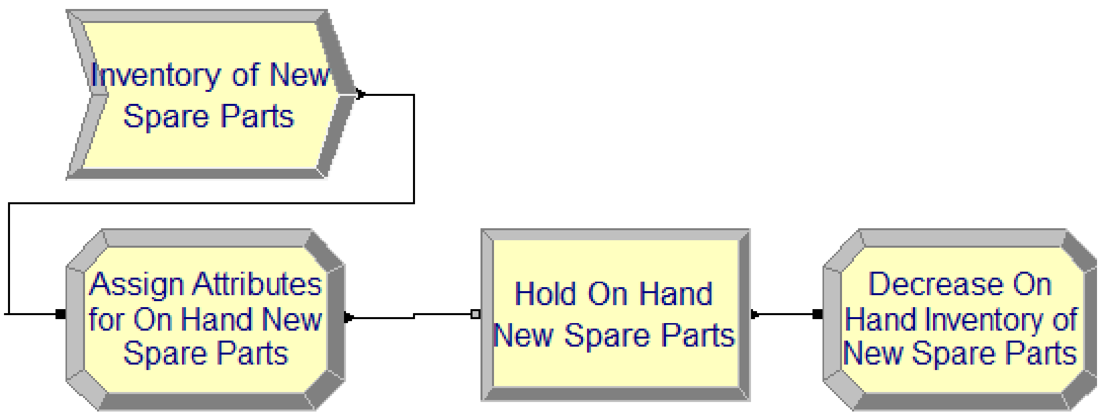


Figure 9: Inventory of new spare parts

Figure 10 demonstrates the inventory of PM and CM spare parts. If the number of on-hand inventory of repaired and new spare parts is 0, then there will be a shortage cost or backorder cost incurred. The PM and CM work orders will be held until new or repaired spare part becomes available. In Figure 10, a 'Record' module is used to count these PM and CM spare parts waiting for new or repaired spare parts. An 'Assign' module is used to define the holding time for each maintenance work order followed by 'Hold' modules for PM and CM work orders. In the 'Hold' module of PM work orders, a condition is used that if the number of on-hand inventory of new spare part becomes greater than 0, then a PM work order is released for further action. In the 'Hold' module of CM work orders, a condition is used that if the number of on-hand inventory of new or repaired spare part is greater than 0, then a CM work order is released for further action. A 'Clone' module is then used to send a cloned work order for the calculation of this shortage cost and the original work order is sent to a 'Decide' module with the condition that if the number of on-hand inventory of new spare parts is greater than 0, then this PM or CM work order is sent to the inventory of new spare parts 'Label' module of Figure 8 for further action. On the other hand, if this condition is not satisfied then the condition of the number of on-hand inventory of repaired spare being greater than 0 is satisfied, then this CM work order is sent to release a repairable spare part from the inventory of repairable spare parts.

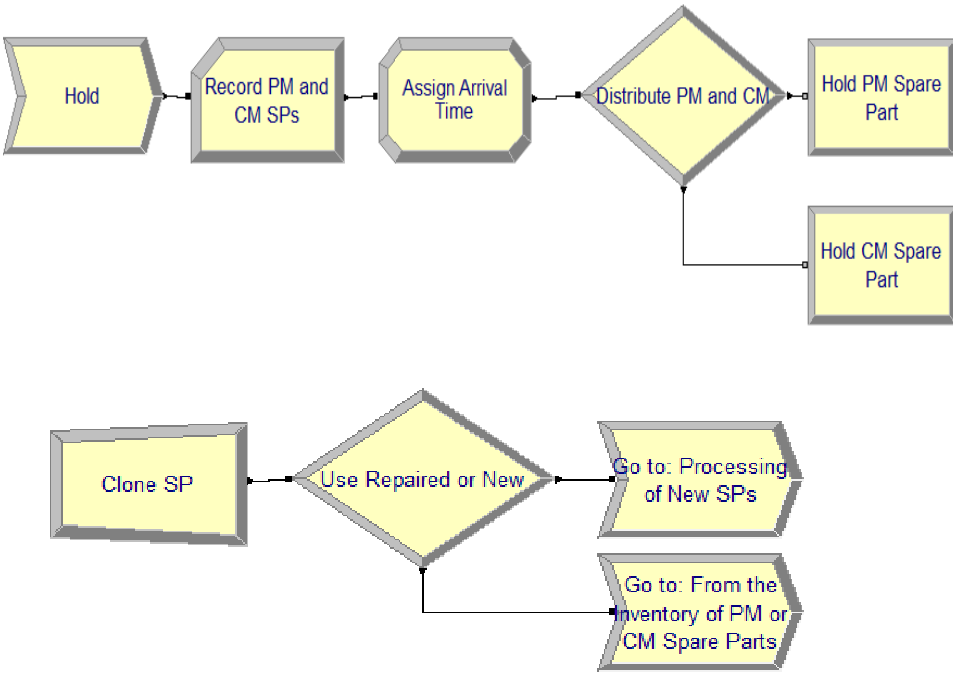


Figure 10: Holding PM and CM work orders

New spare parts are ordered using an ordering process as shown in Figure 11. These new spare parts can be ordered for both PM and CM spare parts. A ‘Clone’ module is then used to send one PM or CM spare part to follow the procedure in Figure 8 of processing of new spare parts and one spare part continues the procedure as shown in this Figure. A ‘Process’ module is used to order new spare parts. Another ‘Process’ module is used to define the ‘Lead Time’ process. This lead time is the time between ordering of new spare parts and receiving of those new spare parts. An ‘Assign’ module is then used to order new spare part as per EOQ. These ‘Assign’ modules are then connected to ‘Dispose’ modules in the end. This same process of ordering of new spare parts is followed for all CM and PM spare parts as well.

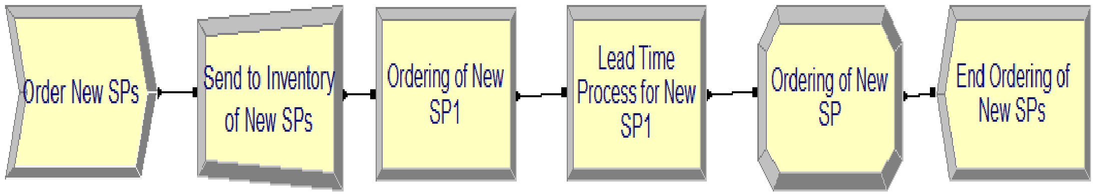


Figure 11: Ordering of new spare parts

Figure 12 shows the inspection and repair process of PM and CM spare parts. When a faulty PM or a CM spare part enters the inspection ‘Process’ module, it is first inspected for its repairability which is assigned to faulty spare parts using ‘Assign’ modules as described in Figure 6. A ‘Decide’ module is then used to decide whether to repair or discard the spare part. This is conducted by using the condition that if no. of operating hours < is less than the maximum operating hours, no. of repairs < maximum number of repairs and repairability or physical damage is 1, then the spare part is repairable, otherwise the spare part is discarded by using a discard ‘Process’ module and a ‘Dispose’ module in the end. The attribute of repairability or physical damage is an attribute of PM and CM spare part which tells that to what extent a spare part is repairable and to what extent it has physical damage. For PM spare part, this attribute has a value of 1 always because it is assumed that PM spare parts are always repairable and have no physical damage whatsoever. On the other hand, CM spare parts can have repairability or physical damage of either 0 or 1 which means that if this attribute for

CM spare parts is 0, it means they are not repairable and must be discarded. However, if this attribute for CM spare parts is 1, it means they are repairable. After the 'Decide' module of deciding to repair or discard spare parts, a repair 'Process' module is used based on the repair time assigned to faulty spare part using the 'Assign' modules as described in Figure 6.

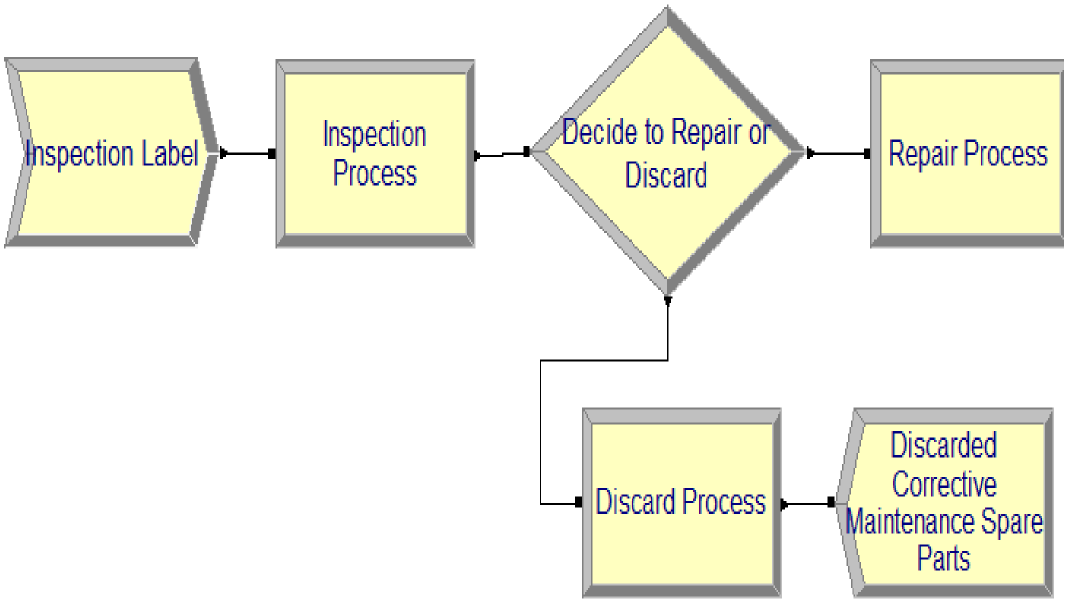


Figure 12: Inspection and repair process of spare parts

Figure 13 shows the simulation model for the inventory of repaired spare parts which is similar to the inventory of new spare parts in Figure 9. After a PM or CM spare part enters the inventory of repaired spare parts, an 'Assign' module is used to increase the number of on-hand inventory of repaired spare parts. Moreover, a variable of Total Book Value which has an initial value of 0 is declared. This Total Book Value is made equal to the sum of the Book Value of a particular spare part. So before a repaired CM or an overhauled PM spare part is held in the inventory of repaired spare parts, when it passes through this 'Assign' module, it will increase the Total Book Value of all repairable spare parts by adding its own book value to the total book value. This 'Assign' module is followed by a 'Hold' module to hold repaired spare parts. This 'Hold' module is linked to the 'Signal' module in Figure 7. A repaired spare part is released when a signal is received. 'This 'Hold' module is connected to another 'Assign' module in which the same variable of Total Book Value is declared which subtracts the book value of the repaired spare part with the total book value. So when a repaired spare part leaves the inventory of repaired spare parts, the total book value of the whole repaired spare parts in the inventory of repaired spare parts decreases.

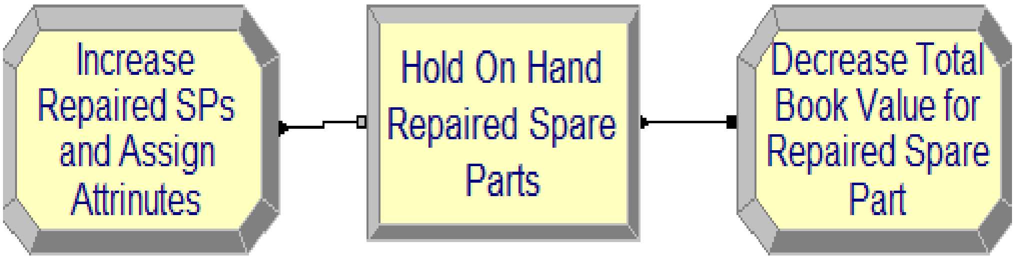


Figure 13: Inventory of repaired spare parts

Figure 14 demonstrates the procedure of installing or storing repaired and new spare parts at the facilities via a material handling 'Process' modules. For single-facility inventory system, only one facility is used in the end as a 'Dispose' module of 'Facility Repaired or New Spare Parts'.

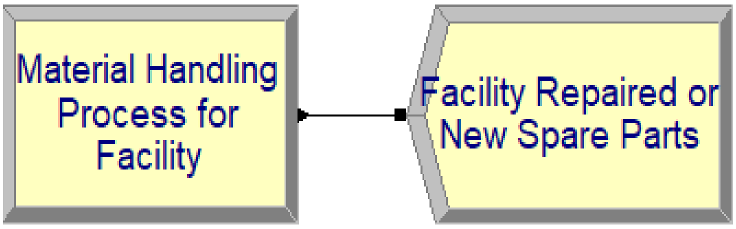


Figure 14: Installation or storing of spare parts in the facilities

Holding cost is also calculated for both repaired and new spare parts that remain in the inventory of repaired and new spare parts respectively. Figure 15 shows the method of calculating this holding cost of new spare parts in the Arena simulation software. This same method is used to calculate holding cost for repaired spare parts as well. An entity is generated at the of the simulation run to count the number of repaired and new spare parts stored in the inventory using a 'Record' module. In the same 'Record' module a counter is defined to count the number of on-hand inventory of new spare parts and a second counter is defined by an equation which is used to calculate the holding cost for new spare parts, by taking the product of on-hand inventory of new spare parts, price per spare part and holding cost fraction. Finally a 'Dispose' module is used in the end. In the 'Assign' modules of PM and CM spare parts, book value of the spare parts is also defined by the equation by taking the ratio of the no. of operating hours to the maximum operating hours, multiplying the result with the book value and subtracting the book value by this result.

In the 'Assign' module used in the inventory of new spare parts, an 'Attribute' of book value is defined which is equal to the spare part price. The book value of new spare parts is always equal to their price as they are not used or depreciated. For repaired spare parts, book value depends upon their usage and that is on the ratio of no. of operating hours to max. operating hours.


Figure 15: Holding cost calculation of new spare parts

**3.3.1.2. *SFIS-S-QR model validation.*** The SFIS-S-QR model was validated by running the simulation by generating only one PM spare part from a single facility and by setting the entities per arrival to 1, maximum arrivals to 1 and Time Between Failures to 10 minutes. First creation for this PM spare part was done at 0.5 minutes to delay the creation of spare parts so that some spare parts are held in the inventory of new spare parts which are created in a separate submodel. By running this simulation model for a replication length or simulation running time of 1 day, the number of spare parts that are held in the inventory of new spare parts (NOHSP1) is now 96 which is one below the EOQ of 97 for SP1, which is fine. This means that this one new spare part is being utilized for PM. By changing the maximum arrivals to 25, the NOHSP1 changes to 72 as 25 of these new spare parts are being utilized for PM. The ordering cost in both these cases is 0 as no ordering of spare parts is required in these cases. When the maximum arrivals is set to 185 and the Time Between Failures is set to 5 minutes, for example, the number of orders created as a result is just 1 and this gives an ordering cost of 0.83 M.U. The NOHSP1 becomes 9 which is also the re-order quantity for SP1. This happens because when there are 185 spare parts, 88 of the 97 spare parts are utilized from the inventory of new spare parts, leaving 9 spare parts as the remaining on-hand inventory which is the re-order point for SP1. An order of 97 SP1 spare parts is placed based on EOQ which increases the total NOHSP1 to 106. The remaining number of SP1 spare parts that need to be ordered are 97. Hence, out of the 106 NOHSP1, 97 are utilized for PM and the remaining SP1 spare parts in the inventory of new spare parts are 9. This is valid. The same procedure is applied for 2 and 3 orders. When the maximum arrivals is set to 250 and the Time Between Failures is set to 5 minutes, for example, the number of orders created as a result are 2 and this gives an ordering cost of 1.6667 M.U. The NOHSP1 becomes 41. This is also fine. Finally, when the maximum arrivals is set to 300 and the Time Between Failures is set to 2 minutes, for example, the number of orders created as a result are 3 and this gives an ordering cost of 2.50 M.U. The NOHSP1 becomes 88. This is also fine. Therefore, this simulation is validated for PM spare parts. Table 1 summarizes the validation results for PM spare parts.

Table 1: Summary of validation results for PM spare parts

| **Maximum Arrivals of Spare Parts** | **Time Between Failures (minutes)** | **NOHSP1** | **# of Orders** | **Ordering Cost (M.U)** |
|---|---|---|---|---|
| 1 | 10 | 96 | 0 | 0 |
| 25 | 10 | 72 | 0 | 0 |
| 185 | 5 | 9 | 1 | 0.8333 |
| 250 | 5 | 41 | 2 | 1.6667 |
| 300 | 2 | 88 | 3 | 2.5000 |

The same procedure is followed for validating CM spare parts by running the simulation model and generating one CM spare part from a single facility. The same results are obtained when we set entities per arrival to 1, maximum arrivals to 1 and Time Between Failures to 10 minutes. When the maximum arrivals is set to 2 and the Time Between Failures is set to 10 minutes, for example, the number of orders created as a result is 0 and this gives an ordering cost of 0 M.U. The NOHSP1 becomes 95 and the ROHSP1 becomes 1 as 1 CM spare part is discarded and the other CM spare part is repaired. This is also fine. When the maximum arrivals is set to 3 and the Time Between Failures is set to 10 minutes, for example, the number of orders created as a result is 0 and this gives an ordering cost of 0 M.U. The NOHSP1 becomes 95 and the ROHSP1 becomes 1 as 1 CM spare part is discarded and the other 2 CM spare parts are repaired. Therefore, in total 2 new spare parts are utilized and 1 repaired spare part is utilized for corrective maintenance of the 3 CM spare parts. This is also fine. However, when the maximum arrivals is set to 100 and the Time Between Failures is set to 2 minutes, still no orders are created and this gives an ordering cost of 0 M.U. The NOHSP1 becomes 40 and the ROHSP1 becomes 3. When the maximum arrivals is set to 250 and the Time Between Failures is set to 2 minutes, 1 order of new spare parts is created and this gives an ordering cost of 0.8333 M.U. The NOHSP1 becomes 54 and the ROHSP1 becomes 5. When the maximum arrivals is set to 350 and the Time Between Failures is set to 2 minutes, 2 orders of new spare parts are created and this gives an ordering cost of 1.6667 M.U. The NOHSP1 becomes 98 and the ROHSP1 becomes 2. Finally, when the maximum arrivals is set to 500 and the Time Between Failures is set to 2 minutes, 3 orders of new spare parts are created and this gives an ordering cost of 2.50 M.U. The NOHSP1 becomes 104 and the ROHSP1 becomes 13. Table 2 summarizes the validation results for CM spare parts.

Table 2: Summary of validation results for CM spare parts

| **Maximum Arrivals of Spare Parts** | **Time Between Failures (minutes)** | **NOHSP1** | **ROHSP 1** | **# of Orders** | **Ordering Cost (M.U)** |
|---|---|---|---|---|---|
| 1 | 10 | 96 | 0 | 0 | 0 |
| 2 | 10 | 95 | 1 | 0 | 0 |
| 3 | 10 | 95 | 1 | 0 | 0 |
| 100 | 2 | 40 | 3 | 0 | 0 |
| 250 | 2 | 54 | 5 | 1 | 0.8333 |
| 350 | 2 | 98 | 2 | 2 | 1.6667 |
| 500 | 2 | 104 | 13 | 3 | 2.5000 |

In all of these scenarios, the parameters were observed to follow one equation which was created to determine the number of spare parts that were repaired in the corrective maintenance case. This equation was created to further carry out the validation of corrective maintenance. The equation first subtracts the number of on-hand inventory of new spare part 1 with the total number of new spare parts. The result of this is subtracted from the total number of CMSP1 spare parts. The result of this is then added to the number of on-hand inventory of repaired spare part 1.

To validate this equation, an example of 2 orders of new spare parts is taken into consideration. The total number of CMSP1 spare parts is 350 in this case. The total number of new spare parts including the existing number of new spare parts are 291. NOHSP1 is equal to 98 and ROHSP1 is equal to 2. As a result of this, the total number of repaired SP1 spare parts becomes equal to 159 which matches with the ‘Number In’ and ‘Number Out’ of the repair process given in the Arena simulation report.

Another example of 3 orders of new spare parts is taken into consideration. The total number of CMSP1 spare parts is 500 in this case. The total number of new spare parts including the existing number of new spare parts are [97 + (97 × 3)] = 388. NOHSP1 is equal to 104 and ROHSP1 is equal to 13. Consequently, the total number of repaired SP1 spare parts becomes equal to 229 which matches with the ‘Number In’ and ‘Number Out’ of the repair process given in the Arena simulation report.

It is also observed that as the Time Between Failures of spare parts is changed, the number of spare parts that are held in the inventory of repaired and new spare parts and are released from these inventories changes. Moreover, as the maximum number of arrivals of spare parts is increased, more number of repaired and new spare parts leave the inventories of repaired and new parts respectively and hence the holding cost to hold these repaired and new spare parts also increases. Therefore, in this sub-section both PM and CM spare parts’ simulation model was validated using a range of the maximum arrivals. This validation produced meaningful results in the end. This Arena simulation validation example will now be used to carry out some other scenarios in the forthcoming sections of this report and a discussion will be based on those scenarios.

**3.3.1.3.** ***SFIS-S-QR illustrative example.*** For illustrating the proposed SFIS-S-QR model, single-facility (1 facility) inventory system with one type of repairable spare part is considered. Table 3 shows the simulation time and quantity values used and Table 4 shows the resources and cost values used. Various input probability distributions and constant values were used as input parameters to the Arena simulation software.

Table 3 are used to define the various attributes, units of those attributes, number of resources, processing times of various processes used in this inventory system and Table 4 are used to define the busy, idle and usage costs for all cases of single-facility and multi-facility, single and multi-repairable spare parts. As observed from Table 3 that some probability distributions are assigned to some time factors. Furthermore, number of replications in the Arena simulation software that were considered was 1 with a Replication Length (simulation running time) of 7 days. The number of hours of work per day that were considered were 24 hours.

Table 3: Attribute time and quantity parameters and their values

| INPUT PARAMETER | PM | CM | UNIT |
|---|---|---|---|
| Time Between Failures for PM and CM Spare Parts | As per Schedule | EXPO(0.5) | Hours |
| No. of Operating Hours | UNIF(1000,2000) | UNIF(700,800) | Hours |
| No. of Repairs | POIS(2) | POIS(1) | Repairs |
| Max. Operating Hours | 2000 | 1500 | Hours |
| Max. No. of Repairs | 6 | 3 | Repairs |
| Inspection Time | EXPO(1) | EXPO(1) | Hours |
| Repair Time | EXPO(3) | EXPO(2) | Hours |
| Lead Time | TRIA(1,3,7) | TRIA(1,3,7) | Hours |
| Holding Cost Fraction | 0.1 | 0.1 | - |

Table 4: Resource and cost parameters and their values

| Process | # of Resource | Processing Time (Hours) PM | Processing Time (Hours) CM | Cost Busy / Hour, Idle / Hour & Usage / Hour (M.U) |
|---|---|---|---|---|
| Material Handling | 1 | 0.10 | 0.10 | 14 [49], 8, 7 |
| Inspection and Repair Technician | 1 | EXPO(1) | EXPO(1) | 125 [50], 65, 35 |
| Resource PM and CM SPs | 1 | Time for Shortage of Repaired and New Spare Parts | Time for Shortage of Repaired and New Spare Parts | 150, 45, 80 |
| LT SPs Process Resource | 100 (This 100 Figure is added so as to avoid having queue in the Lead Time Process module in the simulation as lead time is not actually a process and parts quickly go through this process. | TRIA(1,3,7) | TRIA(1,3,7) | 100, 75, 50 |
| Ordering of New SP1 | 1 | 0.25 | 0.25 | 50 [51], 35, 30 |
| Discard Process Resource | 1 | 1 | 1 | 420 [52],200,150 |

Preventive maintenance spare parts follow a fixed schedule as preventive maintenance of spare parts is scheduled before maintenance takes place. Table 5 shows PM spare parts' schedule. This Table shows the number of spare parts that are entering in every hour on each day from the facilities.

Table 5: PM spare parts' schedule

| Spare Parts Arrival Rate (No. of spare parts / hour) | Duration (Days) |
|---|---|
| 5 | 1 |
| 2 | 1 |
| 3 | 1 |
| 6 | 1 |
| 4 | 1 |
| 3 | 1 |
| 5 | 1 |

In Table 5, the Arena simulation software takes the spare parts' arrival rate in exponential distribution. For example, according to the PM spare parts' schedule Table, entities per arrival of 5 on the first day means that it has an exponential distribution of mean 5 spare parts per hour of arrival. So approximately 120 PM spare parts will arrive on the first day. Similarly, entities per arrival of 2 on the second day means that it has an exponential distribution of mean 2 spare parts per hour of arrival. So approximately 48 PM spare parts will arrive on the second day.

Table 6 presents details of the quantities of spare parts that went in and came out of the various processes. It also shows the productivity of both the inspection and repair processes. This productivity is the ratio of the spare parts out to spare parts in. Table 7 shows the average, minimum and maximum number of spare parts waiting in the various processes. Table 8 shows the various costs (busy, idle and usage costs) that are linked to various processes. Finally, Table 9 shows the number of on-hand inventory of repaired, new, PM and CM spare parts and their corresponding holding costs at the end of the simulation run.

Table 6: Spare parts' process quantities in and out

| Process | Number In | Number Out | Productivity (%) |
|---|---|---|---|
| Inspection | 877.00 | 105.00 | 11.97 |
| Repair | 89.0000 | 4.0000 | 4.49 |

Table 7: Spare parts' waiting for processes

| Process | Average | Maximum |
|---|---|---|
| Inspection | 383.11 | 771.00 |
| Repair | 48.1469 | 85.0000 |

Table 8: Resources' busy, idle and usage costs

| Process | Busy Cost (M.U) | Idle Cost (M.U) | Usage Cost (M.U) | Total of Busy and Usage Cost (M.U) |
|---|---|---|---|---|
| Inspection and Repair Technician | 20,630.72 | 11.0000 | 3,850.00 | 24,480.72 |
| LT SPs | 3,665.01 | 1,257,040.87 | 450.00 | 4,115.01 |
| Material Handling Shortage of All Spare Parts | 2,349.20 | 1.1607 | 11,760.00 | 14,109.2 |
| Ordering New SP1 | 112.50 | 5,801.25 | 270.00 | 382.5 |
| Resource PM and CM SPs | 8,455.97 | 5,023.21 | 10,720.00 | 19,175.97 |
| Total Cost (M.U) | 41,933 | 1,310,205 | 29,443 | 71,376 |

Table 9: Number of on-hand inventory of spare parts', quantities and costs

| Spare Parts Quantities | Actual Ending Quantity | Holding Cost (M.U) |
|---|---|---|
| NOHSP1 | 0.00 | 0.00 |
| ROHSP1 | 0.00 | 0.00 |
| PMSP1 and CMSP1 Waiting | 139.00 | Total for PMSP1 and CMSP1, 8,455.97 (Backorder Cost) |

Tables 6 to 9 show comprehensive results of the SFIS-S-QR. Most of the defined processes of this inventory system were utilized with the orders of new spare parts being generated for the single spare part. Some of the spare parts' for that type were discarded whereas some of them were repaired as well. All spare parts do not leave the various processes of this inventory system. This means some of the spare parts were waiting to be processed in the queue of various processes. Running the Arena simulation for a comparatively longer period of time will result in more number of PM and CM spare parts to be processed. In Arena simulation software, the busy cost is the cost incurred when the resource is busy in processing spare parts, idle cost is the cost incurred when a resource in a particular process is not being used and usage cost is the cost incurred per usage for using a resource in a particular process. Most of the cost is from the idle cost which is justified by the same fact that as PM and CM spare parts wait in the various processes of this inventory system, this leads to the resources in those processes to remain underutilized and hence this incurs less busy cost and less usage cost and more idle cost for resources. It can also be observed from the results that PMSP1 and CMSP1 have to wait or be held in the inventory until either repaired or new spare parts or both repaired and new spare parts become available. This holding process of PM or CM spare part incurs some cost (shortage cost) which is given by the resource name of ‘Resource PM and CM SPs’ in the Tables 8. In addition to this, there were no repaired or new spare parts remaining in the end of the simulation run as given by the variable’ quantities of ROHSP1 and NOHSP1 respectively. Consequently, by analyzing this single-facility inventory system for a single repairable item in this simulation run, it was observed that this simulation generated a big order of new spare parts (9 orders) for that type of spare part. However, this resulted in many of the spare parts to remain inside various ‘Process’ modules without successfully leaving those ‘Process’ modules. As seen from the Tables above that the value of ROHSP1 and NOHSP1 are 0, which are the number of on-hand repaired and new spare parts after the simulation run. This NOHSP1 quantity is acceptable and therefore it is suggested to have the same EOQ value for SP1 as this will result in a lower value of NOHSP1. Consequently, it is suggested to improve this inventory system by modifying it. Modifications can be done in various ways, for example by taking in less demand of PM and CM spare parts’ from the facility. In other words, increasing the Time Between Failures (TBF) of spare parts or assigning a value for the maximum arrivals of PM and CM spare parts instead of assigning these to infinite. Furthermore, different processes in this simulation could be conducted faster or more inspection and repair facilities could be added to make the whole inventory system process faster so that more number of spare parts leave various ‘Process’ modules successfully. These modifications or improvements could be considered as a future work of this research.

**3.3.2. SFIS-S model using L-4-L ordering policy.** The Single-Facility Inventory System for a single repairable item using lot-lot ordering policy (SFIS-S-L4L) handles the inventory system when an exact number of new spare parts for that one type of spare part are ordered every time based on the number of PM or CM spare parts that came from the facility. The lot-lot inventory system is also called Just In Time (JIT) inventory system.

**3.3.2.1.** ***SFIS-S-L4L model development.*** SFIS-S-L4L model was developed using the Arena simulation software. Following are the details of this simulation model. It applies to single-facility and multi-facility, single and multi-repairable spare parts. In case of single repairable spare parts, only PMSP1 and CMSP1 spare parts were used. Figure 16 shows the changes in the Arena Simulation software modules when L-4-L inventory system was used.

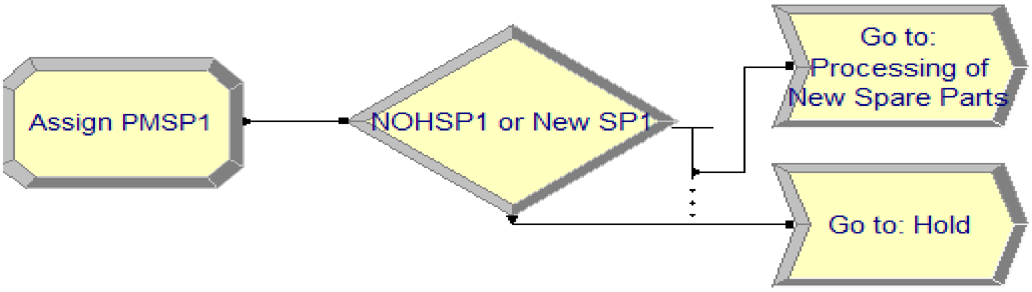


Figure 16: Changes in the PM spare parts' section after implementing L4L inventory policy

The Figure shows that after assigning the various parameters to the PM spare parts, a 'Decide' module is used to segregate the spare parts in to the two conditions of NOHSP1 > 0 and NOHSP1 ≵ 0. For the condition of NOHSP1 > 0, the spare parts follow the usual path of 'Go to: Processing of New spare parts'. For the condition of NOHSP1 ≵ 0, the spare parts follow the 'Go to: Hold' path, whereby the spare parts are kept in hold until new spare parts are ordered based on the lot size.

Figure 17 shows the change in the ordering of new spare parts section.

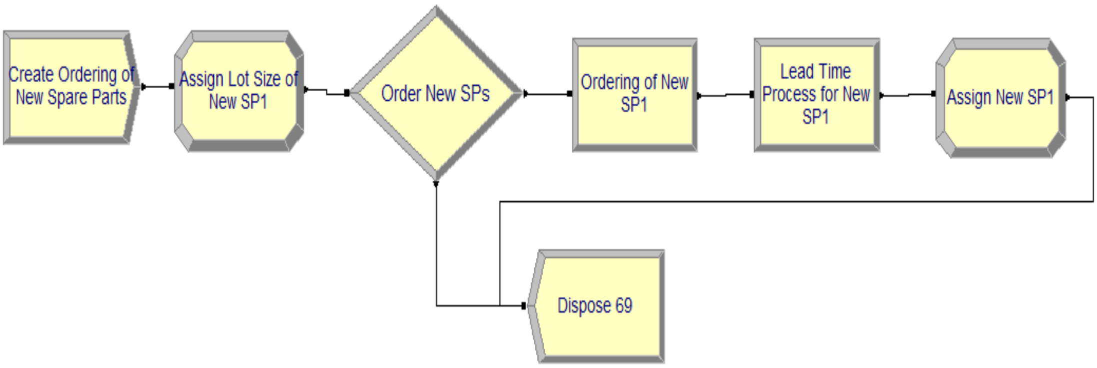


Figure 17: Changes in the PM spare parts' section after implementing L4L inventory policy

In this Figure new spare are generated by using a 'Create' module in the beginning. This 'Create' module creates new spare parts every 24 hours with the first spare parts being created after the first 24 hours. This 'Create' module is followed by an 'Assign' module which defines a variable 'LotSize SP1' as the sum of the number of PM spare parts on hold queue and the number of CM spare parts on hold queue. A 'Decide' module is then used to determine whether the value of NOHSP1 LotSize SP1

> 0 or not. If it is 0 then ordering of new spare parts takes place, followed by Lead Time process for New SP1 in the 'Process' module and then Assign New SP1 'Assign' module. If NOHSP1 LotSize SP1 is greater than 0, then no ordering of new spare parts are necessary and the false part of this 'Decide' module is connected to the 'Dispose' module. The Ordering of New SP1 'Process' module and the Lead Time Process for New SP1 'Process' module are the same as before. The Assign New SP1 'Assign' module defines the variable NOHSP1 as NOHSP1 + LotSize SP1, which will calculate the value of NOHSP1 at the end of the simulation run. Finally, a 'Dispose' module is added in the end.

**3.3.2.2. *SFIS-S-L4L model validation.*** The SFIS-S-L4L model was validated by running the simulation by generating only one PM spare part from a single facility and by setting the entities per arrival to 1, maximum arrivals to infinite and Time Between Failures to 1 day. First creation for this PM spare part was done at 0.5 minutes to delay the creation of spare parts so that some spare parts are held in the inventory of new spare parts, which are created in a separate submodel. These same parameters are defined for 'Create Ordering of New Spare Parts' 'Create' module in the Ordering of New Spare Parts section with the exception of the first creation of new spare parts which occurs at 1439$^{th}$ minute, which means that first ordering of new spare parts is conducted in the end of the first day. Time Between Failures of 1440 minutes is defined, which means that ordering of new spare parts is conducted in the end of each day. By running this simulation model for a replication length of 1 day, the number of orders generated for the spare part is 1 as the Entities per Arrival is 1 and the number of spare parts that are held in the inventory of new spare parts in the end (NOHSP1) is 0. This is fine. The same procedure is repeated for a replication length of 2, 3, 5 and 24 days. Another validation scenario is considered in which a beginning inventory of 1 is considered for a replication length of 3 days. For all of these scenarios the entities per arrival is 1 and the Time Between Failures is 1 day. The last two scenarios have a replication length of 24 days, entities per arrival of 1, time between arrival of 1 day and maximum arrivals of spare parts as infinite. The last scenario have a beginning inventory of 10 for both NOHSP1 and ROHSP1. The ending inventory in this case is 0 and 32 for NOHSP1 and ROHSP1 respectively. Table 10 summarizes the results for validation of PM spare parts for the L4L ordering policy.

Table 10: Summary of validation results for PM spare parts

| Length (days) | # of Spare Parts In | Start NOHSP1 | Start ROHSP1 | Max. Arrivals of Spare Parts | # of Orders | Max. Lot Size | End NOHS P1 | End ROH SP1 |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | Infinite | 1 | 1 | 0 | 0 |
| 2 | 2 | 0 | 0 | Infinite | 2 | 1 | 0 | 1 |
| 3 | 3 | 0 | 0 | Infinite | 3 | 1 | 0 | 2 |
| 1 | 3 | 1 | 0 | Infinite | 2 | 1 | 0 | 2 |
| 5 | 5 | 0 | 0 | Infinite | 5 | 1 | 0 | 4 |
| 24 | 24 | 0 | 0 | Infinite | 24 | 1 | 0 | 22 |
| 24 | 24 | 10 | 10 | Infinite | 24 | 1 | 0 | 32 |

For all of these cases, the number of PM spare parts in is always equal to the number of orders generated as 1 Entity per Arrival is used in all cases and as seen by the fourth case, the number of PM spare parts in is always equal to the sum of the orders generated and the initial value of NOHSP1. The same procedure is followed for CM spare parts. The SFIS-S-L4L model was validated by running the simulation by generating only one CM spare part from a single facility and by setting the entities per arrival to 1, maximum arrivals to infinite and Time Between Failures to 1 day. First creation for this PM spare part was done at 0.5 minutes to delay the creation of spare parts so that some spare parts are held in the inventory of new spare parts, which are created in a separate submodel. These same parameters are defined for Create Ordering of New Spare Parts 'Create' module in the Ordering of New Spare Parts section with the exception of the first creation of new spare parts which occurs at 1439$^{th}$ minute, which means that first ordering of new spare parts is conducted in the end of the first day. Time Between Failures of 1440 minutes is defined, which means that ordering of new spare parts is conducted in the end of each day. By running this simulation model for a replication length of 1 day, the number of orders generated for the spare part is 1 as the Entities per Arrival is 1 and the number of spare parts that are held in the inventory of new spare parts (NOHSP1) and repaired spare parts (ROHSP1) in the end are 0. This is fine. The same procedure is repeated for a replication length of 2, 3, 5 and 24 days. Another validation scenario is considered in which a beginning inventory of 1 is considered. For all of these scenarios the entities per arrival is 1 and the Time Between Failures is 1 day. The last two scenarios have a replication length of 24 days, entities per arrival of 1, time between arrival of 1 day and maximum arrivals of spare parts as infinite. The last scenario have a beginning inventory of 10 for both NOHSP1 and ROHSP1. The ending inventory of repaired and spare parts in the last scenario is 0 because CM spare parts use both repaired and new spare parts and in the end of the simulation run many spare parts are discarded. Many spare parts also reach the inspection and the repair process and after passing through the repair process, these repaired spare parts are stored temporarily in the inventory of repaired spare parts but are later on utilized for corrective maintenance. This same procedure is observed when new spare parts are ordered which are stored temporarily in the inventory of new spare parts which are then utilized for corrective maintenance. Table 11 summarizes the results for validation of CM spare parts.

Table 11: Summary of validation results for CM spare parts

| Length (days) | # of Spare Parts In | Start NOHSP1 | Start ROHSP1 | Max. Arrivals of Spare Parts | # of Orders | Max. Lot Size | End NOH SP1 | End ROH SP1 |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | Infinite | 1 | 1 | 0 | 0 |
| 2 | 2 | 0 | 0 | Infinite | 2 | 1 | 0 | 0 |
| 3 | 3 | 0 | 0 | Infinite | 3 | 1 | 0 | 0 |
| 1 | 3 | 1 | 0 | Infinite | 2 | 1 | 0 | 0 |
| 5 | 5 | 0 | 0 | Infinite | 4 | 1 | 0 | 0 |
| 24 | 24 | 0 | 0 | Infinite | 16 | 1 | 0 | 0 |
| 24 | 24 | 10 | 10 | Infinite | 0 | 0 | 4 | 0 |

**3.3.2.3. *SFIS-S-L4L illustrative example.*** For illustrating the proposed SFIS-S-L4L model, single-facility (1 facility) inventory system with one type of repairable spare part is considered. Same input parameters, quantities, resources and cost values were used as in the earlier case. The assumptions in the L4L case are that orders are made every day and that there are no new spare parts in the inventory (NOHSP1=0) initially. In addition to this, the number of replications in the Arena simulation software that were considered was 1 and a Replication Length of 7 days was assigned. Tables 12, 13, 14 and 15 summarizes the results. These Tables are similar to the Tables that were shown for the SFIS-S-QR inventory case. In Table 13, the number of preventive and corrective maintenance spare parts on hold are shown as an average value and as a maximum value. The average value is the average of all the number of spare parts that were generated during the simulation run, whereas the maximum value is the maximum number of spare parts that was attained during the simulation run of 7 days and 24 hours of work per day.

Table 12: Spare parts' process quantities in and out

| Process | Number In | Number Out | Productivity (%) |
|---|---|---|---|
| Inspection | 726.00 | 158.00 | 21.76 |
| Repair | 127.0000 | 0.00 | 0.00 |

Table 13: Spare parts' waiting for processes and variable values

| Process/ Variable | Average | Maximum |
|---|---|---|
| Hold CMSP1 | 18.0951 | 53.0000 |
| Hold PMSP1 | 44.0850 | 118.00 |
| Discard Process | 0.02996510 | 2.0000 |
| Inspection | 300.83 | 595.00 |
| Repair | 46.8789 | 126.00 |
| LotSize SP1 | 103.73 | 158.00 |
| NOHSP1 | 0.00 | 0.00 |
| ROHSP1 | 0.00 | 0.00 |

Table 14: Resources' busy, idle and usage costs

| Process | Busy Cost (M.U) | Idle Cost (M.U) | Usage Cost (M.U) | Total of Busy and Usage Cost (M.U) |
|---|---|---|---|---|
| Discard | 13,020.00 | 27,400.00 | 4,650.00 | 17,670.00 |
| Inspection and Repair Technician | 17,538.60 | 1,575.17 | 5,565.00 | 23,103.60 |
| LT SPs | 0.00 | 1,260,000 | 300.00 | 300.00 |
| Material Handling Shortage of All Spare Parts | 2,192.40 | 91.1406 | 10,969.00 | 13,161.40 |
| Ordering New SP1 | 75.0000 | 5,826.92 | 210.00 | 285.00 |
| Resource PM and CM SPs | 19,917.48 | 1,090.50 | 19,360.00 | 39,277.48 |
| Total Cost (M.U) | 52,743 | 1,307,912 | 41,054 | 93,797.00 |

Table 14 shows the various types of costs incurred during the simulation run for the SFIS-S-L4L inventory system. These types of costs that are generated in this inventory system are similar to the types that were generated in the SFIS-S-QR inventory system. The overall concept remains the same. Each resource in a process incurs a busy cost, an idle cost and a usage cost.

Table 15: Number of on-hand inventory of spare parts' quantities and costs

| Spare Parts Quantities | Actual Ending Quantity | Holding Cost (M.U) |
|---|---|---|
| NOHSP1 | 0.00 | 0.00 |
| ROHSP1 | 0.00 | 0.00 |
| PMSP1 and CMSP1 Waiting | 849 | Total for PMSP1 and CMSP1, 19,917.48 (Backorder Cost) |

Tables 12 to 15 show comprehensive results of the SFIS-S-L4L. Most of the defined processes of this inventory system were utilized with the orders of new spare parts being generated for the single spare part. Some of the spare parts' for that type were discarded whereas some of them entered the repaired process as well. In this SFIS-S-L4L case, the average lot size generated for SP1 is approximately 103. 7 orders of new spare parts were generated within the simulation replication length of 7 days. No new spare parts and repaired spare parts were held in the inventory of new and repaired spare parts respectively in the end of the simulation run. The total busy cost for the SFIS-S-L4L case is much higher than that for the SFIS-S-QR case. The output from the repair process is 0 because a single resource is used for the inspection and the repair process and that single resource is busy only in the inspection process and hence a large number of spare parts are held in the repair process queue. If two different resources are used for the inspection and the repair process instead then the PM and CM spare parts pass through the repair 'Process' module and are overhauled and repaired respectively.

## 3.4. SFIS Simulation Models for a Multi Repairable Item

Single-Facility Inventory System for the multi repairable item (SFIS-M) handles a single facility with multiple types of spare parts.

**3.4.1. SFIS-M model using (Q, R) ordering policy.** This type of Single-Facility Inventory System for multiple repairable item using (Q, R) ordering policy handles the inventory system when a fixed number of new spare parts for multiple types of spare parts are ordered based on EOQ every time the number of new spare parts reaches the Re-Order Point (ROP) of new spare parts. In this ordering policy, more than 1 repairable spare part is used. Abbreviation SFIS-M-QR will be used to show the Single-Facility Inventory System for multiple repairable items using (Q, R) ordering policy.

**3.4.1.1. *SFIS-M-QR model development.*** SFIS-M-QR model was developed using the Arena simulation software. Same Arena simulation model was used but with all spare parts PMSP1, PMSP2 and PMSP3, CMSP1, CMSP2 and CMSP3,. In addition to this, 3 preventive maintenance spare parts are further divided based on the percentage of demand of these 3 spare parts (50% for SP1, 30% for SP2 and 20% for SP3). Same percentages of demand are assigned to corrective maintenance spare parts as well. Various 'Decide' modules are used in the Arena simulation software to distribute the three different types of spare parts. Figure 18 shows that two 'Decide' modules are used to separate the three different spare parts in this multi repairable item case.

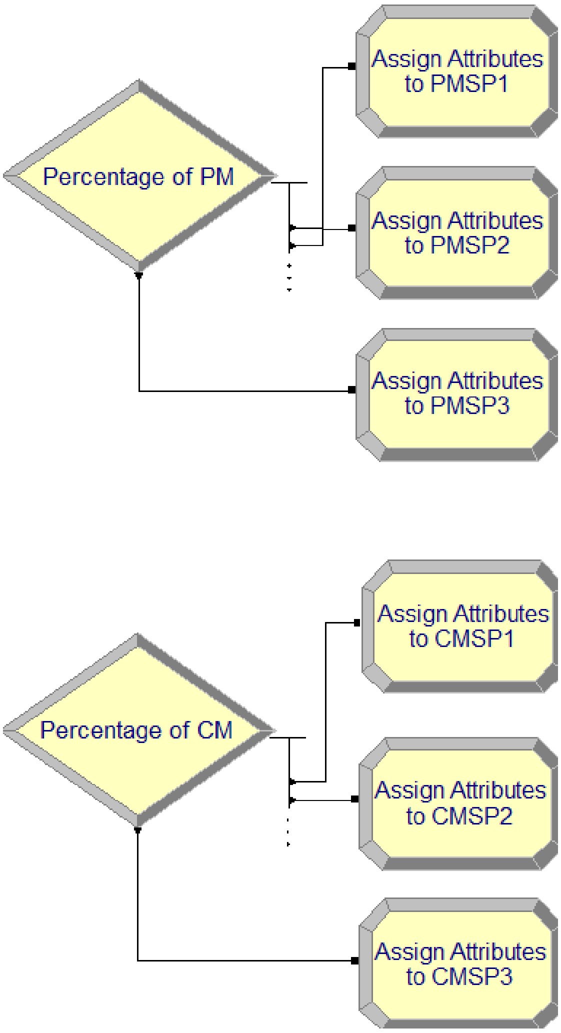


Figure 18: Assigning attributes to multiple repairable item case

**3.4.1.2. *SFIS-M-QR model validation.*** Simulation validation was carried out for single repairable item. This validation also applies to multiple repairable items as well. By handling the first type of spare part at a time and then the second type of spare part and then the third type of spare part, this SFIS-M-QR model is validated. This will produce similar results to the SFIS-S-QR model validation. The difference between the validation of multiple spare parts and single spare part is that, in multiple spare part, each type of spare part is validated turn by turn.

**3.4.1.3.** ***SFIS-M-QR illustrative example.*** Simulation model was developed using the Arena simulation software considering SFIS-M-QR. Same Tables as before were used but with three different spare parts. Table 16 show the data used and Tables 17, 18, 19 and 20 show the results for SFIS-M-QR.

Table 16: Attribute time and quantity parameters and their values

| INPUT PARAMETER | PM | CM | UNIT |
|---|---|---|---|
| Time Between Failures for PM and CM Spare Parts | As per Schedule | EXPO(0.5) | Hours |
| No. of Operating Hours for SP1, SP2 and SP3 | UNIF(1000,2000), UNIF(1000,3000) and UNIF(1000,1500) | UNIF(700,800), UNIF(600,700) and UNIF(800,900) | Hours |
| No. of Repairs for SP1, SP2 and SP3 | POIS(2), POIS(3) and POIS(5) | POIS(1), POIS(1) and POIS(2) | Repairs |
| Max. Operating Hours for SP1, SP2 anfd SP3 | 2000, 2800 and 1300 | 1500, 2800 and 1300 | Hours |
| Max. No. of Repairs | 6, 5 and 3 | 3,2 and 2 | Repairs |
| Inspection Time | EXPO(1), EXPO(2) and EXPO(5) | EXPO(1), EXPO(2) and EXPO(5) | Hours |
| Repair Time | EXPO(3), EXPO(4) and EXPO(7) | EXPO(2), EXPO(3) and EXPO(5) | Hours |
| Lead Time | TRIA(1,3,7), TRIA(1,4,7) and TRIA(1,5,7) | TRIA(1,3,7), TRIA(1,4,7) and TRIA(1,5,7) | Hours |
| Max. Operating Hours and Repair Time Value for Overhauled Spare Part | Repair Time New Value = EXPO(7) Max. Operating Hours + 1000 | | Hours |
| Holding Cost Fraction | 0.1 | 0.1 | - |

Table 17 presents details of the quantities of spare parts that went in and came out of the various processes. Table 18 shows the average, minimum and maximum number of spare parts waiting in the various processes. Table 19 shows the various costs (busy, idle and usage costs) that are linked to various processes. Table 20 shows the number of on-hand inventory of repaired, new, PM and CM spare parts.

Table 17: Spare parts' process quantities in and out

| Process | Number In | Number Out | Productivity (%) |
|---|---|---|---|
| Inspection | 864.00 | 64.0000 | 7.41 |
| Repair | 35.0000 | 2.0000 | 5.71 |

Table 18: Spare parts' waiting for processes

| Process | Average | Maximum |
|---|---|---|
| Inspection | 388.71 | 799.00 |
| Repair | 18.1326 | 33.0000 |

Table 19: Resources' busy, idle and usage costs

| Process | Busy Cost (M.U) | Idle Cost (M.U) | Usage Cost (M.U) | Total of Busy and Usage Cost (M.U) |
|---|---|---|---|---|
| Inspection and Repair Technician | 20,747.04 | 11.0000 | 2,345.00 | 23,092.04 |
| LT SPs | 2,336.11 | 1,258,247.92 | 300.00 | 2,636.11 |
| Material Handling Shortage of All Spare Parts | 2,317.00 | 19.6901 | 11,592.00 | 13,909.00 |
| Ordering New SP1 | 50.0000 | 5,845.00 | 120.00 | 170.00 |
| Ordering New SP2 | 12.5000 | 5,871.25 | 30.0000 | 42.50 |
| Ordering New SP3 | 12.5000 | 5,871.25 | 30.0000 | 42.50 |
| Resource PM and CM SPs | 903.25 | 7,289.03 | 880.00 | 1,783.25 |
| Total Cost (M.U) | 38,558 | 1,311,123 | 19,647 | 58,205.00 |

Table 20: Number of on-hand inventory of spare parts' quantities and costs

| Spare Parts Quantities | Actual Ending Quantity | Holding Cost (M.U) |
|---|---|---|
| NOHSP1 | 39.0000 | 3,900.00 |
| NOHSP2 | 16.0000 | 2,400.00 |
| NOHSP3 | 68.0000 | 13,600.00 |
| ROHSP1 | 0.00 | 0.00 |
| ROHSP2 | 0.00 | 0.00 |
| ROHSP3 | 0.00 | 0.00 |
| PMSP1 and CMSP1 Waiting | 11 | Total for PMSP1 and CMSP1, 903.25 (Backorder Cost) |

Tables 17 to 20 show comprehensive results of this SFIS-M-QR. Most of the defined processes of this inventory system were utilized with the orders of new spare parts being generated for all three spare parts. Some of the spare parts' were discarded whereas some of them were repaired as well. All spare parts do not leave the various processes of this inventory system. This means some of the spare parts were waiting to be processed in the queue of various processes. Running the Arena simulation for a comparatively longer period of time will result in more number of PM and CM spare parts to be processed. Most of the cost is from the idle cost which is justified by the same fact that as PM and CM spare parts wait in the various processes of this inventory system, this leads to the resources in those processes to remain underutilized and hence this incurs less busy cost and less usage cost and more idle cost for resources. It can also be observed from the results that PMSP1 and CMSP1 have to wait or be held in the inventory until either repaired or new spare parts or both repaired and new spare parts become available. This holding process of PM or CM spare part incurs some cost (shortage cost) which is given by the resource name of' Resource PM and CM SPs 'in Table 19. In addition to this, there were some new spare parts remaining in the end of the simulation run as given by the variables' quantities of NOHSP1, NOHSP2 and NOHSP3. These incurred cost as well. Consequently, by analyzing this single-facility inventory system for multiple spare parts in this simulation run, it was observed that this simulation generated 4, 1 and 1 order of new spare parts for SP1, SP2 and SP3 respectively. However, this resulted in many of the spare parts to remain inside various 'Process' modules without successfully leaving those 'Process' modules. As seen from the previous Tables that the value of NOHSP1, NOHSP2 and NOHSP3 are 39, 16 and 68 respectively which are acceptable quantities of spare parts after the simulation run. Therefore, the EOQ values defined for SP1, SP2 and SP3 are justified in this case. Consequently, it is suggested to improve this inventory system by modifying it. Modifications can be done in various ways, for example by taking in less demand of PM and CM spare parts' from the facilities. In other words, increasing the Time Between Failures (TBF) of spare parts or assigning a value for the maximum arrivals of PM and CM spare parts instead of assigning these to infinite. Furthermore, different processes in this simulation could be conducted faster or more inspection and repair facilities could be added to make the whole inventory system process faster so that more number of spare parts leave various 'Process' modules successfully, without waiting and without forming a queue of spare parts outside the various processes. These modifications or improvements could be considered as a future work of this research.

**3.4.2. SFIS-M model using L4L ordering policy.** This type of Single-Facility Inventory System for multiple repairable item using L4L ordering policy handles the inventory system when an exact number of new spare parts for the three types of spare parts are ordered every time based on the number of PM or CM spare parts that came from the facility.

**3.4.2.1. *SFIS-M-L4L model development.*** SFIS-M-L4L model was developed using the Arena simulation software. Same Arena simulation model was used but with all spare parts PMSP1, PMSP2 and PMSP3, CMSP1, CMSP2 and CMSP3,. In addition to this, 3 preventive maintenance spare parts are further divided based on the percentage of demand of these 3 spare parts (50% for SP1, 30% for SP2 and 20% for SP3). Same percentages of demand are assigned to corrective maintenance spare parts as well.

**3.4.2.2. *SFIS-M-L4L model validation.*** Simulation validation was carried out for single repairable item. This validation also applies to multiple repairable items as well. By handling the first type of spare part at a time and then the second type of spare part and then the third type of spare part, this SFIS-M-L4L model is validated. This will produce similar results to the SFIS-S-L4L model validation. The difference between the validation of multiple spare parts and single spare part is that, in multiple spare part, each type of spare part is validated turn by turn.

**3.4.2.3. *SFIS-M-L4L illustrative example.*** Simulation model was developed using the Arena simulation software considering SFIS-M-L4L. Same input data Tables as the SFIS-S-QR case were used for the case of SFIS-S-L4L inventory system. Tables 21, 22, and 23 summarizes the results for SFIS-M-L4L case. Table 21 shows the productivity of both the inspection and repair processes. Table 22 shows the average and the maximum value of spare parts that were waiting in various processes of the inventory system. Table 23 shows the various costs that were incurred when the simulation for this inventory system was run.

Table 21: Spare parts' process quantities in and out

| Process | Number In | Number Out | Productivity (%) |
|---|---|---|---|
| Inspection | 715.00 | 46.0000 | 6.43 |
| Repair | 18.0000 | 0.00 | 0 |

Table 22: Spare parts' waiting for processes and variable values

| Process/ Variable | Average | Maximum |
|---|---|---|
| Hold CMSP1 | 9.0937 | 30.0000 |
| Hold CMSP2 | 6.0532 | 18.0000 |
| Hold CMSP3 | 4.6771 | 16.0000 |
| Hold PMSP1 | 21.9603 | 61.0000 |
| Hold PMSP2 | 9.6475 | 32.0000 |
| Hold PMSP3 | 7.4858 | 23.0000 |
| Discard Process | 0.02729317 | 2.0000 |
| Inspection | 353.28 | 683.00 |
| Repair | 6.1800 | 18.0000 |
| LotSize SP1 | 53.1512 | 85.0000 |
| LotSize SP2 | 27.7182 | 49.0000 |
| LotSize SP3 | 21.2882 | 33.0000 |
| NOHSP1 / NOHSP2 / NOHSP3 | 0.00 | 0.00 |
| ROHSP1 / ROHSP2 / ROHSP3 | 0.00 | 0.00 |

Table 23: Resources' busy, idle and usage costs

| Process | Busy Cost (M.U) | Idle Cost (M.U) | Usage Cost (M.U) | Total of Busy and Usage Cost (M.U) |
|---|---|---|---|---|
| Discard | 11,340.00 | 28,169.91 | 4,200.00 | 15,540.00 |
| Inspection and Repair Technician | 17,952.03 | 1,575.17 | 1,645.00 | 19,597.03 |
| LT SPs | 0.00 | 1,260,000.00 | 900.00 | 900.00 |
| Material Handling Shortage of All Spare Parts | 2,209.20 | 81.0667 | 11,053.00 | 13,262.20 |
| Ordering New SP1 / SP2 / SP3 | 75.0000 | 5,826.92 | 210.00 | 285.00 |
| Resource PM and CM SPs | 21,438.69 | 1,090.50 | 10,080.00 | 31,518.69 |
| Total Cost (M.U) | 53,165 | 1,308,565 | 28,508 | 81,673.00 |

Table 24 shows the actual ending inventory for each of the new spare parts and repaired spare parts. It also shows the number of PM and CM spare parts waiting in the inventory of PM and CM spare parts, which incurs a backorder cost.

Table 24: Number of on-hand inventory of spare parts' quantities and costs

| Spare Parts Quantities | Actual Ending Quantity | Holding Cost (M.U) |
|---|---|---|
| NOHSP1 / NOHSP2 / NOHSP3 | 0.00 | 0.00 |
| ROHSP1 / ROHSP2 / ROHSP3 | 0.00 | 0.00 |
| PMSP1 and CMSP1 Waiting | 456.00 | Total for PMSP1 and CMSP1, 21,438.69 (Backorder Cost) |
| PMSP2 and CMSP2 Waiting | 233.00 | |
| PMSP3 and CMSP3 Waiting | 174.00 | |

Tables 21 to 24 show comprehensive results of the SFIS-M-L4L. Most of the defined processes of this inventory system were utilized with the orders of new spare parts being generated for the single spare part. Some of the spare parts' for that type were discarded whereas some of them entered the repaired process as well. In this SFIS-M-L4L case, the average lot sizes generated for SP1, SP2 and SP3 are approximately 53, 27 and 21 respectively. 7 orders of new spare parts were generated within the simulation replication length of 7 days. No new spare parts and repaired spare parts were held in the inventory of new and repaired spare parts respectively in the end of the simulation run. The total busy cost for the SFIS-M-L4L case is higher than that for the SFIS-S-L4L case as three spare parts are used in the SFIS-M-L4L case as opposed to just one spare part in the SFIS-S-L4L case. When some on-hand inventory of spare parts are considered for SP1, SP2 and SP3 then the ordering of new spare parts for these spare parts are different. This is because, the Arena simulation software utilizes the on-hand inventory of spare parts first to cater for preventive and corrective maintenance. After the on-hand inventory of spare parts are utilized for SP1, SP2 and SP3, the simulation software then creates ordering of new spare parts for SP1, SP2 and SP3. In this scenario when some on-hand inventory of spare parts are considered for SP1, SP2 and SP3, the numbers of orders generated for SP1, SP2 and SP3 are less than the case when no on-hand inventory of spare parts are considered. The output from the repair process is 0 because a single resource is used for the inspection and the repair process and that single resource is busy only in the inspection process and hence a large number of spare parts are held in the repair process queue., which makes the repair facility of SFIS-M-L4L inventory system less productive.

# Chapter 4. Simulation Models of Inventory Systems for Repairable Items – Multiple Operating Facilities

This chapter discusses the simulation that was developed for multi-facility inventory system in a centralized inventory system environment using the Arena simulation software.

## 4.1. Multi-Facility Inventory Systems for Repairable Items: Overview

Multi-Facility Inventory System (MFIS) handles multiple facilities. The concept in multi-facility inventory remains the same as that in the single-facility inventory system. The facilities have both preventive and corrective maintenance spare parts. Preventive Maintenance (PM) spare parts are sent for overhauling in the repair facility and this is replaced by a new spare part taken from the inventory of new spare parts. On the other hand, Corrective Maintenance (CM) spare parts are sent to the repair facility. The CM spare parts can either be repaired or discarded if not repairable. This CM spare parts is replaced by either a repaired spare part taken from the inventory of repaired spare parts or a new spare part taken from the inventory of new spare parts.

In addition to this, the multi-facility inventory system can either be for single (MFIS-S) in which just one type of spare part is involved or multiple (MFIS-M) repairable items in which many types of spare parts are involved. Inventory system for repairable items can either be designed for (Q, R) lot sizing or Lot-Lot (L4L). (Q, R) lot sizing is when a fixed number of new spare parts are ordered every time the number of new spare parts become equal to or less than the Re-Order Point (ROP) of new spare parts. On the other hand, L4L sizing is conducted based on the demand of new spare parts at a particular point in time.

Figure 19 shows the multi-facility inventory system flowchart with 3 facilities for the (Q, R) inventory system. In this Figure, the overall concept of managing spare parts from the facilities remain the same as that in a single-facility inventory system. When more facilities are added, this will increase the number of preventive maintenance and corrective maintenance spare parts that enter the inventory system. As a result of this, the repair facility and other sections of the inventory system becomes occupied with many spare parts. The various processes of this inventory system become more busy and the PM and CM spare parts have to wait longer to be processed.

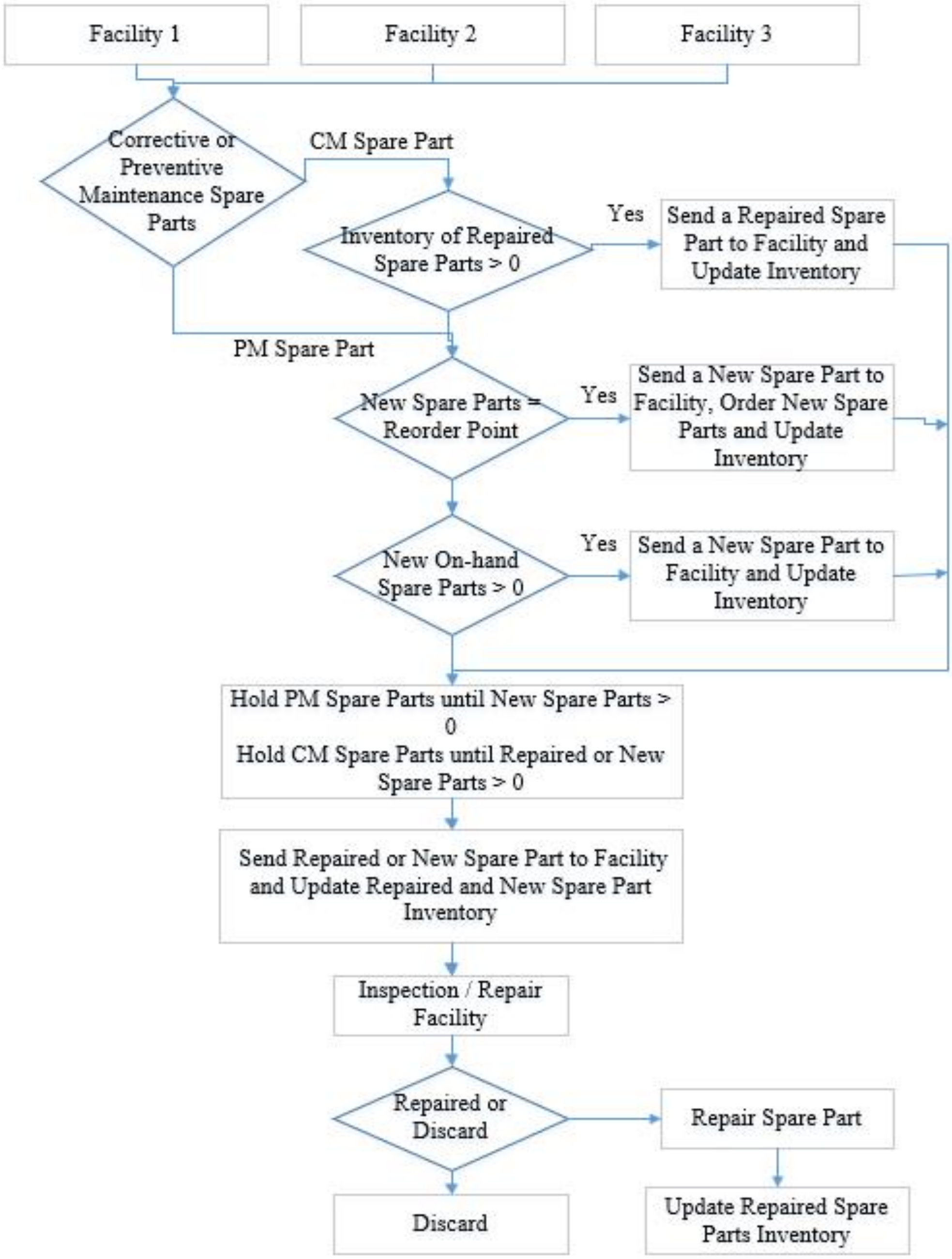


Figure 19: Flowchart of multi-facility inventory system for the (Q, R) system

All faulty spare parts go through an inspection process for repairability. If CM spare parts are repairable, then these spare parts are sent to the repair facility for repair after which the spare parts are held in the inventory of repaired spare parts in order to be reused for corrective maintenance. Some PM spare parts are overhauled so that they can be used for a prolonged amount of time. If the CM spare parts are not repairable, then these spare parts are discarded as shown in Figure 19.

Moreover, the multi-facility inventory system can either be for single repairable item (SFIS-S) in which just one type of spare part is involved or multiple repairable items (SFIS-M) in which many types of spare parts are involved. Inventory system for repairable items can either be (Q, R) or Lot-Lot (L4L), modeled using lot size / reorder point. Ordering policy (Q, R) is the policy of ordering a fixed number of new spare parts every time the number of new spare parts reaches the Re-Order Point (ROP) of new spare parts. On the other hand, L4L ordering policy is conducted based on the demand for new spare parts at a particular point in time.

## 4.2. MFIS Simulation Models for a Single Repairable Item

Multi-Facility Inventory System for a single repairable item (MFIS-S) handles multiple facilities with just one type of spare part.

**4.2.1. MFIS-S model using (Q, R) ordering policy.** This type of Multi-Facility Inventory System for a single repairable item using (Q, R) ordering policy handles the inventory system when a fixed number of new spare parts for that one type of spare part are ordered every time the number of new spare parts become equal to or less than the Re-Order Point (ROP) of new spare parts. Abbreviation MFIS-S-QR will be used to show the Multi-Facility Inventory System for a single repairable item using (Q, R) ordering policy.

**4.2.1.1. *MFIS-S-QR model development.*** MFIS-S-QR model was developed using the Arena simulation software. The overall Arena simulation model remains the same for multi-facility inventory as that for single-facility inventory system. The only difference is that 2 more facilities are added in the Arena simulation model of multi-facility inventory system. PM and CM spare parts enter this inventory system in the same way as in the case of single-facility inventory system. However, in this case, PM spare part (PMSP1) and CM spare part (CMSP1) come from the three facilities and enter this multi-facility inventory system. After these PM and CM spare parts go through the various processes inside this multi-facility inventory system, repaired and new spare parts exit this multi-facility inventory system and are then assigned to those three facilities where preventive or corrective maintenance is required. Figure 20 shows the step of faulty spare parts entering the system from the facilities having one type of faulty spare part.

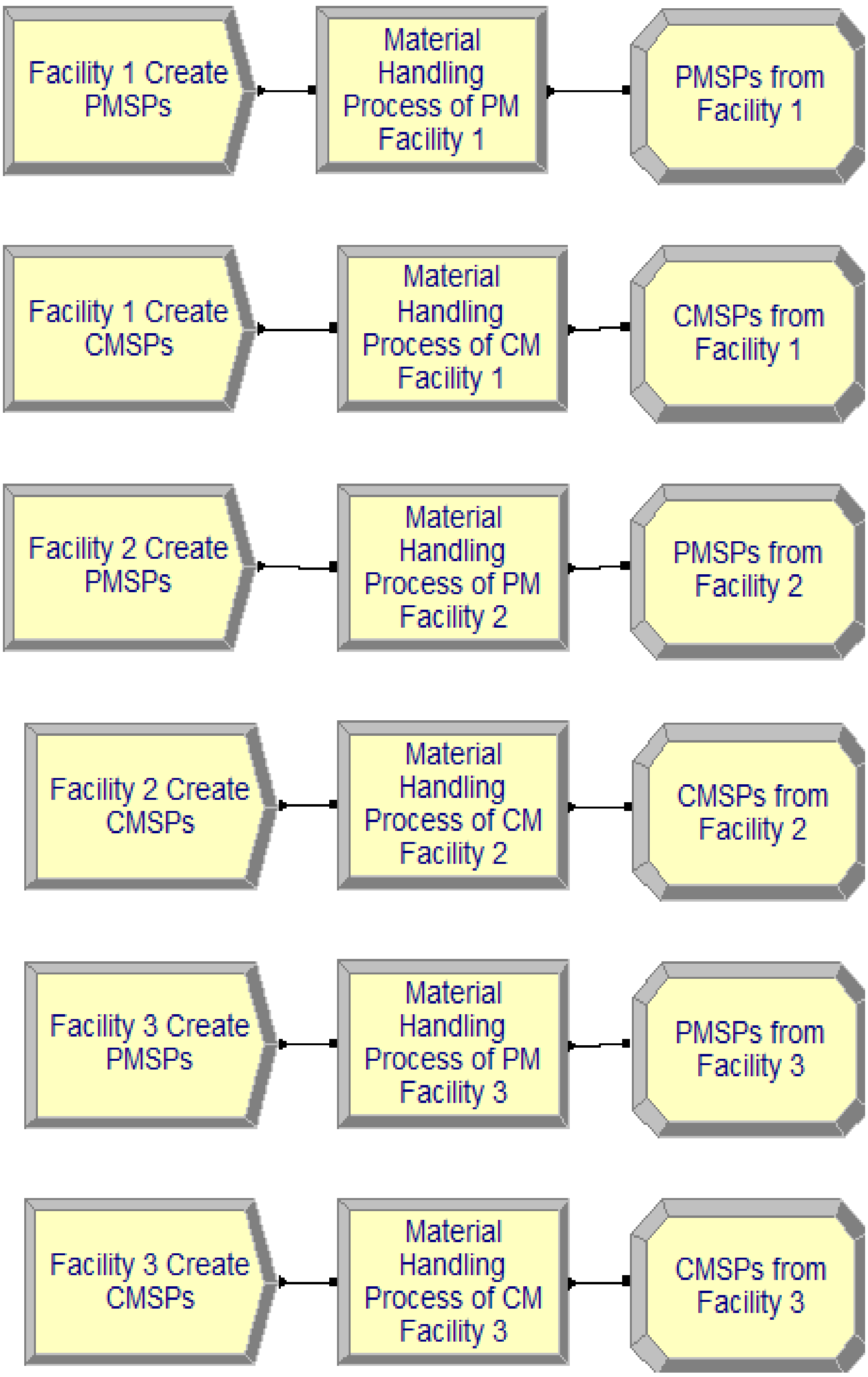


Figure 20: Creation of spare parts and their assignments

In Figure 20, two 'Create' modules are used for each facility. One 'Create' module is used for preventive maintenance and the other 'Create' module is used for corrective maintenance. Figure 21 shows the procedure of sending the spare parts to the facilities. 'Decide' modules are used to send the spare parts to the correct facilities from where they came in. The rest of the modules and the procedure remain the same as that in the single-facility inventory system.

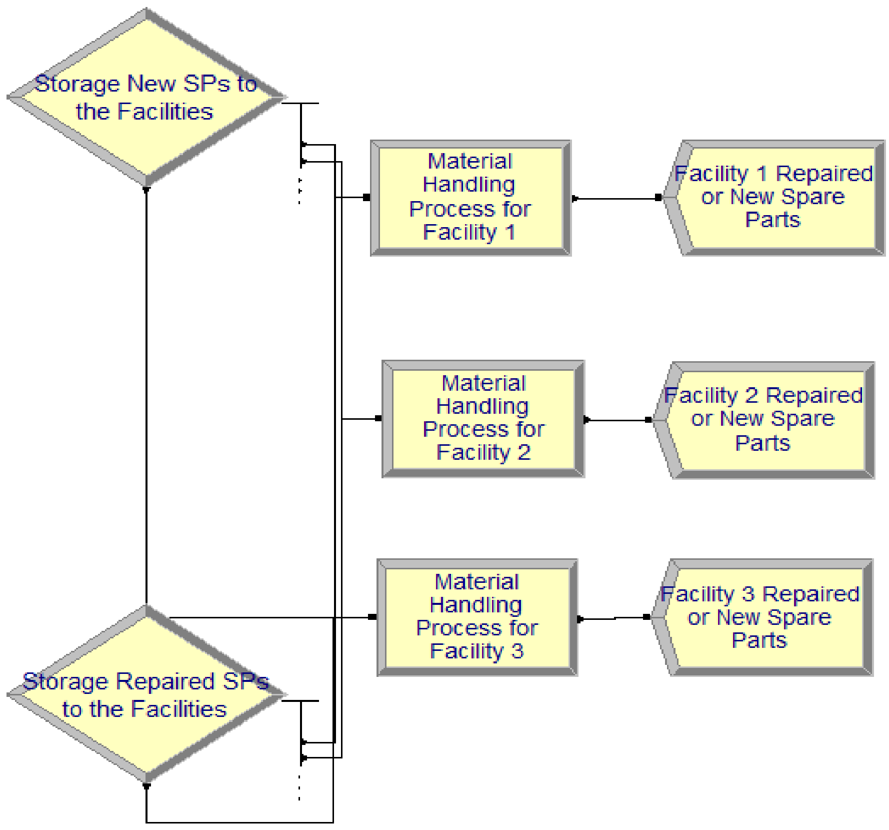


Figure 21: Installation or storing of spare parts in the facilities

**4.2.1.2. *MFIS-S-QR model validation.*** Simulation validation was carried out for single-facility, single repairable item. This validation also applies to multiple – facility, single repairable item as well. By handling one facility at a time and then the second facility and then the third facility, this MFIS-S-QR model is validated. This will produce similar results to the SFIS-S-QR model validation.

**4.2.1.3. *MFIS-S-QR illustrative example.*** For illustrating the proposed MFIS-S-QR model, multi-facility (3 facilities) inventory system with one type of repairable spare part is considered. Same input parameters and their values were used for this multi-facility inventory case as is in the case of the single-facility inventory system.

Additionally, number of replications in the Arena simulation software that were considered was 1 and a Replication Length of 7 days was assigned.

Table 25 presents details of the quantities of spare parts that went in and came out of the various processes. Table 26 shows the average, minimum and maximum number of spare parts waiting in the various processes. Table 27 shows the various costs (busy, idle and usage costs) that are linked to various processes. Finally, Table 28 shows the number of on-hand inventory of repaired, new, PM and CM spare parts and their corresponding holding costs at the end of the simulation run.

Table 25: Spare parts' process quantities in and out

| Process | Number In | Number Out | Productivity (%) |
|---|---|---|---|
| Inspection | 1160.0000 | 86.0000 | 7.41 |
| Repair | 71.0000 | 8.0000 | 11.27 |

Table 26: Spare parts' waiting for processes

| Process | Average | Maximum |
|---|---|---|
| Inspection | 551.70 | 1073.00 |
| Repair | 34.1285 | 63.0000 |

Table 27: Resources' busy, idle and usage costs

| Process | Busy Cost (M.U) | Idle Cost (M.U) | Usage Cost (M.U) | Total of Busy and Usage Cost (M.U) |
|---|---|---|---|---|
| Discard | 6,300.00 | 30,600.00 | 2,250.00 | 8,550.00 |
| Inspection and Repair Technician | 20,856.75 | 10.0131 | 3,325.00 | 24,181.75 |
| LT SPs | 3,393.39 | 1,257,454.96 | 550.00 | 3,943.39 |
| Material Handling Shortage of All Spare Parts | 2,350.60 | 0.4324 | 11,760.00 | 14,110.60 |
| Ordering New SP1 | 137.50 | 5,783.75 | 330.00 | 467.50 |
| Resource PM and CM SPs | 5,500.84 | 5,909.75 | 12,400.00 | 17,900.84 |
| **Total Cost (M.U)** | 38,539 | 1,311,687 | 30,615 | 69,154.00 |

Table 28: Number of on-hand inventory of spare parts' quantities and costs

| Spare Parts Quantities | Actual Ending Quantity | Holding Cost (M.U) |
|---|---|---|
| NOHSP1 | 12.0000 | 1200.00 |
| ROHSP1 | 0.00 | 0.00 |
| PMSP1 and CMSP1 Waiting | 155 | Total for PMSP1 and CMSP1, 5,500.84 (Backorder Cost) |

Tables 25 to 28 show comprehensive results of the MFIS-S-QR. Most of the defined processes of this inventory system were utilized with the orders of new spare parts (11 orders) being generated for the one spare part. Some of the spare parts' for that type of spare part were discarded whereas some of them were repaired as well. All spare parts do not leave the various processes of this inventory system. This means some of the spare parts were waiting to be processed in the queue of various processes. Running the Arena simulation for a comparatively longer period of time will result in more number of PM and CM spare parts to be processed. Most of the cost is from the idle cost which is justified by the same fact that as PM and CM spare parts wait in the various processes of this inventory system, this leads to the resources in those processes to remain underutilized and hence this incurs less busy cost and less usage cost and more idle cost for resources. It can also be observed from the results that PMSP1 and CMSP1 have to wait or be held in the inventory until either repaired or new spare parts or both repaired and new spare parts become available. This holding process of PM or CM spare part incurs some cost (shortage cost) which is given by the resource name of' Resource PM and CM SPs 'in Table 27. This cost is also called the backorder cost. In addition to this, there were some new spare parts remaining in the end of the simulation run as given by the variable' quantities of NOHSP1. Consequently, by analyzing this multi-facility inventory system for a single repairable item in this simulation run, it was observed that this simulation generated a big order of new spare parts for that type of spare part. However, this resulted in many of the spare parts to remain inside various 'Process' modules without successfully leaving those 'Process' modules. As seen from the Tables above that the value of NOHSP1 is 12, which is the number of on-hand new spare parts after the simulation run. This number is fine and therefore it is suggested to keep the same EOQ value for SP1 as this will result in a lower value of NOHSP1. Consequently, it is suggested to improve this inventory system by modifying it. Modifications can be done in various ways, for example by taking in less demand of PM and CM spare parts' from the facility. In other words, increasing the Time Between Failures of spare parts or assigning a value for the maximum arrivals of PM and CM spare parts instead of assigning these to infinite. Furthermore, different processes in this simulation could be conducted faster or more inspection and repair facilities could be added to make the whole inventory system process faster so that more number of spare parts leave various 'Process' modules successfully. These modifications or improvements could be considered as a future work of this research which could assist in improving this particular inventory system and ordering policy.

**4.2.2. MFIS-S model using L-4-L ordering policy.** The Multi-Facility Inventory System for a single repairable item using L-4-L ordering policy (MFIS-S-L4L) handles the inventory system when an exact number of new spare parts for multiple spare parts are ordered every time based on the number of PM or CM spare parts that came from the various facilities.

**4.2.2.1. *MFIS-S-L4L model development.*** The overall Arena simulation model remains the same for multi-facility inventory as that for single-facility inventory system. The only difference is that 2 more facilities are added in the Arena simulation model of multi-facility inventory system. PM and CM spare parts enter this inventory system in the same way as in the case of single-facility inventory system. However, in this case, PM spare parts (PMSP1, PMSP2 and PMSP3) and CM spare parts (CMSP1, CMSP2 and CMSP3) come from the three facilities and enter this multi-facility inventory system. After these PM and CM spare parts go through the various processes inside this multi-facility inventory system, repaired and new spare parts exit this multi-facility inventory system and are then assigned to those three facilities where preventive or corrective maintenance is required.

**4.2.2.2. *MFIS-S-L4L model validation.*** Simulation validation was carried out for single-facility, single repairable item. This validation also applies to multiple – facility, single repairable item as well. By handling one facility at a time and then the second facility and then the third facility, this MFIS-S-L4L model is validated. This will produce similar results to the SFIS-S-L4L model validation.

**4.2.2.3 *MFIS-S-L4L illustrative example.*** For illustrating the proposed MFIS-S-L4L model, multi-facility (3 facilities) inventory system with one type of repairable spare part is considered. Same input parameters, quantities, resources and cost values were used as in the earlier case. The assumptions in the L4L case are that orders are made every day and that there are no new spare parts in the inventory (NOHSP1=0, NOHSP2=0 and NOHSP3=0) initially. Apart from this, number of replications in the Arena simulation software that were considered was 1 and a Replication Length of 7 days was assigned. Tables 29, 30 and 31 summarizes the results of this type of inventory system. As can be observed that the results are in the same form as that of SFIS-S-L4L inventory system case.

Table 29: Spare parts' process quantities in and out

| Process | Number In | Number Out | Productivity (%) |
|---|---|---|---|
| Inspection | 960.00 | 134.00 | 13.96 |
| Repair | 102.0000 | 0.00 | 0.00 |

Table 30: Spare parts' waiting for processes and variable values

| Process/ Variable | Average | Maximum |
|---|---|---|
| Hold CMSP1 | 33.1738 | 110.00 |
| Hold PMSP1 | 53.1490 | 177.00 |
| Discard Process | 0.01498364 | 1.0000 |
| Inspection | 477.80 | 859.00 |
| Repair | 38.8970 | 102.00 |
| LotSize SP1 | 137.16 | 240.00 |
| NOHSP1 | 0.00 | 0.00 |
| ROHSP1 | 0.00 | 0.00 |

Table 31: Resources' busy, idle and usage costs

| Process | Busy Cost (M.U) | Idle Cost (M.U) | Usage Cost (M.U) | Total of Busy and Usage Cost (M.U) |
|---|---|---|---|---|
| Discard | 13,440.00 | 27,200.00 | 4,800.00 | 18,240.00 |
| Inspection and Repair Technician | 17,863.99 | 1,575.17 | 4,725.00 | 22,588.99 |
| LT SPs | 0.00 | 1,260,000 | 300.00 | 300.00 |
| Material Handling Shortage of All Spare Parts | 2,350.60 | 0.4324 | 11,760.00 | 14,110.60 |
| Ordering New SP1 | 75.0000 | 5,826.92 | 210.00 | 285.00 |
| Resource PM and CM SPs | 21,508.94 | 1,090.50 | 12,080.00 | 33,588.94 |
| Total Cost (M.U) | 55,239 | 1,307,621 | 34,875 | 90,114.00 |

Table 32 shows the actual ending inventory for the new spare part and the repaired spare part. It also shows the number of PM and CM spare parts waiting in the inventory of PM and CM spare parts. As observed again that the results in this Table are similar to the results that were generated for the SFIS-S-L4L inventory system case as both these cases involved use of a single spare part.

Table 32: Number of on-hand inventory of spare parts' quantities and costs

| Spare Parts Quantities | Actual Ending Quantity | Holding Cost (M.U) |
|---|---|---|
| NOHSP1 | 0.00 | 0.00 |
| ROHSP1 | 0.00 | 0.00 |
| PMSP1 and CMSP1 Waiting | 1167 | Total for PMSP1 and CMSP1, 21,508.94 |

Tables 29 to 32 show comprehensive results of the MFIS-S-L4L. Most of the defined processes of this inventory system were utilized with the orders of new spare parts (7 orders) being generated for the single spare part. Some of the spare parts' for that type were discarded whereas some of them entered the repaired process as well. In this MFIS-S-L4L case, the average lot size generated for SP1 is approximately 137. As can be seen from the Tables that 7 orders of new spare parts were generated and 6 of them left the ordering 'Process' module within the simulation replication length of 7 days. No new spare parts and repaired spare parts were held in the inventory of new and repaired spare parts respectively in the end of the simulation run. The total busy cost for the MFIS-S-L4L case is much higher than that for the MFIS-S-QR case. A Lot size average of approximately 137 spare parts and a maximum of 240 spare parts are generated for SP1 for the multi-facility inventory case during a replication length of 7 days as compared to an average lot size of approximately 103 only and a maximum lot size of 158 for the single-facility inventory case. The output from the repair process is 0 because a single resource is used for the inspection and the repair process and that single resource is busy only in the inspection process and hence a large number of spare parts are held in the repair process queue. If two different resources are used for the inspection and the repair process instead then the PM and CM spare parts pass through the repair 'Process' module and are overhauled and repaired respectively.

## 4.3. MFIS Simulation Models for a Multi Repairable Item

Multi-Facility Inventory System for multi repairable item (MFIS-M) handles multiple facilities with multiple spare parts.

**4.3.1. MFIS-M Model using (Q, R) ordering policy.** This type of Multi-Facility Inventory System for multiple repairable item using (Q, R) ordering policy handles the inventory system when a fixed number of new spare parts for multiple types of spare parts are ordered every time the number of new spare parts become equal to or less than the Re-Order Point (ROP) of new spare parts. Abbreviation MFIS-M-QR will be used to show the Mingle-Facility Inventory System for multiple repairable items using (Q, R) ordering policy.

**4.3.1.1.** ***MFIS-M-QR model development.*** MFIS-M-QR model was developed using the Arena simulation software. Same Arena simulation model was used but with all spare parts, PMSP1, PMSP2 and PMSP3, CMSP1, CMSP2 and CMSP3 and 3 facilities. In addition to this, 3 preventive maintenance spare parts are further divided based on the percentage of demand of these 3 spare parts (50% for SP1, 30% for SP2 and 20% for SP3). Same percentages of demand are assigned to corrective maintenance spare parts as well. Various 'Decide' modules are used in the Arena simulation software to distribute the three different types of spare parts.

**4.3.1.2.** ***MFIS-M-QR model validation.*** Simulation validation was carried out for single-facility, single repairable item. This validation also applies to multi-facility, multiple repairable items as well. By handling the first type of spare part at a time and then the second type of spare part and then the third type of spare part from all three facilities simultaneously, this MFIS-M-QR model is validated. This will produce similar results to the SFIS-S-QR model validation.

**4.3.1.3.** ***MFIS-M-QR illustrative example.*** Simulation model was developed using the Arena simulation software considering MFIS-M-QR. Same Tables as before were used but with three different spare parts and three facilities. Following are the results for MFIS-M-QR. Table 33 presents details of the quantities of spare parts that went in and came out of the various processes. Table 34 shows the average, minimum and maximum number of spare parts waiting in the various processes. Table 35 shows the various costs (busy, idle and usage costs) that are linked to various processes. Table 36 shows the number of on-hand inventory of repaired, new, PM and CM spare parts and their corresponding holding costs in the end of the simulation run.

These Tables are similar to the Tables that were shown for the SFIS-M-QR inventory system case as both these Tables involved the use of multiple repairable spare parts. The difference is that this inventory system or ordering policy is for multiple facilities, whereas the SFIS-M-QR case was for a single facility.

Table 33: Spare parts' process quantities in and out

| Process | Number In | Number Out | Productivity (%) |
|---|---|---|---|
| Inspection | 1152.00 | 49.0000 | 4.25 |
| Repair | 30.0000 | 1.0000 | 3.33 |

Table 34: Spare parts' waiting for processes

| Process | Average | Maximum |
|---|---|---|
| Inspection | 555.81 | 1102.00 |
| Repair | 14.3424 | 29.0000 |

Table 35: Resources' busy, idle and usage costs

| Process | Busy Cost (M.U) | Idle Cost (M.U) | Usage Cost (M.U) | Total of Busy and Usage Cost (M.U) |
|---|---|---|---|---|
| Discard | 7,980.00 | 29,800.00 | 2,850.00 | 10,830.00 |
| Inspection and Repair Technician | 20,302.05 | 10.0131 | 1,785.00 | 22,087.05 |
| LT SPs | 3,202.94 | 1,257,515.60 | 450.00 | 3,652.94 |
| Material Handling Shortage of All Spare Parts | 2,350.60 | 0.4324 | 11,760.00 | 14,110.60 |
| Ordering New SP1 | 75.0000 | 5,827.50 | 180.00 | 255.00 |
| Ordering New SP2 | 25.0000 | 5,862.50 | 60.0000 | 85.00 |
| Ordering New SP3 | 12.5000 | 5,871.25 | 30.0000 | 42.50 |
| Resource PM and CM SPs | 2,383.39 | 6,844.98 | 2,560.00 | 4,943.39 |
| Total Cost (M.U) | 36,331 | 1,311,900 | 19,675 | 56,006.00 |

Table 36: Number of on-hand inventory of spare parts' quantities and costs

| Spare Parts Quantities | Actual Ending Quantity | Holding Cost (M.U) |
|---|---|---|
| NOHSP1 | 4.0000 | 400.00 |
| NOHSP2 | 23.0000 | 3450.00 |
| NOHSP3 | 32.0000 | 6400.00 |
| ROHSP1 | 0.00 | 0.00 |
| ROHSP2 | 0.00 | 0.00 |
| ROHSP3 | 0.00 | 0.00 |
| PMSP1 and CMSP1 Waiting | 32 | Total for PMSP1 and CMSP2, 2,383.39 (Backorder Cost) |
| PMSP2 and CMSP2 Waiting | 0.00 | 0.00 |
| PMSP3 and CMSP3 Waiting | 0.00 | 0.00 |

Tables 33 to 36 show comprehensive results of this MFIS-M-QR. Most of the defined processes of this inventory system were utilized with the orders of new spare parts being generated for all three spare parts. Some of the spare parts' were discarded whereas some of them were repaired as well. All spare parts do not leave the various processes of this inventory system. This means some of the spare parts were waiting to be processed in the queue of various processes. Running the Arena simulation for a comparatively longer period of time will result in more number of PM and CM spare parts to be processed. Most of the cost is from the idle cost which is justified by the same fact that as PM and CM spare parts wait in the various processes of this inventory system, this leads to the resources in those processes to remain underutilized and hence this incurs less busy cost and less usage cost and more idle cost for resources. It can also be observed from the results that PMSP1 and CMSP1 have to wait or be held in the inventory until either repaired or new spare parts or both repaired and new spare parts become available. This holding process of PM or CM spare part incurs some cost (shortage cost) which is given by the resource name of' Resource PM and CM SPs 'in Table 35. In addition to this, there were some new spare parts remaining in the end of the simulation run as given by the variables' quantities of NOHSP1, NOHSP2 and NOHSP3. These incurred cost as well. Consequently, by analyzing this multi-facility inventory system for multiple spare parts in this simulation run, it was observed that this simulation generated 6, 2 and 1 orders of new spare parts orders for SP1, SP2 and SP3 respectively. However, this resulted in many of the spare parts to remain inside various 'Process' modules without successfully leaving those 'Process' modules. As seen from the Tables above that the value of NOHSP1, NOHSP2 and NOHSP3 are 4, 23 and 32 respectively which are acceptable quantities of spare parts after the simulation run. Therefore, the EOQ values defined for SP1, SP2 and SP3 are justified in this case. Consequently, it is suggested to improve this inventory system by modifying it. Modifications can be done in various ways, for example by taking in less demand of PM and CM spare parts' from the facilities. In other words, increasing the Time Between Failures of spare parts or assigning a value for the maximum arrivals of PM and CM spare parts instead of assigning these to infinite. Furthermore, different processes in this simulation could be conducted faster or more inspection and repair facilities could be added to make the whole inventory system process faster These modifications or improvements could be considered as a future work of this research.

**4.3.2. MFIS-M model using L4L ordering policy.** This type of Multi-Facility Inventory System for multiple repairable item using L4L ordering policy handles the inventory system when an exact number of new spare parts for the three types of spare parts are ordered every time based on the number of PM or CM spare parts that came from the facility.

**4.3.2.1.** ***MFIS-M-L4L model development.*** MFIS-M-L4L model was developed using the Arena simulation software. Same Arena simulation model was used but with all spare parts, PMSP1, PMSP2 and PMSP3, CMSP1, CMSP2 and CMSP3. In addition to this, 3 preventive maintenance spare parts are further divided based on the percentage of demand of these 3 spare parts (50% for SP1, 30% for SP2 and 20% for SP3). Same percentages of demand are assigned to corrective maintenance spare parts as well.

**4.3.2.2.** ***MFIS-M-L4L model validation.*** Simulation validation was carried out for single repairable item. This validation also applies to multiple repairable items as well. By handling the first type of spare part at a time and then the second type of spare part and then the third type of spare part, this MFIS-M-L4L model is validated. This will produce similar results to the SFIS-S-L4L model validation. The difference between the validation of multiple spare parts and single spare part is that, in multiple spare part, each type of spare part is validated turn by turn.

**4.3.2.3.** ***MFIS-M-L4L illustrative example.*** Simulation model was developed using the Arena simulation software considering MFIS-M-L4L. Same input data Tables as the MFIS-M-QR case were used for the case of MFIS-M-L4L inventory system. Tables 37, 38, 39 and 40 summarizes the results for MFIS-M-L4L case.

These Tables are similar to the Tables that were shown for the MFIS-M-L4L inventory case. In Table 38, the number of preventive and corrective maintenance spare parts on hold are shown as an average value and as a maximum value. This Table also shows the average and the maximum lot size that was generated in the inventory system during the simulation run. The average lot size is the average of all the number of lot sizes that were generated during the simulation run. The maximum lot size is the maximum value of the lot size that was attained during the simulation run of 7 days and 24 hours of work per day.

Table 37: Spare parts' process quantities in and out

| Process | Number In | Number Out | Productivity (%) |
|---|---|---|---|
| Inspection | 960.00 | 42.0000 | 4.38 |
| Repair | 16.0000 | 0.00 | 0.00 |

Table 38: Spare parts' waiting for processes and variable values

| Process/ Variable | Average | Maximum |
|---|---|---|
| Hold CMSP1 | 14.4011 | 46.0000 |
| Hold CMSP2 | 8.6512 | 32.0000 |
| Hold CMSP3 | 5.2078 | 30.0000 |
| Hold PMSP1 | 30.6871 | 107.00 |
| Hold PMSP2 | 16.0744 | 51.0000 |
| Hold PMSP3 | 11.2387 | 39.0000 |
| Discard Process | 0.00748568 | 1.0000 |
| Inspection | 507.67 | 928.00 |
| Repair | 4.6695 | 16.0000 |
| LotSize SP1 | 70.2950 | 132.00 |
| LotSize SP2 | 40.5781 | 70.0000 |
| LotSize SP3 | 26.2914 | 57.0000 |

Table 39: Resources' busy, idle and usage costs

| Process | Busy Cost (M.U) | Idle Cost (M.U) | Usage Cost (M.U) | Total of Busy and Usage Cost (M.U) |
|---|---|---|---|---|
| Discard | 10,920.00 | 28,400.00 | 3,900.00 | 14,820.00 |
| Inspection and Repair Technician | 17,731.46 | 1,575.17 | 1,505.00 | 19,236.46 |
| LT SPs | 0.00 | 1,260,000.00 | 900.00 | 900.00 |
| Material Handling Shortage of All Spare Parts | 2,350.60 | 0.4324 | 11,760.00 | 14,110.60 |
| Ordering New SP1 / SP2 / SP3 | 75.0000 | 5,826.92 | 210.00 | 285.00 |
| Resource PM and CM SPs | 21,532.93 | 1,090.50 | 7,600.00 | 29,132.93 |
| Total Cost (M.U) | 52,760 | 1,308,715 | 26,295 | 79,055.00 |

Table 40: Number of on-hand inventory of spare parts' quantities and costs

| **Spare Parts Quantities** | **Actual Ending Quantity** | **Holding Cost (M.U)** |
|---|---|---|
| NOHSP1 / NOHSP2 / NOHSP3 | 0.00 | 0.00 |
| ROHSP1 / ROHSP2 / ROHSP3 | 0.00 | 0.00 |
| PMSP1 and CMSP1 Waiting | 586.00 | Total for PMSP1 and CMSP1, 21,532.93 (Backorder Cost) |
| PMSP2 and CMSP2 Waiting | 351.00 | |
| PMSP3 and CMSP3 Waiting | 241.00 | |

Tables 37 to 40 show comprehensive results of the MFIS-M-L4L inventory case. Most of the defined processes of this inventory system were utilized with the orders of new spare parts being generated for the single spare part. Some of the spare parts' for that type were discarded whereas some of them entered the repaired process as well. In this MFIS-M-L4L case, the average lot sizes generated for SP1, SP2 and SP3 are approximately 70, 40 and 26 respectively, which are greater than the SFIS-M-L4L inventory case. 7 orders of new spare parts were generated within the simulation replication length of 7 days. No new spare parts and repaired spare parts were held in the inventory of new and repaired spare parts respectively in the end of the simulation run. When some on-hand inventory of spare parts are considered for SP1, SP2 and SP3 then the ordering of new spare parts for these spare parts are different and lot sizes of these spare parts also decreases. This is because, the Arena Simulation software utilizes the on-hand inventory of spare parts first to cater for preventive and corrective maintenance. After the on-hand inventory of spare parts are utilized for SP1, SP2 and SP3, the simulation software then creates ordering of new spare parts for SP1, SP2 and SP3. In this scenario when some on-hand inventory of spare parts are considered for SP1, SP2 and SP3, the numbers of orders generated for SP1, SP2 and SP3 are less than the case when no on-hand inventory of spare parts are considered. In addition to this, the output from the repair process is 0 because a single resource is used for the inspection and the repair process and that single resource is busy only in the inspection process and hence a large number of spare parts are held in the repair process queue. If two different resources are used for the inspection and the repair process instead then the PM and CM spare parts pass through the repair 'Process' module and are overhauled and repaired respectively. Therefore, by defining a different resource for the repair facility and assigning some initial spare parts in the inventory of new spare parts variable, some spare parts' quantities appear in the on-hand inventory of repaired and new spare parts and the lot sizes of SP1, SP2 and SP3 decreases as a result after the simulation run.

# Chapter 5. Case Study on Multi-Facility Inventory System for Repairable Items

This chapter includes a case study on a centralized multi-facility inventory system. Two simulation models were developed, namely the (Q, R) and L4L inventory systems for investigating the ordering policy of the inventory system.

## 5.1. Case Study Development

This case study was conducted using 4 different spare parts and 7 different facilities, which is a larger simulation model. The procedure of developing this case study is the same as that developed in the earlier sections of this report. However, in this case study, the simulation is run for a replication length of 1 month, with 8 hours per day of work. 4 spare parts and 7 facilities were used. The 4 spare parts can be selected by conducting classification of spare parts. These 4 classified spare parts are the most important spare parts that are required to conduct this case study. Tables 41 and 42 show the data used for this case study. For each facility, Time Between Arrivals or Failures (TBF) is defined for corrective maintenance. For each spare part Inspection Time (IT), Repair Time (RT) and Lead Time (LT) are defined. All parameters except lead time in Table 41 are taken as exponential distribution. Assigning these distinct parameters to the spare parts and facilities will assist in developing an enlarged simulation for this case study.

Table 41: Data for SP1 and SP2

| | SP1 | | | | SP2 | | | |
|---|---|---|---|---|---|---|---|---|
| Facility | TBF | IT (PM) | RT (PM) | LT | TBF | IT (PM) | RT (PM) | LT |
| | | IT (CM) | RT (CM) | | | IT (CM) | RT (CM) | |
| Facility 1 | EXP(0.5) | EXP(1) | EXP(3) | TRI(1,3,7) | EXP(0.5) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(1) | EXP(2) | | | EXP(2) | EXP(3) | |
| Facility 2 | EXP(1) | EXP(1) | EXP(3) | TRI(1,3,7) | EXP(1) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(1) | EXP(2) | | | EXP(2) | EXP(3) | |
| Facility 3 | EXP(1.5) | EXP(1) | EXP(3) | TRI(1,3,7) | EXP(1.5) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(1) | EXP(2) | | | EXP(2) | EXP(3) | |
| Facility 4 | EXP(1) | EXP(1) | EXP(3) | TRI(1,3,7) | EXP(1) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(1) | EXP(2) | | | EXP(2) | EXP(3) | |
| Facility 5 | EXP(0.75) | EXP(1) | EXP(3) | TRI(1,3,7) | EXP(0.75) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(1) | EXP(2) | | | EXP(2) | EXP(3) | |
| Facility 6 | EXP(0.8) | EXP(1) | EXP(3) | TRI(1,3,7) | EXP(0.8) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(1) | EXP(2) | | | EXP(2) | EXP(3) | |
| Facility 7 | EXP(0.85) | EXP(1) | EXP(3) | TRI(1,3,7) | EXP(0.85) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(1) | EXP(2) | | | EXP(2) | EXP(3) | |

Table 42: Data for SP3 and SP4

| | SP3 | | | | SP4 | | | |
|---|---|---|---|---|---|---|---|---|
| Facility | TBF | IT (PM) / IT (CM) | RT (PM) / RT (CM) | LT | TBF | IT (PM) / IT (CM) | RT (PM) / RT (CM) | LT |
| Facility 1 | EXP(0.5) | EXP(5) | EXP(7) | TRI(1,3,7) | EXP(0.5) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(5) | EXP(5) | | | EXP(2) | EXP(5) | |
| Facility 2 | EXP(1) | EXP(5) | EXP(7) | TRI(1,3,7) | EXP(1) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(5) | EXP(5) | | | EXP(2) | EXP(5) | |
| Facility 3 | EXP(1.5) | EXP(5) | EXP(7) | TRI(1,3,7) | EXP(1.5) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(5) | EXP(5) | | | EXP(2) | EXP(5) | |
| Facility 4 | EXP(1) | EXP(5) | EXP(7) | TRI(1,3,7) | EXP(1) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(5) | EXP(5) | | | EXP(2) | EXP(5) | |
| Facility 5 | EXP(0.75) | EXP(5) | EXP(7) | TRI(1,3,7) | EXP(0.75) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(5) | EXP(5) | | | EXP(2) | EXP(5) | |
| Facility 6 | EXP(0.8) | EXP(5) | EXP(7) | TRI(1,3,7) | EXP(0.8) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(5) | EXP(5) | | | EXP(2) | EXP(5) | |
| Facility 7 | EXP(0.85) | EXP(5) | EXP(7) | TRI(1,3,7) | EXP(0.85) | EXP(2) | EXP(4) | TRI(1,4,7) |
| | | EXP(5) | EXP(5) | | | EXP(2) | EXP(5) | |

Table 43 summarizes the preventive maintenance schedule for each facility.

Table 43: Facilities' schedule for PM spare parts for 1 month

| **Day** | **No. of spare parts / hour for Facility 1** | **No. of spare parts / hour for Facility 2** | **No. of spare parts / hour for Facility 3** | **No. of spare parts / hour for Facility 4** | **No. of spare parts / hour for Facility 5** | **No. of spare parts / hour for Facility 6** | **No. of spare parts / hour for Facility 7** |
|---|---|---|---|---|---|---|---|
| 1 | 5 | 4 | 3 | 0 | 0 | 1 | 2 |
| 2 | 2 | 1 | 2 | 1 | 0 | 0 | 0 |
| 3 | 3 | 1 | 1 | 2 | 1 | 1 | 1 |
| 4 | 6 | 2 | 0 | 3 | 2 | 2 | 2 |
| 5 | 4 | 3 | 0 | 4 | 3 | 3 | 5 |
| 6 | 3 | 2 | 2 | 2 | 1 | 0 | 2 |
| 7 | 5 | 2 | 1 | 2 | 1 | 0 | 1 |
| 8 | 2 | 2 | 4 | 2 | 0 | 1 | 1 |
| 9 | 3 | 0 | 2 | 0 | 0 | 2 | 3 |
| 10 | 4 | 0 | 2 | 0 | 0 | 3 | 2 |
| 11 | 5 | 1 | 0 | 1 | 1 | 4 | 0 |
| 12 | 1 | 2 | 0 | 1 | 0 | 5 | 4 |
| 13 | 0 | 3 | 0 | 1 | 3 | 6 | 5 |
| 14 | 3 | 4 | 1 | 2 | 2 | 1 | 6 |
| 15 | 2 | 2 | 0 | 2 | 4 | 1 | 7 |
| 16 | 4 | 5 | 4 | 3 | 5 | 2 | 1 |
| 17 | 0 | 4 | 2 | 3 | 2 | 3 | 0 |
| 18 | 2 | 2 | 0 | 5 | 1 | 4 | 1 |
| 19 | 0 | 0 | 3 | 3 | 0 | 2 | 1 |
| 20 | 5 | 0 | 3 | 2 | 0 | 0 | 0 |
| 21 | 1 | 2 | 1 | 1 | 2 | 2 | 0 |
| 22 | 1 | 2 | 1 | 2 | 1 | 1 | 1 |

Table 43 (cont.)

| Day | No. of spare parts / hour for Facility 1 | No. of spare parts / hour for Facility 2 | No. of spare parts / hour for Facility 3 | No. of spare parts / hour for Facility 4 | No. of spare parts / hour for Facility 5 | No. of spare parts / hour for Facility 6 | No. of spare parts / hour for Facility 7 |
|---|---|---|---|---|---|---|---|
| 23 | 2 | 3 | 1 | 3 | 0 | 0 | 2 |
| 24 | 3 | 3 | 2 | 1 | 0 | 1 | 1 |
| 25 | 5 | 4 | 1 | 1 | 1 | 1 | 0 |
| 26 | 6 | 5 | 5 | 1 | 2 | 2 | 4 |
| 27 | 2 | 9 | 4 | 2 | 3 | 3 | 2 |
| 28 | 0 | 7 | 2 | 2 | 4 | 2 | 3 |
| 29 | 0 | 0 | 0 | 3 | 1 | 2 | 1 |
| 30 | 2 | 1 | 0 | 4 | 0 | 4 | 0 |

Table 44 summarizes the process parameters used for this case study.

Table 44: Resource and cost parameters and their values

| Process | # of Resource | Processing Time (Hours) PM | Processing Time (Hours) CM | Cost Busy / Hour, Idle / Hour & Usage / Hour (M.U) | Cost / Order (M.U) |
|---|---|---|---|---|---|
| Material Handling | 5 | 0.10 | 0.10 | 14 [49], 0.5, 0.75 | |
| Inspection and Repair Technician 1 and 2 | 5 | EXPO(1) | EXPO(1) | 125 [50], 0.5, 0.75 | |
| Ordering of New SP1, SP2, SP3 and SP4 | 1 | 0.25 | 0.25 | - | 50 |
| Discard Process Resource | 1 | 1 | 1 | 420 [52],0.5,0.75 | |

## 5.2. Simulation Model Development

The simulation model for this case study was developed in a similar procedure as that in the earlier sections of this thesis report. Each of the four PM and CM spare part that came from the facility was assigned an arrival percentage of 25%. Figure 22 and Figure 23 shows the 7 facilities and 4 spare parts that were used for this case study in the simulation software respectively. Each facility in this case study has two modules in the simulation to generate PM and CM spare parts. One module is used to generate PM spare parts whereas the other module is used to generate CM spare parts. These modules are then connected to the material handling process modules in order to transfer spare parts from the facilities to the inventory system.

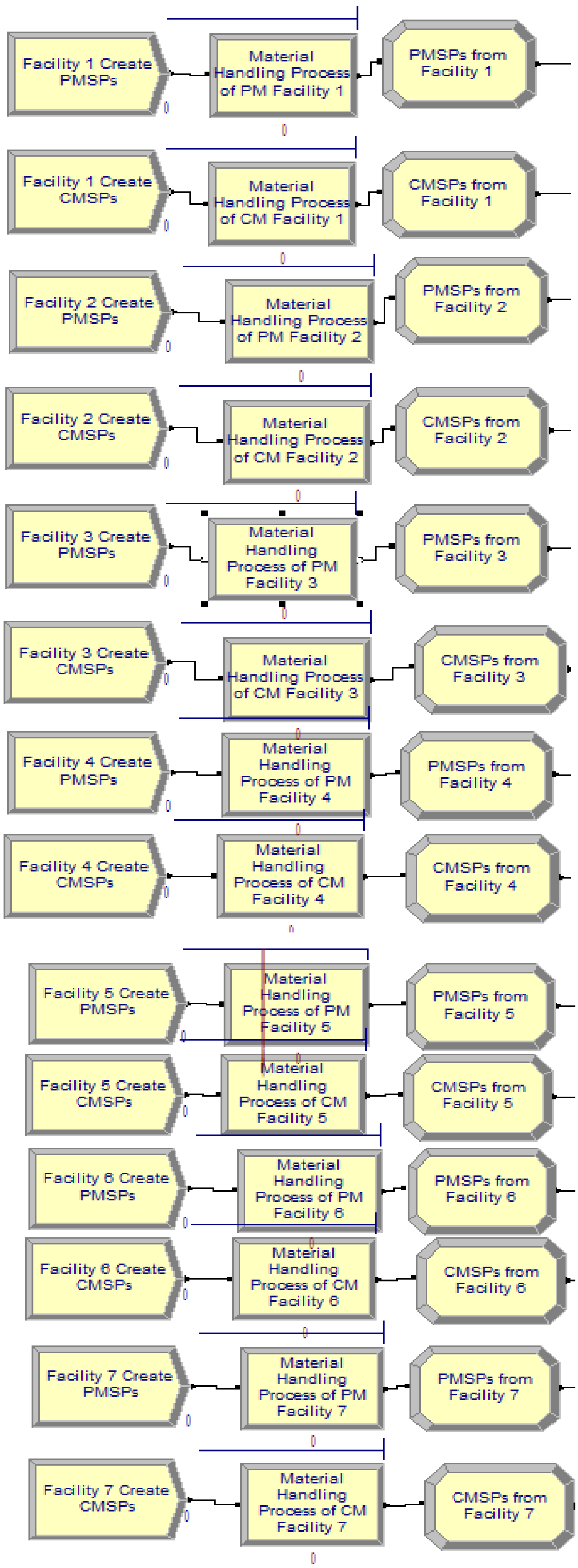


Figure 22: Creation of 7 facilities

Figure 23 shows how four PM spare parts are distributed to various locations in the inventory system. This is similar to the procedure described in the earlier chapters of the report.

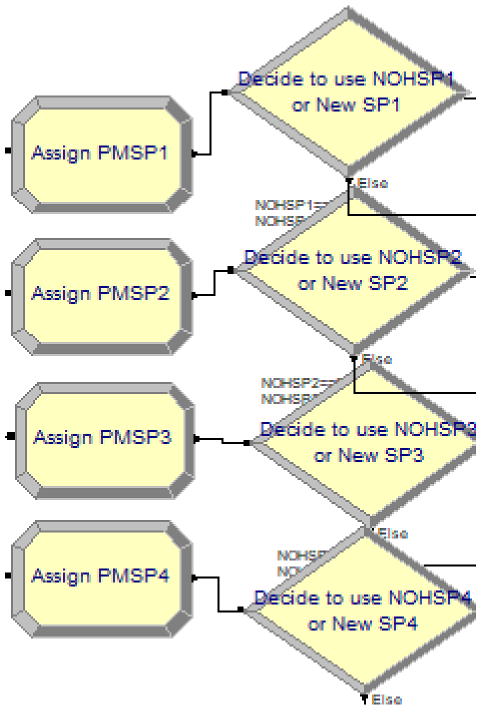


Figure 23: Distribution of 4 PM and CM spare parts

## 5.3. Running the Simulation Model

This sub section includes the results of this case study along with a discussion of the results. The simulation was run by considering that all 7 facilities start sending PM and CM spare parts to the inventory system at the same time. In addition to this, a single facility sends PM and CM spare parts also at the same time.

**5.3.1. Results for the (Q. R) inventory system.** Tables 45, 46, 47, 48 and 49 summarizes the results for the (Q, R) inventory system. These Tables are similar to the Tables that were shown in the illustrative example section of this report.

Table 45: Spare parts' process quantities in and out

| Process | Number In | Number Out | Productivity (%) |
|---|---|---|---|
| Inspection | 5352.00 | 474.00 | 8.86 |
| Repair | 195.00 | 161.00 | 82.56 |

Table 46: Spare parts' waiting for processes

| Process | Average | Maximum |
|---|---|---|
| Inspection | 2372.97 | 4873.00 |
| Repair | 12.7778 | 30.0000 |

Table 47: Resources' busy, idle and usage costs

| Process | Busy Cost (M.U) | Idle Cost (M.U) | Usage Cost (M.U) | Total of Busy and Usage Cost (M.U) |
|---|---|---|---|---|
| Discard | 99,120.00 | 1.5427 | 177.75 | 99,297.75 |
| Inspection and Repair Technician | 291,142.34 | 9.5358 | 483.75 | 291,626.09 |
| LT SPs | 21,161.11 | 5,946.42 | 26.0000 | 21,187.11 |
| Material Handling Shortage of All Spare Parts | 14,921.20 | 66.9744 | 7997.25 | 22,918.45 |
| Ordering New SP1 | 175.00 | 8,271.80 | 450.00 | 625.00 |
| Ordering New SP2 | 175.00 | 8,312.50 | 300.00 | 475.00 |
| Ordering New SP3 | 175.00 | 8,277.50 | 420.00 | 595.00 |
| Ordering New SP4 | 175.00 | 8,277.50 | 420.00 | 595.00 |
| Resource PM and CM SPs | 8,083.74 | 46.5271 | 99.50 | 8,183.24 |
| Total Cost (M.U) | 435,078 | 39,210 | 10,374 | 445,452.00 |

Table 48: Actual ordering costs

| Spare Part | Actual Ordering Cost (M.U) |
|---|---|
| SP1 | 7,500.00 |
| SP2 | 5,000.00 |
| SP3 | 7,000.00 |
| SP4 | 7,000.00 |

Table 49: Number of on-hand inventory of spare parts' quantities and costs

| On-Hand Inventory | Spare Part | Actual Ending Quantity | Holding Cost (M.U) |
|---|---|---|---|
| New Spare Parts | SP1 | 20.00 | 2,000.00 |
| | SP2 | 99.00 | 14,850.00 |
| | SP3 | 16.00 | 3,200 |
| | SP4 | 21.00 | 4,200 |
| Repaired Spare Parts | SP1 | 0.00 | 0.00 |
| | SP2 | 0.00 | 0.00 |
| | SP3 | 0.00 | 0.00 |
| | SP4 | 0.00 | 0.00 |
| PM and CM Spare Parts (Backordered Spare Parts) | SP1/SP2/SP3/SP4 | 58.0000/2.0000/118.00/21.0000 | 8,083.74 (Backorder Cost) |

Actual ordering cost in this case study was calculated by multiplying the number of spare parts that entered the ordering process with the ordering cost per order. This ordering cost calculation is added inside a ‘Record’ module of the ‘holding cost calculation based on percentage of holding cost’ section and is calculated just 2 minutes before the simulation ends. Tables 45 to 49 show comprehensive results for the (Q, R) inventory system of this case study. Two different resources were used for the inspection and repair process. Most of the defined processes of this inventory system were utilized with the orders of new spare parts being generated for all four spare parts. Some of the spare parts’ were discarded whereas some of them were repaired as well. All spare parts do not leave the various processes of this inventory system. This means some of the spare parts were waiting to be processed in the queue of various processes. idle cost is also incurred which is justified by the fact that as PM and CM spare parts wait in the various processes of this inventory system, this leads to the resources in those processes to remain underutilized and hence this incurs idle cost for resources. In addition to this, there were some new spare parts remaining in the end of the simulation run. This incurred cost as well. Consequently, by analyzing this case study on multi-facility inventory system for a larger number of spare parts and facilities in this simulation run of 1 month, it was observed that this simulation generated significant 15, 10, 14 and 14 orders of new spare parts for SP1, SP2, SP3 and SP4 respectively. However, this resulted in many of the spare parts to remain inside various ‘Process’ modules without successfully leaving those ‘Process’ modules. As seen from the Tables that the value of NOHSP1, NOHSP2, NOHSP3 and NOHSP4 are 20, 99, 16 and 21 respectively. There are were some PM and CM spare parts waiting to be held in the inventory of PM and CM spare parts in the end of the simulation run. This incurred backorder cost as given in the Table 49.

**5.3.2. Results for the L4L inventory system.** This case study was repeated for the L4L inventory case as well. The procedure of developing this case study is the same as that developed in the earlier sections of this report. However, in this case study, the simulation is run for a replication length of 1 month, with 8 hours per day. The ordering policy in this case is different Tables 50, 51, 52, 53 and 54 summarizes the results for the L4L inventory system. Tables 50 and 51 are similar to the Tables that were shown in the earlier sections of the report.

These Tables also shows the results for the number of spare parts entering and leaving inspection and repair processes and the average and the maximum number of spare parts waiting in various processes respectively.

Table 50: Spare parts' process quantities in and out

| Process | Number In | Number Out | Productivity (%) |
|---|---|---|---|
| Inspection | 5125.00 | 489.00 | 9.54 |
| Repair | 222.00 | 169.00 | 76.13 |

Table 51: Spare parts' waiting for processes and variable values

| Process/ Variable | Average | Maximum |
|---|---|---|
| Hold CMSP1 | 4.6457 | 28.0000 |
| Hold CMSP2 | 4.7665 | 23.0000 |
| Hold CMSP3 | 5.4282 | 28.0000 |
| Hold CMSP4 | 5.7057 | 24.0000 |
| Hold PMSP1 | 11.2948 | 43.0000 |
| Hold PMSP2 | 10.8219 | 46.0000 |
| Hold PMSP3 | 10.7749 | 41.0000 |
| Hold PMSP4 | 10.2858 | 39.0000 |
| Discard Process | 18.1295 | 46.0000 |
| Inspection | 2345.67 | 4642.00 |
| Repair | 20.2126 | 53.0000 |
| LotSize SP1 | 41.9357 | 60.0000 |
| LotSize SP2 | 39.4697 | 59.0000 |
| LotSize SP3 | 42.7692 | 59.0000 |
| LotSize SP4 | 41.0368 | 59.0000 |
| NOHSP1 / NOHSP2 / NOHSP3 / NOHSP4 | 0.00 / 0.00 / 0.00 / 0.00 | 0.00 / 0.00 / 0.00 / 0.00 |
| ROHSP1 / ROHSP2 / ROHSP3 / ROHSP4 | 0.3100 / 0.1864 / 0.06683766 / 0.00 | 4.0000 / 3.0000 / 3.0000 / 1.0000 |

Table 50 shows that the productivity of the inspection process is much lower than the productivity of the repair process. This is because there is just one inspection process which handles all the four different types of PM and CM spare parts from all the 7 facilities. Therefore, there is a longer queue of PM and CM spare parts waiting to enter the inspection process as compared to the repair process. This results in the inspection process to become clogged with spare parts and hence this gives a low productivity for the inspection process.

Table 52: Resources' busy, idle and usage costs

| Process | Busy Cost (M.U) | Idle Cost (M.U) | Usage Cost (M.U) | Total of Busy and Usage Cost (M.U) |
|---|---|---|---|---|
| Discard | 94,920.00 | 6.7279 | 170.25 | 95,090.25 |
| Inspection and Repair Technician | 271,373.86 | 79.553 | 501.00 | 271,874.86 |
| LT SPs | 0.00 | 6000.00 | 58.0000 | 58.00 |
| Material Handling Shortage of All Spare Parts | 14,579.60 | 79.2291 | 7,812.75 | 22,392.35 |
| Ordering New SP1 / SP2 / SP3 / SP4 | 362.50 | 8,145.67 | 900.00 | 1,262.50 |
| Resource PM and CM SPs | 34,669.82 | 2.0583 | 148.00 | 34,817.82 |
| Total Cost (M.U) | 416,993 | 38,750 | 12,290 | 394,302.00 |

Table 53: Actual ordering costs

| Spare Part | Actual Ordering Cost (M.U) |
|---|---|
| SP1 | 15,000.00 |
| SP2 | 15,000.00 |
| SP3 | 15,000.00 |
| SP4 | 15,000.00 |

Table 54: Number of on-hand inventory of spare parts' quantities and costs

| On-Hand Inventory | Spare Part | Actual Ending Quantity | Holding Cost M.U) |
|---|---|---|---|
| New Spare Parts | SP1, SP2, SP3 and SP4 | 0.00 | 0.00 |
| Repaired Spare Parts | SP4 | 1.00 | 6.0000 |
| PM and CM Spare Parts (Backordered Spare Parts) | SP1 | 1337.00 | 34,669.82 (Backorder Cost) |
| | SP2 | 1260.00 | |
| | SP3 | 1326.00 | |
| | SP3 | 1286.00 | |

Tables 52 to 54 show comprehensive results for the L4L inventory system of this case study. Most of the defined processes of this inventory system were utilized with the orders of new spare parts being generated for all four spare parts. Some of the spare parts' were discarded whereas some of them were repaired as well. All spare parts do not leave the various processes of this inventory system. This means some of the spare parts were waiting to be processed in the queue of various processes. idle cost is also incurred which is justified by the same fact that as PM and CM spare parts wait in the various processes of this inventory system, this leads to the resources in those processes to remain underutilized and hence this incurs idle cost for resources. In addition to this, there was just one repaired and no new spare parts remaining in the end of the simulation run. Consequently, by analyzing this case study on multi-facility inventory system for a larger number of spare parts and facilities in this simulation run of 1 month, it was observed that this simulation generated significant orders of new spare parts (30 orders) for the L4L inventory case for all the four types of spare parts. However, this resulted in many of the spare parts to remain inside various 'Process' modules without successfully leaving those 'Process' modules. It can also be observed that there is a significant number of PM and CM spare parts that are held in the inventory of PM and CM spare parts in the end of the simulation run. This incurred backorder cost as given in Table 54. This means that if the simulation is run for a longer period of time or if a greater number of repaired spare parts are available or if a greater number of orders of new spare parts are generated, then these PM and CM spare parts that are waiting in the inventory of PM and CM spare parts will be processed for preventive and corrective maintenance.

By comparing the (Q, R) and L4L inventory systems in this case study, it can be observed that in the end of the simulation run, the L4L inventory system incurs a lower busy cost than the (Q, R) inventory system. However, in the end of the simulation run, the (Q, R) inventory system incurs a higher holding cost for the repaired and new spare parts as compared to the L4L inventory system. This is justified because in the (Q, R) inventory system there is an abundance of new spare parts in the inventory of new spare parts to cater for preventive and corrective maintenance. In addition to this, there is already an existing inventory of new spare parts in the inventory of new spare parts in the (Q, R) inventory system case. This incurs a higher holding cost.

On the other hand, there is no existing inventory of new spare parts in the inventory of new spare parts in the L4L inventory system case and new spare parts are ordered according to the number of PM and CM spare parts that were stored in the inventory of PM and CM spare parts. Due to this, in the end of the simulation run there are a large number of PM and CM spare parts stored in the inventory of PM and CM spare parts in the L4L inventory system case. Therefore, by conducting this case study by using a larger number of spare parts and facilities, it can be concluded that the (Q, R) inventory system costs more in terms of ordering new spare parts and costs less in terms of holding PM and CM spare parts (backorder or shortage cost) and the L4L inventory system costs more in terms of holding PM and CM spare parts (backorder or shortage cost) and costs less in holding repaired and new spare parts in the inventory. As a result of this, as compared to the L4L inventory system case, in the (Q, R) inventory system case, a greater number of new and repaired spare parts are stored in the inventory of repaired and new spare parts.

In this case study, 4 spare parts and 7 facilities were the maximum that could considered. If a larger number of spare parts and facilities are considered than this, the simulation becomes extremely slow and also becomes congested with many simulation modules.

## 5.4. Sensitivity Analysis

Sensitivity Analysis was conducted by varying some parameters. Sensitivity analysis is a method of varying some parameters to see their effect on some other parameters. Conducting sensitivity analysis was vital in this thesis because this would show that how some costs, for example total inventory costs which is the sum of the ordering cost and holding cost, backorder cost and inspection and repair cost varies when some parameters related to the inventory system are varied. The parameters that will be varied are ordering cost, holding cost fraction and number of inspection and repair resources. By conducting this sensitivity analysis, the effect of changing the parameters on the total inventory cost is observed. The total inventory cost is the sum of ordering cost and holding cost. The percentage deviation of the parameters from the base are ±20%, ±40% and ±60%. Ordering cost has a base value of 500 M.U while holding cost has a base value of 0.1 and the number of inspection and repair processes have a base value of 5. Initially, the ordering cost per order is changed from -20% to +60% and the holding cost fraction and the number of inspection and repair resources are kept constant at their base value. Similarly, holding cost fraction is changed next and the other two parameters are kept constant. Finally, the number of inspection and repair resources are changed and the other two parameters are kept constant. This sensitivity analysis was conducted for a replication length of 1 month with 8 hours of work per day.

Table 55 and Table 56 summarizes the results of the sensitivity analysis for the (Q, R) and L4L inventory system case respectively.

Table 55: Sensitivity analysis results for the (Q, R) system

| **Changing Parameter** | **Percentage Deviation of Parameters** | | | | | | |
|---|---|---|---|---|---|---|---|
| | -60% | -40% | -20% | Base Value | +20% | +40% | +60% |
| | Total Inventory Cost (Ordering Cost + Holding Cost) (M.U) | | | | | | |
| Ordering Cost | 34,850 | 40,150 | 45,450 | 50,750 | 56,050 | 61,350 | 66,650 |
| Holding Cost Fraction | 36,200 | 41,050 | 45,900 | 50,750 | 55,600 | 60,450 | 65,300 |
| Number of Inspection and Repair Resources | 54,500 | 56,850 | 56,800 | 50,750 | 53,900 | 58,444 | 48,452 |

Table 56: Sensitivity analysis results for the L4L system

| **Changing Parameter** | **Percentage Deviation of Parameters** | | | | | | |
|---|---|---|---|---|---|---|---|
| | -60% | -40% | -20% | Base Value | +20% | +40% | +60% |
| | Total Inventory Cost (Ordering Cost + Holding Cost) (M.U) | | | | | | |
| Ordering Cost | 24,006 | 36,006 | 48,006 | 60,006 | 72,006 | 84,006 | 96,006 |
| Holding Cost Fraction | 60,002.4 | 60,003 | 60,004 | 60,006 | 60,007 | 60,008 | 60,009 |
| Number of Inspection and Repair Resources | 60,001 | 60,000 | 60,080 | 60,006 | 60,087 | 60,000 | 60,146 |

As can be observed from Table 55 that the total inventory cost varies from 34,850 M.U to 66,650 M.U when the ordering cost is varied, whereas the total inventory cost varies from 36,200 M.U to 65,300 M.U when the holding cost is varied. Changing the number of inspection and repair resources also has an effect on the total inventory cost (sum of ordering cost and holding cost). As the number of resources decreases from 20% to 60%, the total inventory cost varies between 54,500 M.U to 56,850 M.U, but generally decreases. This is due to the fact that as the number of resources in the repair facility decrease, the percentage of spare parts being repaired decrease as well. This leads to an increase in the number of orders of new spare parts for preventive and corrective maintenance and hence a decrease in the holding cost of repaired and new spare parts. Increasing the number of resources from 20% to 40%, decreases the number of orders of some new spare parts but overall increases the number of orders and number of on-hand new spare parts and hence increasing the holding cost. Increasing the number of resources from 40% to 60%, does not increase the holding cost of new spare parts but instead some more new parts are utilized and some less new spare parts are utilized than the +40% case. Generally, when a greater number of spare parts enter and leave the inspection and repair processes when the number of resources of inspection and repair processes increases, the consumption of repaired spare parts increases which increases the holding cost of new spare parts.

Table 56 shows the results obtained after conducting sensitivity analysis for the L4L inventory system case. As can be observed from Table 56 that ordering cost varies from 24,006 M.U to 96,006 M.U, whereas the holding cost is very small in all cases. This is because in the end of the simulation run, there are very few repaired and no new spare parts for the L4L inventory system case. All the repaired and new spare parts are utilized before the simulation run ends. The number of orders of new spare parts generated remains the same after each percentage deviation of the ordering cost per order. This happens when the ordering cost per order is varied in the sensitivity analysis. In the second case, when the ordering cost is fixed, the holding cost is very small for each percentage deviation of the holding cost fraction as there is very little or no holding cost in the L4L inventory case. This as a result generates an ordering cost of 60,000 M.U for each percentage deviation. Changing the number of inspection and repair resources does not affect the total inventory cost (sum of ordering cost and holding cost) as the number of orders generated remains the same for each percentage deviation of the number of inspection and repair resources. Tables 57 and 58 summarizes the results obtained for the number of inspection and repair resources parameter after the sensitivity analysis for both the (Q, R) and L4L inventory system cases respectively. These Tables show the change in the average inspection time, average repair time, utilization, total inspection repair cost and total inventory cost. It was important to analyze this data from the perspective of an MRO. Analyzing the average inspection waiting time will assist an MRO to improve its inspection process by adding or reducing the number of resources in the inspection process. The same reasoning applies for the repair process. The utilization parameter in will further assist an MRO to take decisions regarding the utilization of resources in these processes. It will also assist an MRO to control the inspection waiting time and the repair waiting time for the various processes in the inventory system.

Table 57: Inspection and repair resources factors for the (Q, R) system

| Factor | Percentage Deviation of the Number of Inspection and Repair Resources Parameter | | | | | | |
|---|---|---|---|---|---|---|---|
| | -60% | -40% | -20% | Base Value | +20% | +40% | +60% |
| Average Inspection Waiting Time (hours) | 118.09 | 110.48 | 105.15 | 103.74 | 102.83 | 98.2720 | 99.44 |
| Average Repair Waiting Time (hours) | 32.7645 | 28.5495 | 20.6061 | 15.6061 | 16.0605 | 17.1212 | 17.9471 |
| Utilization | 0.9896 | 0.9879 | 0.9902 | 0.9921 | 0.9912 | 0..9902 | 0.9893 |
| Total Inspection and Repair Busy Cost (M.U) | 116,931.8 | 174,977 | 232,173 | 291,142 | 349,862 | 405,522 | 464,175 |
| Total Inventory Cost (M.U) | 54,500 | 56,850 | 56,800 | 50,750 | 53,900 | 58,444 | 48,452 |

Table 58: Inspection and repair resources factors for the L4L system

| Factor | Percentage Deviation of the Number of Inspection and Repair Resources Parameter | | | | | | |
|---|---|---|---|---|---|---|---|
| | -60% | -40% | -20% | Base Value | +20% | +40% | +60% |
| Average Inspection Waiting Time (hours) | 121.54 | 112.99 | 118.11 | 108.68 | 104.94 | 102.43 | 100.65 |
| Average Repair Waiting Time (hours) | 11.3898 | 15.4877 | 18.6367 | 18.3982 | 21.8193 | 19.2844 | 20.8335 |
| Utilization | 0.8902 | 0.9177 | 0.927 | 0.9337 | 0.9376 | 0.9399 | 0.9428 |
| Total Inspection and Repair Busy Cost (M.U) | 105,588 | 158,179 | 217,094 | 271,373.86 | 325,819 | 386,779 | 439,422 |
| Total Inventory Cost (M.U) | 60,001 | 60,000 | 60,080 | 60,006 | 60,087 | 60,000 | 60,146 |

As can be seen from Table 57 that as the number of resources for inspection and repair increases, the average inspection and repair waiting time generally decreases. This is justified because as more number of resources are available for inspection and repair of spare parts, the average time that spare parts have to wait for inspection and repair decreases. As observed from Table 58 that the average inspection waiting time generally decreases as well as the number of resources is increased. The average repair time, however, increases in Table 58. As can be observed from the same Tables that the average inspection waiting time for the (Q, R) inventory system case is lower than that for the L4L inventory system, whereas the average repair waiting time for the (Q, R) inventory system case is higher than that for the L4L inventory system. There is some difference in the inspection waiting time of spare parts for the (Q, R) and L4L inventory system cases but there is also a difference in the repair waiting time of spare parts for the (Q, R) and L4L inventory system cases. This could be because in the (Q, R) inventory system case, there is already an existing inventory of new spare parts to cater for preventive and corrective maintenance as opposed to the L4L inventory system case, so the simulation software takes longer time to repair PM and CM spare parts as the requirement for preventive and corrective maintenance is filled by the new spare parts. The resource utilization is determined by taking the utilization (for example, Number of Resources Busy/Number of Resources Scheduled) at each instant in time and then the simulation software calculates a time-weighted average for this. This is higher for the (Q, R) inventory system case and lower for the L4L inventory system case because the average repair waiting time in the (Q, R) inventory system case is higher than that in the L4L inventory system case. This means that in the (Q, R) inventory system case more number of resources are mostly busy which leads to higher repair waiting time and higher resource utilization than the L4L inventory system case. Consequently, this leads to a higher inspection and repair busy cost for the (Q, R) inventory system than the L4L inventory system case.

Figures 24 and 25 summarizes the data in the Tables 57 and 58 in graphical forms respectively.

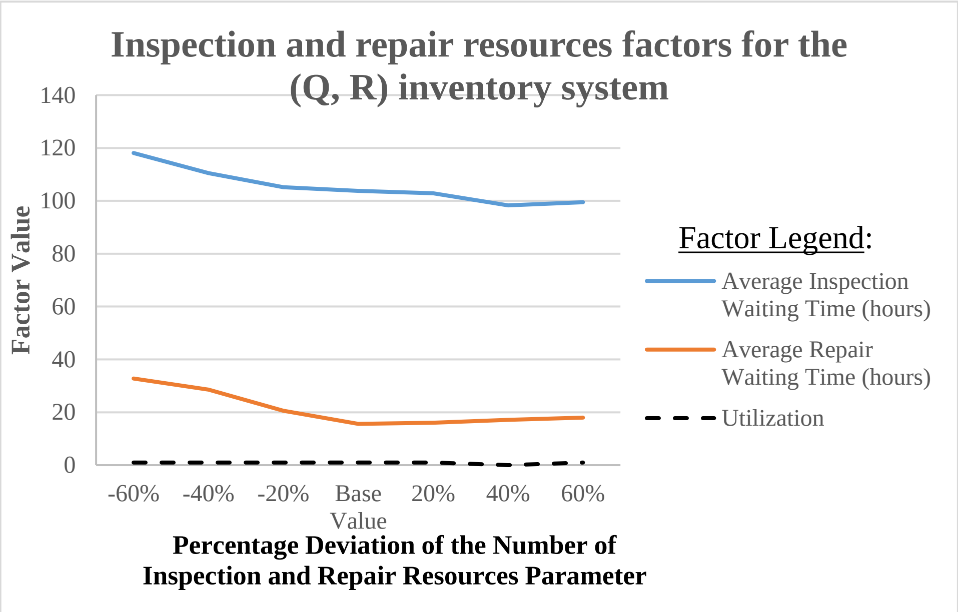


Figure 24: Analysis of inspection and repair resources for the (Q, R) system

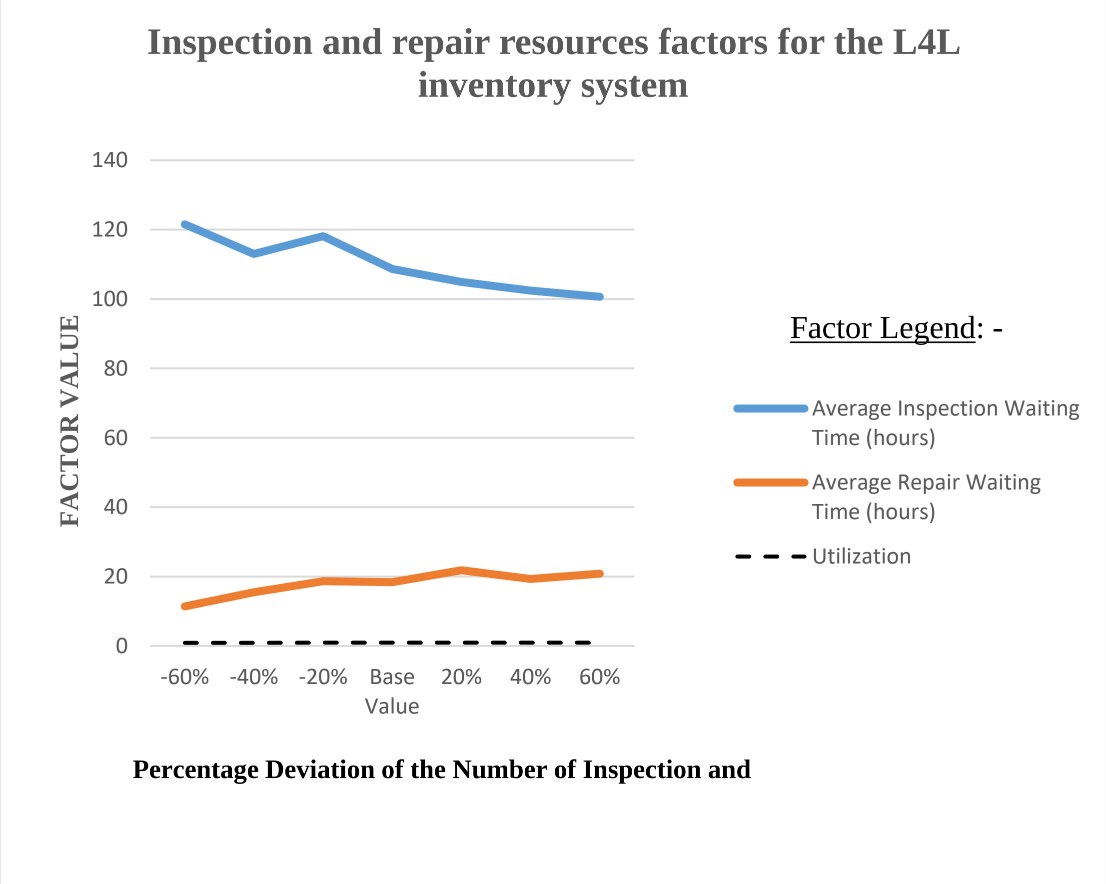


Figure 25: Analysis of inspection and repair resources for the L4L system

The explanation of these graphs follow the same explanation that was given for the Tables 57 and 58 earlier.

Tables 59, 60, 61 and 62 summarizes the sensitivity analysis for the (Q, R) and L4L inventory systems showing all types costs, In addition to this, Table 62 also shows the fill rate and the service level of all the spare parts in total for both the (Q, R) and L4L inventory systems.

Table 59: Sensitivity analysis for change in ordering costs per order' summary

| **% Deviation of Ordering Cost Per Order** | **Total Inventory Cost (Ordering Cost + Holding Cost) (M.U)** | |
|---|---|---|
| | **(Q, R)** | **L4L** |
| -60% | 34,850 | 24,006 |
| -40% | 40,150 | 36,006 |
| -20% | 45,450 | 48,006 |
| Base Value | 50,750 | 60,006 |
| +20% | 56,050 | 72,006 |
| +40% | 61,350 | 84,006 |
| +60% | 66,650 | 96,006 |
| Average | 50,750 | 60,006 |

Table 60: Sensitivity analysis for change in holding cost fraction summary

| % Deviation of Holding Cost Fraction | Total Inventory Cost (Ordering Cost + Holding Cost) (M.U) | |
|---|---|---|
| | (Q, R) | L4L |
| -60% | 36,200 | 60,002.40 |
| -40% | 41,050 | 60,003.60 |
| -20% | 45,900 | 60,004.80 |
| Base Value | 50,750 | 60,006 |
| +20% | 55,600 | 60,007.20 |
| +40% | 60,450 | 60,008.40 |
| +60% | 65,300 | 60,009.60 |
| Average | 50,750 | 60,006 |

Table 59 shows that by changing the ordering cost per order, the (Q, R) inventory system costs more than the L4L inventory system till the -40% case in terms of the total inventory cost, which is the sum of the ordering cost and holding cost. Table 60 shows that by changing the holding cost fraction, the total inventory cost is higher for the L4L inventory system than the (Q, R) inventory system till the +20% case. These results are expected as for the L4L inventory system case, the orders of new spare part are generated every day instead. This incurs a higher ordering cost for the L4L inventory system than that for the (Q, R) inventory system.

Table 61: Sensitivity analysis total costs' summary

| % Deviation of Number of Inspection and Repair Resources | Ordering Cost (M.U) | | Holding Cost (M.U) | | Backorder Cost (M.U) | | Inspection and Repair Cost (M.U) | |
|---|---|---|---|---|---|---|---|---|
| | (Q, R) | L4L | (Q, R) | L4L | (Q, R) | L4L | (Q, R) | L4L |
| -60% | 26,500 | 60,000 | 28,000 | 1.0 | 9,283.44 | 34,403.62 | 116,931 | 105,588.46 |
| -40% | 25,500 | 60,000 | 31,350 | 0.0 | 7,073.18 | 34,755.30 | 174,977 | 158,179.73 |
| -20% | 26,000 | 60,000 | 30,800 | 80 | 9,651.63 | 34,722.37 | 232,173 | 217,094.57 |
| Base Value | 26,500 | 60,000 | 24,250 | 6.0 | 8,083.74 | 34,669.82 | 291,142 | 271,373.86 |
| +20% | 25,000 | 60,000 | 28,900 | 87.0 | 6,268.09 | 34,755.78 | 349,862 | 325,819.61 |
| +40% | 25,500 | 60,000 | 32,944 | 0.0 | 10,789.5 | 34,631.50 | 405,522 | 386,779.83 |
| +60% | 26,000 | 60,000 | 22,452 | 146 | 12,927.0 | 34,698.51 | 464,175 | 439,422.21 |
| Average | 25,857 | 60,000 | 28,385 | 45.7 | 9,153.81 | 34,662.41 | 290,683 | 272,036.90 |

Table 62: Sensitivity analysis fill rate and service level summary

| % Deviation of Number of Inspection and Repair Resources | Fill Rate (%) | | Service Level (%) | |
|---|---|---|---|---|
| | (Q, R) | L4L | (Q, R) | L4L |
| -60% | 41.38 | 47.31 | 52.14 | 34.60 |
| -40% | 40.68 | 45.45 | 52.41 | 36.30 |
| -20% | 40.16 | 47.24 | 53.62 | 36.97 |
| Base Value | 41.14 | 45.40 | 53.61 | 36.89 |
| +20% | 41.01 | 45.53 | 54.03 | 37.04 |
| +40% | 41.38 | 46.92 | 53.93 | 37.11 |
| +60% | 42.91 | 45.08 | 54.70 | 37.16 |
| Average | 41.24 | 46.13 | 53.49 | 36.58 |

As shown in Table 61, that the average ordering cost for the (Q, R) inventory system is much less than that for the L4L inventory system. On the other hand, the average holding cost for the (Q, R) inventory system is much more than that for the L4L inventory system. In contrast to this, there is a high backorder cost for the L4L inventory system. The inspection and repair cost for the (Q, R) inventory system is more than that for the L4L inventory system.

As shown in Table 62, the average fill rate, which is the percentage of spare parts required for repair is higher for the L4L inventory system than the (Q, R) system. The fill rate was calculated by dividing the number of spare parts that entered inside the repair process with the number of spare parts that exited the inspection process. However, the average service level, which is the percentage of spare parts that is satisfied immediately is more for the (Q, R) inventory system than that for the L4L inventory system. This is because in the (Q, R) inventory system, there is already an existing inventory of new spare parts available to cater for preventive ad corrective maintenance of spare parts. This makes the process of handling PM and CM spare parts a bit faster in case of the (Q, R) inventory system when compared to the L4L inventory system. The service level was calculated by dividing the total number of PM and CM spare parts that exited the inventory system with the total number of PM and CM spare parts that entered the inventory system.

## 5.5. Managerial Insights

By conducting this case study, some managerial decisions regarding the management of spare parts can be made. The purpose of conducting this enlarged case study was to determine the best spare parts ordering policy either (Q, R) or L4L in terms of inspection and repair time of spare parts, resource utilization, total cost of repair and inspection processes, backorder cost and the total cost of the inventory system which includes the ordering cost and holding cost of spare parts. This will help an organization to decide on the ordering policy it can implement when managing either preventive maintenance or corrective maintenance spare parts. In addition to this, different types of costs can be taken to into consideration when managing inventory of spare parts. The different types of costs are the busy cost which is the cost incurred when a resource is busy in a particular process, idle cost is the cost incurred when a resource is not busy or idle and finally the usage cost which is the cost incurred for using a particular resource of a process. By conducting this case study, it was determined that there were a number of preventive maintenance (PM) and corrective maintenance (CM) spare parts that were on hold in the end of the simulation run. This incurred cost as well, which is the backorder cost incurred when both the repaired and new spare parts are not available. For the L4L inventory system case, it was observed that these PM and CM spare parts have a much higher value for all four spare parts than that for the (Q, R) inventory system case. This is because in the L4L inventory case, there is no initial inventory of new spare parts present in the inventory of new spare parts. For the (Q, R) inventory system case, these PM and CM spare parts are zero. These PM and CM spare parts should be effectively and efficiently managed as these PM and CM that are stored in the inventory of PM and CM spare part represent the backorder cost of an inventory system. Managing these PM and CM spare parts will assist in calculating the desired service level of spare parts. Service level of spare parts is the percentage of spare parts that is satisfied immediately. Therefore, as soon as a proportion of PM and CM spare parts that are initially stored in the inventory of PM and CM spare parts leave this inventory in order to be processed further in the inventory system, this proportion of PM and CM spare parts represent the service level of spare parts. It is desirable from a managerial point of view to achieve sufficient service level with minimum inventory costs. It was also vital in this case study to control the distribution of arrival of the failed spare parts to the repair facility. This depends on the intensity of usage of spare parts by various facilities and the maintenance policy adopted by those facilities. Considering this case study, each facility was assigned a different Time Between Failures (TBF) for CM spare parts. In addition to this, each facility was given a different schedule of PM spare parts arrival. Besides this, in order to have a good spare parts management strategy, it is desirable to handle those spare parts that are slow-moving with highly stochastic and erratic demands. Additionally, both PM and CM spare parts can be managed differently when the resource capacity in various processes' changes, for example the resources in the repair process changes. Apart from this, this case study can be used to determine the average fill rate of spare parts, which is the percentage of spare parts required for repair. In this case study the average fill rate can be determined from the ratio of number of spare parts out from the inspection process to the number of spare parts entering inside the repair process. For the (Q, R) inventory system case, the average fill rate was lower than the L4L inventory system.

As this case study was simulated for 1 month with 8 hours per day of work, one more important implication was made while carrying out this case study. The orders of new spare parts were generated every day at the last minute of the $8^{th}$ hour to avoid any shortages of repaired and new spare parts but still some shortages were observed. If the total costs for both (Q, R) and L4L inventory systems are compared, it will be observed that the L4L inventory system costs more than the (Q, R) inventory system. The (Q, R) inventory system takes into account the cost of holding repaired and new spare parts in the inventory, whereas the L4L inventory system takes into account the cost of holding PM and CM spare parts (backorder cost) in the inventory. On the other hand, the L4L inventory system costs less when inspecting and repairing spare parts in the inspection and repair processes respectively.

Therefore, spare parts can be managed differently under different ordering policies, inventory systems and resources, for example a L4L system generally ensures that the lead time of spare parts is less than 24 hours. This will ensure less holding cost of spare parts and less use of resources in managing the spare parts. The following points summarizes the case study: -

- When the ordering cost per order is changed from -60% to +60%, the total inventory cost (ordering cost + holding cost) for the (Q, R) inventory system is lower with an average of 50,750 M.U than the L4L inventory system with an average of 60,006 M.U.
- When the holding cost fraction is changed from -60% to +60%, the total inventory cost (ordering cost + holding cost) for the (Q, R) inventory system is lower with an

average of 50,750 M.U than the L4L inventory system with an average of 60,006 M.U.

- When the number of resources of inspection and repair processes are changed from -60% to +60%, the total inventory cost (ordering cost + holding cost) for the (Q, R) inventory system is lower with an average of 54,242 M.U than the L4L inventory system with an average of 60,045.71 M.U.
- L4L inventory system has a higher backorder cost with an average of 34,662.41 M.U than the (Q, R) inventory system with an average of 9,153.81 M.U.
- (Q, R) inventory system has a higher cost of holding repaired and new spare parts with an average of 290,683.76 M.U than the L4L inventory system with an average of 272,036.90 M.U.
- Better ordering policy in terms of total cost is the (Q, R) inventory system.
- When the number of resources of inspection and repair processes are changed from -60% to +60%, the average inspection waiting time for the (Q, R) inventory system with an average of 105.43 hours is lower than that for the L4L inventory system with an average of 109.91 hours. The average repair waiting time in this case for the (Q, R) inventory system with an average of 21.24 hours is higher than that for the L4L inventory system with an average of 17.98 hours. The average inspection and resource utilization in this case for the (Q, R) inventory system with an average of 0.9901 is higher than that for the L4L inventory system with an average of 0.9270.
- The average fill rate for the (Q, R) and L4L inventory systems are 41.24% and 46.13% respectively.
- The average service level for the (Q, R) and L4L inventory systems are 53.49% and 36.58% respectively.

# Chapter 6. Research Summary, Conclusion and Future Work

This chapter provides a summary for this research work along with an explanation on the research contribution, conclusion and future work.

## 6.1. Research Summary

This thesis work began by reviewing the existing literature on inventory system management. Many of the researchers conducted research in this area by considering very few types of processes, process times and process costs that are involved in inventory systems. It was also determined that very few researchers used probability distributions in the various factors of managing spare parts in an inventory, for example in the time required to repair faulty spare parts or time required to procure new spare parts. After conducting an extensive literature review, it was also determined that most of the researchers classified spare parts in an inventory based on their importance, used mathematical programming approaches and optimization methods in inventory systems and used heuristics algorithms in inventory systems. Very few researchers have used simulation methods in inventory systems in a very limited way. None of the research papers that have been reviewed addressed the problem of managing both repaired and new spare parts for preventive and corrective maintenance in detail considering the various time factors, probability distributions and costs that are involved in procuring of new spare parts, repairing of faulty spare parts and overhauling of spare parts in a multi-facility centralized inventory system environment. This was the main research area of this research work.

After giving a background of inventory systems, the main problem of this thesis was defined as given in the earlier paragraph. Research objectives of this research work were then stated which assisted in carrying out this research work. After describing the significance of this research and the organization of this report, literature review and the main findings from these literature review were then presented.

The purpose of this thesis was to manage a multi-facility repairable inventory system in a centralized inventory system environment using a simulation model that was developed using the Arena simulation software for both the single-facility and multi-facility (Q, R) and Lot-Lot (L4L) inventory system cases using single and multiple repairable spare parts. Therefore, this research work began by simulating a single-facility inventory system using first a single spare part and then multiple spare parts for both the (Q, R) and (L4L) inventory systems. This was followed by simulating multi-facility inventory system using first a single spare part and then multiple spare parts for both the (Q, R) and (L4L) inventory systems. For all these cases, the simulation models were first validated and illustrative examples of these simulation models of inventory systems were presented. Various types of results were generated which were tabulated in their respective chapters. Some of the types of data that were generated as a result of these simulation runs were the input and output from the inspection and repair processes, the average and the maximum number of spare parts waiting in various processes, the costs incurred in various processes, the total cost of ordering new spare parts in the end of the simulation run, holding costs, backorder costs etc. A discussion of these illustrative examples were then shown. For the illustrative examples, 3 facilities and 3 spare parts were considered with a simulation replication length of 7 days.

This same procedure was repeated in a case study, in which the simulation was enlarged by using 7 facilities and 4 spare parts with a replication length of 1 month. Sensitivity analysis was also conducted in which the ordering cost per order, holding cost fraction and the number of resources for inspection and repair resources were varied and the their corresponding effect in the total inventory cost, which is the sum of ordering cost and holding cost was noted. A thorough discussion and managerial insights on this case study were then presented.

## 6.2. Research Contribution and Conclusion

The main contribution in this research work was to manage both repaired and new spare parts for preventive and corrective maintenance in detail. Various time factors, probability distributions and costs that are involved in different processes of an inventory system were considered in a multi-facility centralized inventory system environment. Two types of inventory systems, namely the (Q, R) and L4L inventory systems were developed and discussed which contributed significantly in this research work.

After developing and running the simulation for the case study, It was observed that the (Q, R) inventory system gave the highest cost of holding repaired and new spare parts and also the highest cost for using various processes in this inventory system. In addition to this, the L4L inventory system gave the highest cost of ordering of new spare parts and holding PM and CM spare parts (backorder cost) in the inventory. The results of the various scenarios that were considered in this research work were then used to suggest some improvements or suggest some more modifications to this inventory system. The following points summarizes the main findings from the different types of simulation models that were developed in this research work: -

- By applying these simulation models for different demand from facilities, the total ordering cost of new spare parts or total holding cost can be determined in the end of the simulation run. Additionally, the best ordering policy in terms of less total ordering cost, holding cost or total cost of the inventory system can be determined.
- Similarly, by varying the demand from facilities, the total backorder cost of inventory systems can be determined.
- Simulation can be set to generate different number of orders on different days.
- The number of resources in the inspection and repair processes in the simulation models can be changed as well to see the overall effect on the total cost of different inventory systems.
- The effect of changing the number of resources of inspection and repair processes on the inspection waiting time, repair waiting time and resource utilization can be determined as well.
- Inspection waiting time, repair waiting time and waiting time in other processes and their corresponding resource utilization can be determined and compared by considering different demands from facilities.
- Process times in these simulation models can be changed to have different probability distributions to cater for different scenarios in inventory systems.
- The average fill rate and the service level of spare parts in different inventory systems can be compared using the simulation models developed in this research work.
- The simulation models can be used only for simulating PM spare parts or only for simulating CM spare parts or both for different inventory systems.

The simulation model developed in this research work has certain limitations. The number of facilities and the spare parts that could be taken into consideration in this research work has limitations. For example, as seen in the case study that 7 facilities and 4 spare parts were considered. If the number of facilities and the spare parts are exceeded beyond this, the simulation tends to become slow and extremely congested with modules which makes it harder to observe and analyse the simulation run. In addition to this, the simulation process that was conducted for this research work did not involve any optimization. It provided reaction to several operating conditions in a repairable item inventory environment. As the number of parameters that were considered in this simulation model increases, the difficulty in finding the optimal solution also increases. Additionally, a simulation depicts a real-life scenario but does not exactly simulate real world conditions. The simulation model developed for an inventory system in this research work has considered probability distributions for the various time factors which again might be based on some past data or user experience rather than taking exact values of the various time factors involved in the various processes of inventory systems, for example inspection time, repair time, lead time etc. Hence, it does not display an exact solution to the problem.

### 6.3. Future Work

The prospect of extending this research work can be by considering a greater number of facilities and a greater number of distinct spare parts and by using a decentralized inventory system environment, in which each facility may have its own repair facility and inventory of repaired spare parts. This will be an echelon based inventory system. Besides this, a greater number of attributes could be considered which could be used as criteria to decide whether to send the spare parts to the repair facility or discard the spare parts. Additionally, a service facility could also be used which will be responsible for the uninstallation and installation of spare parts. The costs of this service facility serving different facilities could be taken into account. Furthermore, only PM spare parts or only CM spare parts can be simulated in different inventory systems. Apart from this, more inspection and repair processes in the repair facility could be considered with the condition that if one repair facility exceeds its capacity to repair spare parts then the repair work could be diverted to other repair facilities.

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