NPS-AM-14-C11P16R02-061

PROCEEDINGS
OF THE
ELEVENTH ANNUAL ACQUISITION RESEARCH SYMPOSIUM

THURSDAY SESSIONS
VOLUME II

Maintenance Enterprise Resource Planning: Information Value Among Supply Chain Elements

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Published April 30, 2014

Approved for public release; distribution is unlimited.

Prepared for the Naval Postgraduate School, Monterey, CA 93943.

The research presented in this report was supported by the Acquisition Research Program of the Graduate School of Business & Public Policy at the Naval Postgraduate School.

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Panel 16. Defense Supply Chain Modeling Insights

Thursday, May 15, 2014	
11:15 a.m. – 12:45 p.m.	**Chair: Ken Mitchell Jr.,** Director, Research and Analysis, Defense Logistics Agency ***Mixture Distributions for Modeling Lead Time Demand in Coordinated Supply Chains*** Barry Cobb, Virginia Military Institute Alan W. Johnson, Air Force Institute of Technology ***Maintenance Enterprise Resource Planning: Information Value Among Supply Chain Elements*** Rogers Ascef, Naval Postgraduate School Alex Bordetsky, Naval Postgraduate School Geraldo Ferrer, Naval Postgraduate School ***Multi-Objective Optimization of Fleet-Level Metrics to Determine New System Design Requirements: An Application to Military Air Cargo Fuel Efficiency*** Parithi Govindaraju, Purdue University Navindran Davendralingam, Purdue University William Crossley, Purdue University

Maintenance Enterprise Resource Planning: Information Value Among Supply Chain Elements

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Abstract

Maintenance Supply Chain (MSC) involves Maintenance, Repair, and Overhaul (MRO) organizations and the relationships within and across suppliers and customers. These organizations work with the probability of equipment failure, maintenance, and the use requirements of spare parts. All of these elements increase uncertainty in this environment. Besides, it is difficult to integrate and process information to maintain good inventory control. This high uncertainty and lack of integration of information cause spare parts inventory excesses and shortages that are used in maintenance.

This research proposes a new model based on information processing theories to connect the lateral elements of the supply chain, increase vertical information and transform the MSC into a system to decrease shortages and excesses of inventory. This research will incorporate a simulation to compare the new model with traditional models of inventory control to inventory cost. This study claims that when using the new model with different demands of maintenance, inventory cost is lower than with traditional models of inventory control.

The research uses information processing theory as the framework to decrease uncertainty, and consequently decrease excesses and shortages of spare parts in MSC.

Introduction

The 2007 United States Census showed that expenses in Repair and Maintenance Service were US$ 137 billion. In comparison, Aircraft Manufacturing sales were US$ 84 billion (United States, 2007). Fabry & Schmitz-Urban wrote that the maintenance sector in Germany had greater turnover (€ 250 billion) than many other industrial sectors, such as Vehicle Manufacturing (€ 135 billion) (Fabry & Schmitz-Urban, 2010). “American businesses and consumers spend approximately US$ 1 Trillion every year on assets they already own," a good part of this on maintenance expenses (Cohen, Agrawal, & Agrawal, 2006, p. 130).

When Pan Am and Eastern Airlines went bankrupt, they held an excess inventory of spare parts of approximately $700 million and $200 million, respectively (Ghobbar & Friend, 2007). In the military environment, a 2009 U.S. Department of Defense (DoD) report stated that nearly 17% of all items in the inventory were inactive, and they valued approximately US$ 15 billion (DoD, 2009). Most of these items had been purchased as spares for maintenance purpose, a problem that illustrates the challenge of managing the Maintenance Supply Chain (MSC).

The maintenance environment includes components with stochastic failure rate, different types of failure to be repaired, great numbers of spare parts for repair and long lead-times to perform maintenance and to purchase spare parts. Frequently, maintenance does not incorporate fluctuations in equipment usage, changes in environmental conditions and equipment age (Jones, 2006, p. 18.1). The maintenance supply chain elements tend to be disconnected from each other, causing shortages and excesses of materials. All these factors can result in delays and high uncertainty in the maintenance process. High uncertainty and lack of information integration cause excess and shortage of spare parts. This misinformation causes low availability of aircraft, equipment or systems, increasing holding costs.

Some researchers have proposed solutions to mitigate the problem. Ghobbar & Friend studied aircraft companies and found that at least 50% of companies were not satisfied with their system of inventory control (Ghobbar & Friend, 2007). Newman proposed an MRP model of preventive maintenance (Newman, 1985). Molinder used simulation to analyze the effects of different sources of uncertainty (Molinder, 1997). Ettkin & Jahnig (1986) presented a framework to adapt MRPII to maintenance functions with the benefit of waste reduction. Swanson (2003) discussed the use of information-process theory in maintenance management. She conducted a survey in many maintenance, repair and overhaul (MRO) organizations to show how uncertainty is affected by the use of information systems in maintenance operations. In spite these contributions, the literature still lacks a model that integrates all MRO elements.

This paper seeks to fill this gap. The purpose of this experiment is to test a new integrated model between maintenance supply chain elements to match inventory level with maintenance requirements to decrease inventory cost. This study compares the new model with traditional inventory model of control with different amounts of maintenance demand to inventory costs. This research is important because the result reduces uncertainty and, consequently, decreases cost and increases equipment availability.

This study applies an information processing approach to analyze the information integration between the elements of the maintenance supply chain. It expands on the idea that new information, such as ERP, can increase the capacity of information processing, and consequently can decrease uncertainty and costs. The specific research question addressed in this chapter is

Does Maintenance Enterprise Resource Planning (MERP) decrease inventory costs compared with the use of traditional inventory models?

This study is divided in five sections: literature review, proposed model, methodology, results and discussions. The proposed model shows how the model integrates the information. The methodology presents the hypothesis and experimental procedure of the research. Finally, the study analyzes and explains the result, and suggests future research.

Literature Review

Information Processing Theory

Frequently, the information about failed components isn't available, maintenance information doesn't integrate across supply divisions, and, the inventory control has to use past information to predict the purchasing material. This entire gap causes high uncertainty in the MSC environment. Galbraith defines "uncertainty as the difference between the amount of information necessary to perform a task and the information already possessed by the company" (Galbraith, 1977). He analyzed the relation between uncertainty and information to formulate the information processing theory. His theory claims that "the greater the task uncertainty, the greater the amount of information that must be processed among decision makers during task execution in order to achieve a given level of performance" (Galbraith, 1974). He argued that there are two organizational strategies to manage the uncertainty: to reduce the need for information processing or to increase the capacity to process information.

To reduce the need for information requires the creation of slack resources or the existence of self-contained tasks. Moreover, Galbraith indicated that investment in vertical information system and the creation of lateral relations increase the volume to process information. He argued that "the greater the uncertainty, the lower the decision-making and the integration is then maintained by lateral relations" (Galbraith, 1974).

The concept of this information theory was used in many activities. There are studies in the application of theory to propose structural modification in organizations with vertical analysis and horizontal information systems to increase the information process (Bolon, 1998). Swanson applied the information-processing model to analyze maintenance management (Swanson, 2003). She found that maintenance organizations respond to environmental complexity with the use of computerized maintenance management systems, preventive and predictive maintenance systems, coordination, and increased workforce.

Other research presents a new perception of information sharing within supply chains based on organizational information processing theory. Posey and Bari propose a conceptual model that shows that if information within and across supply chains are more compatible with each other, they can increase information-processing capabilities (Posey & Bari, 2009). Flynn and Flynn explain that some firms found alternatives to processing information by using "management-intensive solutions, rather than technology-intensive solutions" (Flynn & Flynn, 1999, p. 1044).

This study uses the two strategies to coordinate uncertainty in Galbraith information process theory, and compare their efficiency. As the reductionist approach to manage uncertainty, we use the most common model of inventory control: Economic Order Quantity (EOQ). The alternative approach, with increased capacity to process information in the Supply Chain, is the Maintenance Enterprise Resource Planning (MERP).

The two approaches are linked by the ability of the organization to coordinate and process the information. If the firm cannot integrate the information available in multiple departments, if non-routine events are more frequent than the capacity of the firm to process information, or if the technology available cannot increase the information processing capacity of the firm, then the firm must use a reductionist strategy to process information. That is, the firm adopts simple deterministic models for decision making, using basic static information allied to expensive protections, such as inventory buffers, to support the organization in the face of uncertainty.

On the other hand, if the firm can integrate lateral and vertical information within and across organizations, if the firm has low decision-making processing time, and if the firm can integrate the elements of supply chain, then the MERP model can increase the capacity of information processing and decrease the uncertainty in this environment, resulting in lower inventory costs and more responsiveness to any external or internal change. An application of the Galbraith theory with the supply chain model of research is represented in Figure 1.

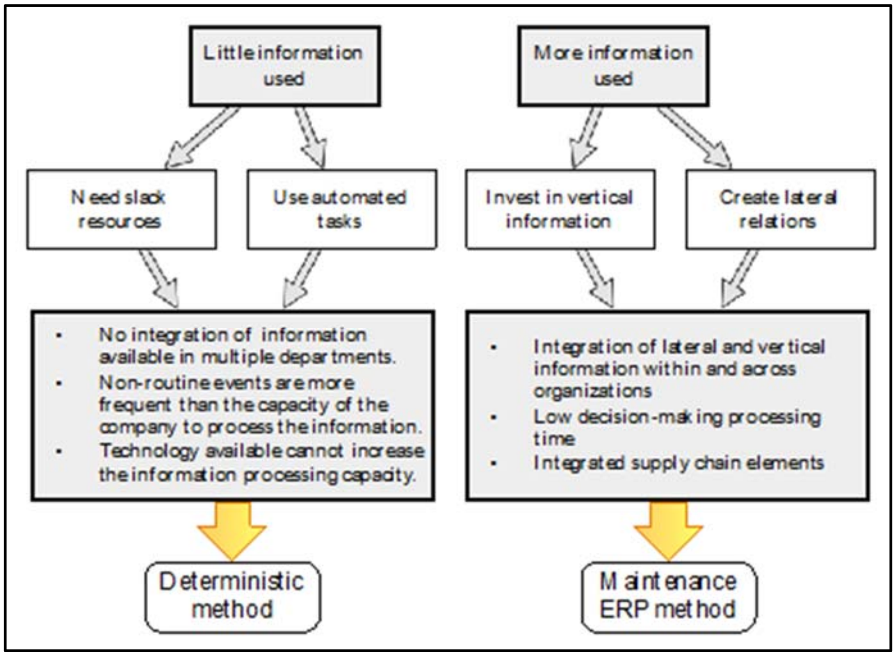

Figure 1. A Supply Chain Application of Galbraith Strategies

Enterprise Resources Planning (ERP)

Vollmann et al. (2005) presented two interesting definitions about ERP. For the information technology community, ERP is a term that integrates the application program in finance, manufacturing, logistics, sales and marketing, human resources, and the other functions in an organization. From the manager's viewpoint, ERP represents a comprehensive software approach to support decisions concurrent with planning and controlling the business (Vollmann, Berry, Whybark, & Jacobs, 2005). ERP seeks to integrate information of the organization through best practice functionality, and system interoperability, with common databases and interfaces (Markus, Axline, Petrie, & Tanis, 2000).

ERP is an offshoot of the tool Material Requirement Planning (MRP). MRP's function is to prepare a master production schedule (MPS) and a list of materials required for the production process. This technique was developed in 1960 and became more accessible with the development of computers that could process the large database that it requires. Subsequently, this technique evolved into the tool known as Manufacturing Resource Planning (MRP II), which expanded the benefit to the incorporate manufacturing planning beyond materials acquisition. The new technology required more computing power while more integrated decision-making was achieved. ERP is an extension of MRP II that seeks to integrate information and processes across the companies in the supply chain, using electronic data interface (EDI). Interested readers are encouraged to read more in Vollmann et al. (2004).

The proposed model uses ERP techniques to reduce uncertainty in the maintenance supply chain. Ghobbar & Friend (2007) surveyed 287 aircraft companies (96 airline operators and 56 maintenance service organizations) to find how they determined reorder point systems for their parts and components for operation and maintenance. They found that 66% of the maintenance organizations and 57% of airline operator organizations did not use MRP, "were aware of MRP but had neither used nor investigated it further." The results showed that more than 50% of companies were not satisfied with their inventory management system (Ghobbar & Friend, 2007).

Newman (1985) argued that MRP could be used for Preventive Maintenance Requirement Planning where its use could have multiple benefits: part consumption could be tracked and maintenance personnel could be better used. His model showed some aspect for integrating Maintenance Schedule with Supply Chain Management.

Molinder (1997) studied how an MRP system was affected by stochastic demand and lead times. He used a "simulation with the objective of analyzing the effects of different sources of uncertainty in MRP systems." He found that high variability had a strong effect on the level of safety stock and safety lead-time required. An adaptation of MRP to maintenance had predicted this uncertainty.

Bojanowski (1984) developed a variant of MRP, the Service Requirement Planning (SRP), to prioritize routine mechanical inspection and machine maintenance sequences. Ettkin & Jahnig (1986) presented a framework for adapting MRPII to maintenance function for waste reduction. They thought that this model could be used successfully in maintenance management because of the similarities between manufacturing and maintenance processes.

Wemmerlov & Whybark (1984) show different approaches to choose lot size using MRP, and compare a number of alternatives such as Economic Order Quantities (EOQ), Periodic Order Quantities (POQ), Part Period Balancing (PPB), and Wagner-Within Algorithm (WW). Wemmerlov & Whybark (1984) demonstrated with no uncertainty, the best result was Wagner-Within Algorithm, but with great computational cost. Under demand uncertainty the inventory cost is 0.19% higher with EOQ than with WW, and PPB is 0.67% lower than the WW model. Therefore, all three models can produce good solutions. Under uncertainty, the inventory cost has no difference, "EOQ rule carries with it its own safety stock" (Wemmerlov & Whybark, 1984, p. 16).

Silver et al(Silver, Pyke, & Peterson, 1998) did a experiment with lot sizing for individual items with time-varying demand. They add the Silver-Meal Heuristic (SM) that has similar result with Wagner-Within Algorithm to compare the cost with the other models. They conclude that (SM) and (WW) have better cost than the others models (Silver et al., 1998). Gaither (1983) complement with other experiment that include Gaither model. The experiment shows the performance of the models that can be uses as guidelines for MRP systems.

Whybark & Williams (1976) studied the use of safety stock and safety lead-time in MRP in response to four types of demand uncertainty: demand timing and quantity, and supply timing and quantity.

There is some confusion about remanufactured and maintenance management. The concepts are different, and so is their management; "Remanufactured process is an industrial process in which worn-out products are restored to like-new condition" (Ptak &

Smith, 2011, p. 295). Remanufacturing implies equipment disassembly and complete recovery. “It requires the repair or replacement of worn out or obsolete components and modules” (Ferrer & Whybark, 2001a, p. 87). Generally inoperable units are disassembled, cleaned, repaired, and placed in inventory to assemble a new unit. On the other hand, “Maintenance constitute a series of actions necessary to restore or retain an item in an effective operational state” (Blanchard, Verma, & Peterson, 1995, p. 1). Maintenance Management is the planning and execution of scheduled and unscheduled maintenance to maintain the availability of equipment. Remanufacturing may be considered a type of maintenance.

There are studies evaluating MRP for remanufactured industries such as DePuy et al. (2007), which proposes a new MRP that calculates the number of units produced each period and the number of components needed to assemble the products (DePuy, Usher, Walker, & Taylor, 2007). Ferrer & Whybarck (2001) presents the “first fully integrated material planning system to facilitate the management of remanufacturing facility” (Ferrer & Whybark, 2001b). Other researchers seek to find the optimal number of used products, or “cores,” to procure and disassemble and the optimal quantities of new parts to procure (Gaudette, 2003).

So, there are many studies that apply MRP with environmental uncertainty, many examples of MRP’s use in a variety of industry sectors, and new MRP’s use in the remanufacturing sector. But there are few studies of MRP’s use in the maintenance sector; a few models only mention the possibility. This research fills this gap and presents a model that connects the elements of maintenance supply chain.

Maintenance Enterprise Resource Planning (MERP)

Manufacturing Industry vs. MRO Organizations

Why not use traditional MRP/ERP in the MSC since that it is used a lot in the manufacturing supply chain? First of all, both environments present uncertainty but the maintenance environment has uncertainty practically in all levels of planning. Cohen affirm that “the majority of existing ERP software programs don’t have the capability to manage complex service supply chain scenarios” (Cohen et al., 2006) and Maintenance Supply Chain is one of this scenarios.

The demand of manufacturing supply chain is predictable, on the other hand, MSC is unpredictable because many services is trigged when the failure occurs, some times, scheduled maintenance is not a easy task to forecast too. Because of the dynamics of MSC environment inventory management uses to pre-position resource to decrease the uncertainty. Manufacturing supply chain tries to maximize velocity of resource. The performance metric in manufacturing SC use the degree the fill rate, the MSC works with availability of equipment (Cohen et al., 2006, pp. 132–133) .

To manage MSC, the managers have to work with client information about the equipment as well as failures, operations, utilization forecast. Many times, they cannot forecast when the failures will happen. And when it happens, maintenance shops don’t know the material that they will use to fix the failure. Many times, the material that is used in maintenance is disconnected to production, so uncertainty is present in many processes.

For the manufacturing supply chain, the demand is also a challenging, but they know the material to assemble the system and know the material supplier. Lead-time of the supplier can also be varied, but MSC has a lot of variability because many items are discontinued and difficult to purchase.

Sometimes, the maintenance supply chain can use some concepts of the remanufacturing supply chain such as the overhaul of the equipment, but the management of failure, corrective and preventive maintenance, availability of equipment is unique to the maintenance supply chain.

Although there are similarities among manufacturing industries such as the traditional manufacturing process (e.g., shop floor scheduling and assembly; Gaudette, 2003), both involve suppliers, plants, and customers. There is, however, significant difference according Table 1.

Table 1. Characteristics of Manufacturing Supply Chain vs. Maintenance Supply Chain

*(Gaudette, 2003), **(Ptak & Smith, 2011), ***(Cohen et al., 2006, pp. 131–132)

	Maintenance Supply Chain	Manufacturing Supply Chain
Process *	It requires special operational processes and skills, such as disassembly, inspection, testing, and repair.	Manufacture follows a logic sequence of production.
Time response***	ASAP (same day or next day)	Standard, can be scheduled
Routing **	Probabilistic time and occurrence of maintenance task	Manufacture task is predictive and assembled with logical form
Inventory Management **	High level of uncertainty inherent in the maintenance process and unique in corrective maintenance	Fix material quantity to attend to final product assembly.
Bill of Material	Probabilistic with no fixed material and quantity	Fixed quantity
Nature of demand***	Always unpredictable, sporadic	Predictable, can be forecast
Lead Time	More uncertainty because items can be obsolete, or cannot be manufactured any more, unknown suppliers.	Suppliers known, agreements and contracts are done more predictably.
Number of SKU***	15 to 20 times more	Limited

The different characteristics of the Maintenance Supply Chain show that there is the need to develop a specific planning and control system in this environment. The idea is to adapt the elements of ERP to develop a specific model of the Maintenance Supply Chain.

Independent and Dependent Demand

The Maintenance Enterprise Resource Planning - MERP model seeks to connect the elements of MSC and decrease the degree of separation among the elements of supply chain. When these elements are connected, a new collaboration network is formed. These environments will permit availability of information, decreasing delay and uncertainty and increasing timely response.

The traditional inventory control system works with the assumption that all items are independent in demand, meaning that the demand for an item is independent of other items. Traditional inventory control for this model is the Economic Order Cost (EOQ) model, Production Order Quantity Cost, and Quantity Discount Model(Heizer & Render, 2007, pp. 489–490).

Traditional MRP works with assumption that there are independent demand items and dependent demand items. Independent demand items are end-product items in a manufacturing, such as an aircraft or engine (Vollmann et al., 2005, p. 134). Dependent demand means that the demand for one item is related to the demand for another item. Following an aircraft, the items to assemble the aircraft are dependent demand (Heizer & Render, 2007, pp. 562–563).

MERP model uses the assumption that maintenance is an independent demand. Such the scheduled and unscheduled maintenance that are performed in the aircrafts, engines, generators and landing gears are considered independents events. Dependent demand items are the spare parts that are used to do the maintenance.

Corrective maintenance includes all unscheduled maintenance actions, as a result of system/product failure, to restore the system to a specified condition. Unscheduled Maintenance may be measured in terms of frequency or elapsed time. Preventive maintenance includes all scheduled maintenance actions performed to retain a system or product in a specified operational condition (Jones, 2006, p. 4.18). It covers periodic inspections, critical-item replacement, periodic calibration, and the like. Preventive maintenance may be measured in terms of frequency or elapsed time. In many items use-time between overhaul (TBO), or a scheduled program of maintenance (e.g., cars with maintenance programming of miles driven; aircraft with maintenance programing of hours flown; Blanchard et al., 1995, pp. 16–17).

MERP Description

MERP has three modules that are responsible to integrate and process the information within and across the organization, these modules compose the Planning System. The first module is Maintenance and Operation Planning (MOP) that calculates a long time corrective and preventive maintenance forecast based in client information (e.g., failure rate, equipment use). MOP calculates per-year, the quantity of maintenance and the budge. If this scenario is feasible, the information is transferred to MMPS; if not, new scenario is calculated.

If the scenario is approved, Master Maintenance Planning Schedule (MMPS) calculates the quantity of maintenance per period. To calculate, the MMPS takes information on the items in stock and in production. Afterwards, this function produces the quantity of Work Order that has to be opened. The information of work order is then transferred to Maintenance Material Requirement Planning (MMRP). Based on a bill of maintenance that is dynamic, updates are made to the work order and the system then calculates the quantity of material that is needed to do the maintenance. Afterwards, the MMRP takes information of stock, acquisition, transportation and lead-time, and calculates the quantity that has to be purchased. If this scenario is feasible, the information is transferred to CMMS and PMS; if not, a new scenario is calculated. The representation of MERP is in Figure 2. The correspondence between some modules of MRPII and MERP is in Table 2.

Table 2. Correspondence Between MRP and MERP Modules

Traditional MRPII	MERP
SOP - Sales and Operation Planning	MOP - Maintenance and Operating Planning
MPS - Master Production Schedule	MMPS - Maintenance Master Planning Schedule
MRP - Material Requirement Planning	MMRP - Maintenance Material Requirement Planning

MERP-System Integration and Operation

This section explains the main tasks of each system and how the information are integrated and processed. The explanation is based on Figure 2.

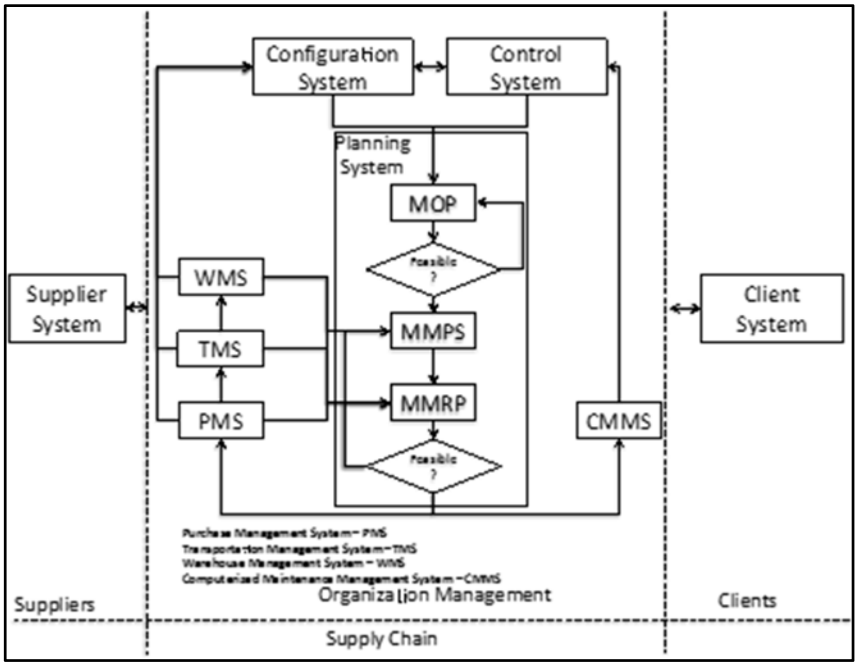

Figure 2. MERP Representation

Configuration System

The main tasks of this function are

- Basic Information: this function is responsible for registering the initial information of the system and its components as part number, NSN, unit of issue, and price.
- Primary Configuration: this function is responsible for registering the basic configuration of the reparable items of the system. The system can be composed of many reparable items. This function assembles the structure of system with quantity and position. Example: One car has two batteries, two air conditioners, or, an airplane has two engines, two generators. An engine of an aircraft has two fuel pumps.
- Maintenance Configuration: this function permits the registration of the type of maintenance that the system and its repairable have. It records the type of maintenance (e.g., Preventive/Predictive Maintenance or Corrective Maintenance), the maintenance cycle, MTBUR, maintenance tasks, tools, man/hour and material that is need to do the maintenance.

Information shared:

- With information about maintenance performed in the organization and in the clients, the system updates the information about configuration, and maintenance to send to Planning System (e.g., MTBUR, TBO, maintenance time, lot size, lead time).

Control System

The main tasks of this function are

- Utilization Control: this function controls the use of equipment and its repairable items in the organization and clients, such as the system records prediction of the use of equipment too.

- Reliability Control: based on failure and maintenance data and utilization of the item, this function calculates the Mean Time Between Failure—MTBF and Mean Time Between Unscheduled Replacement (MTBUR) of the reparable item. This function sends information to Maintenance Configuration about the MTBUR of the item.

MTBUR is the probability of remove a reparable and replace some spare in unscheduled maintenance part during a given period under specified operating conditions (Blanchard et al., 1995, p. 2,112).

$$MTBUR = \frac{1}{\lambda} \quad (1)$$

where λ is referred as the remove and replace spare part spare in unscheduled rate.

- Maintenance Control: this function controls maintenance cost, the maintenance due date, man-hours used, and life cycle cost.

Information shared:

- This function sends information about MTBUR and use of equipment (e.g., update MTBUR, forecast of use of equipment, numbers of equipment in use).

Purchase Management System (PMS)

The main tasks of this function are

- This function control and execute the purchases to the organization.
- Information shared:
- This function receives the purchase planning and updates the stages of purchasing processes and delivery time. This function sends information to MMPS and the MMRP algorithm.

Transportation Management System (TMS)

The main tasks of this function are

- This function plan, control the transportation of equipment and spare parts from clients and suppliers.

Information shared:

- This function supplies information about transportation of the item. It supplies data to MMPS and MMRP.

Warehouse Management System (WMS)

The main tasks of this function are

- This function controls the stock of the warehouses by receiving, picking and shipping the material.

Information shared:

- This function controls the stock and gives information about the quantity of material in stock to MOP, MMPS and MMRP.

Computerized Maintenance Management System (CMMS)

The main tasks of this function are

- This function plan and control the execution of maintenance tasks and updates the information about the material and man/hours that are used in Maintenance Configuration.

Information shared:

- This function receives the maintenance planning and updates the stages of the maintenance processes and delivery time. This function sends information to configuration system, MMPS and MMRP algorithm.

Client System

This module connects information between the client and organization management. The communication can use electronic data interchange (EDI), machine to machine (M2M) techniques, or client-server architecture.

- Item Information: this function is responsible to register the initial information of the equipment, such as the serial number of a part number, manufacture data, or lifetime.
- Real Configuration Management: this function is responsible for assembly of the actual configuration of the equipment. This function controls when the item was installed or removed from the equipment..
- Computerized Maintenance Management System (CMMS): this function registers and controls maintenance that is done with the client, and updates the information about the material and man/hours that are used in Maintenance Configuration.
- Warehouse Management System (WMS): WMS controls the stock with the client, if it is needed, and connects the information about the stock with organization's management.

Supplier System

This module connects information with suppliers. The communication can use electronic data interchange (EDI), machine-to-machine (M2M) techniques, or client-server architecture. The information about stock, purchase, reliability, and transportation are shared and exchanged in this function.

Planning System

Planning System is formed by three modules that connect and process information with the others systems.

Maintenance and Operation Planning (MOP)

This function calculates the quantity of corrective maintenance (CM) and preventive maintenance (PM) in a long-time period (2-5 years). This function receives information about MTBUR, TBO, Configuration, Utilization Forecast, Preventive and Corrective Maintenance Cost and calculates the quantity of maintenance in a period.

A generator of an aircraft is used to illustrate the maintenance forecast calculate. This scenario has 300 aircraft; the quantity per assembly (QPA) is 2 generators. The forecast is to fly an average of 75 hours per month for each aircraft by year y and y + 1. MTBUR rate is 5000 hours, and the Time Between Overhaul (TBO) is 3000 hours. These parameters calculate an estimation of maintenance per year. The parameters are in Table 3.

Table 3. Parameters to Calculate the Quantity of Corrective and Preventive Maintenance

Year	QPA	# of aircraft	Utilization per month	MTBUR	TBO	Period
				5000	3000	
	x	y	h	λ=1/MTBUR	Z=1/TBO	t
y	2	300	75	0.001	0.0003	12
y+1	2	300	75	0.001	0.0003	12

To calculate the average quantity of maintenance, the parameters are multiplied. The formula is at Table 4. The PM maintenance is the same as the average calculated. For CM, a service level (k) is entered to find the item in the stock. In this example, Poisson distribution is used, but it can use another distribution depending on the item. It was used with 90% probability to find the item in stock when it was required. The result is at Table 4.

Table 4. MOP—Quantity of Corrective and Preventive Maintenance

Average CM	Average PM	SL(k)	Qtt CM	Qtt PM
$\mu(cm) = x y h \lambda t$	$\mu(pm) = x y h z t$		$p(k;\lambda) = \frac{\lambda^k}{k!} e^{-\lambda}$	
108	180	0.9	121	180
108	180	0.9	121	180

Master Maintenance Planning Schedule (MMPS)

To calculate the quantity of maintenance that a maintenance shop has to do in a period of time, the model sums the quantity of CM and PM, the quantity of maintenance of a specific reparable and decreases the quantity of equipment that it has in stock and work orders.

Basically, to calculate the master maintenance planning, this function takes information from the Configuration System about the average of maintenance time (MT) of PM and CM, lot size (LS) to do the maintenance (if applicable), and safety stock (SS) of the reparable. To illustrate the calculation, the maintenance time is 1 period; safety stock is 0, and lot size is 1.

The elements of MMPS are

Maintenance Forecast (MF), based in MOP. It can be expressed in

$$MF(t) = (CM+PM)(t)/(p) \qquad (2)$$

where t is a time frame of the period (this research is used “week” as time frame) and p is number of events in the period, in this case 52 week per year.

Example for t = 1,

$$MF(1) = (121+180)/52 = 5.79$$

- Ending Order (EO)(t) is based on information at end of work order in shop, in a period t.
- Starting Inventory (SI) is the quantity of the stock at the end of the period before

$$SI(t) = EI(t-1) \quad (3)$$

Example for t = 2:

$$SI(2) = EI(1) = 0$$

- Ending Inventory (EI) is the quantity of equipment after processing the quantity that arrived and quantity that was used:

$$EI\ (t) = SI(t)+EO(t)+ RO(t)-MF(t) \quad (4)$$

Example for t = 3:

$$EI\ (3) = 0+0+5.79-5.79 = 0$$

- Receiving Order (RO) is when the Maintenance Order will finish and is ready to use. It can be expressed:

$$RO(t) = (MF+SS)\ (t) - (EO+SI)\ (t) \quad (5)$$

Example for t(2):

$$RO(2) = (5.79+0)\ (2)-(0+0)\ (2) = 5.79.$$

RO only can be processed if there is a time period available in function of MT. In RO(1) is 0 because it is not possible to process a maintenance in the same period because the MT = 1.

- Work Order (WO) is the moment that the service order is sent to the shop office to do maintenance. This order is:

$$WO(t) = RO(t+MT) \quad (6)$$

Where MT is maintenance time in week. In this example is 1 week.

Example for t = 1:

$$WO(1) = RO(1+1) = 5.79$$

- PM Order (PWO) is calculated by multiplying the Work Order and the proportion of preventive maintenance over the total of maintenance in a year. It can be expressed:

$$PWO(t) = WO(t) * PM/(PM+CM)(y) \quad (7)$$

Example for t = 1 and y = y:

$$PWO(1) = 5.79*(180/(121+180)(y)) = 5.79*0.6=3.47$$

- CM Order (CWO) is calculated by multiplying the Order and the proportion of corrective maintenance over the total of maintenance in a year. It can be expressed:

$$CWO(t) = WO(t)*(CM/(PM+CM))(y)) \quad (8)$$

Example for t = 1:

$$CWO(1) = 5.79*(121/(121+180)y) = 5.79*0.4 = 2.33$$

The information of PWO and CWO is transferred to MMRP and CMMS at the end of each period; the system recalculates the quantity again. The sequence of the events in a year or in week time frame 1–4 is in Table 5.

Table 5. Master Maintenance Planning Schedule—MMPS to Reparable

Generator		Year	y-1	y			
		Period	52	1	2	3	4
Parameters		Maintenance Forecast (MF)		5.79	5.79	5.79	5.79
Maintenance Time (MT)	1	Ending Order (EO)		5.79			
Lot Size	1	Starting Inventory (SI)		0	0	0	0
Safety Stock	0	Ending Inventory (EI)	0	0	0	0	0
		Rec. Order (RO)		0	5.79	5.79	5.79
Proportion		Work Order (WO)		5.79	5.79	5.79	
PM	CM	PM Order (PWO)		3.47	3.47	3.47	
0.6	0.4	CM Order (CWO)		2.33	2.33	2.33	

Maintenance Material Requirement Planning (MMRP)

After the system generates the Schedule and Corrective planning of Maintenance in MMS, the MMRP function can generate the Material Purchase Planning. In this Example, the Part Number A is used in preventive and corrective maintenance of the generator. In the Preventive Maintenance, the average used is 10, and the corrective maintenance is 7.

The Quantity per Maintenance (QM) is calculated by the average of material that is used in the preventive (QMP) and corrective maintenance (QMC). This information comes from CMMS. Planning Module consolidates the information and sends it to MMRP.

The elements of demand of Part Number "A" of MMS are:

- Preventive Order Demand (POD) represents the material that is used in any preventive maintenance per reparable. It can be expressed:

$$POD(t) = QMP * PWO(t); \quad (9)$$

Example for t = 1:

$$POD(1) = 10*3.46=34.6$$

- Corrective Order Demand (COD) represents the material that is used in any corrective maintenance per reparable. It can expressed:

$$COD(t) = QMC * CWO(t) \quad (10)$$

Example for t = 1:

$$COD(1) = 7*2.33 = 16.29$$

- Total demand (TOD) is the sum of the demand in a time frame:

$$TOD(t) = POD(t)+COD(t) \quad (12)$$

Example for t = 1:

POD(1) = 34.6+16.3 = 50.9.

All calculations can be seen in Table 6.

Table 6. Consolidate Demand of Spare Parts

Part A		Year	y-1	y			
Generator Maintenance	QM	Week Number	52	1	2	3	4
Preventive	10	PO Demand (POD)		34.6	34.6	34.6	34.6
Corrective	7	CO Demand (COD)		16.3	16.3	16.3	16.3
		Total Demand (TOD)		50.9	50.9	50.9	50.9

When the demand is consolidate is possible to calculate the material to purchase. In this example the stock starts with 51.4. The calculation can be seen at Table 7. As was discussed, regarding the lot size used in MRP, this research chose to use EOQ because the computational cost is low and the total cost of inventory is near the other models explained by Vollmann et al. (2004).

The following assumption is used to calculate EOQ. The average of demand in a period of 1-year ( ), K is the fixed cost and H is the holding cost. The EOQ formula is:

$$EOQ = \sqrt{\frac{2K\bar{D}}{H}} \tag{13}$$

The safety stock (SS) is service level required (z), multiplies for the standard deviation in a period of 1 year (STD), and square root of the lead time (Lt).

$$SS = z^{*}STD^{*}\sqrt{Lt} \tag{14}$$

In the example, the item has a fixed cost of $50.00 and the Holding Cost for week is equal the price of the item ($20.00) multiplied by the annual rate of 22%. Transforming this rate per week, the holding cost is $0.21 and the Lead-Time is 4 weeks. The average of demand of 1 year is 50.90. So, the result is:

$$\sqrt{\frac{2*50*50.90}{0.21}} = 154.86$$

SS = 0 because STD is 0 in this example.

Lot size = roundup EOQ = 155

The elements of MMPS are

- Total Demand (TOD) is the sum of demand at Table 6.
- Ending Requisition (ER) is the information when the requisition is active and when the material will arrive. This information comes from TMS and PMS.
- Starting Inventory (SI) is the quantity of the stock at the end of the period before:

$$SI(t) = EI(x-1) \quad (15)$$

Example for t = 2:

$$SI(2) = EI(2-1)=0.5$$

- Ending Inventory (EI) is the quantity of material after processing the quantity that arrived and quantity that is used. It can be expressed:

$$EI(t) = SI(t)+ER(t)+RR(t)-TOD(t) \quad (16)$$

Example for t = 1:

$$Ex: EI(1) = 51.4+0+0-50.9 = 0.5$$

- Receiving Requisition (RR) is when the Requisition Order will finish and is ready to use. This time is used to make the decision to order or not.

$$\text{If } SI(t)+ER(t)-TOD(t)< SS(t), \text{ then } RR(t) = EOQ \quad (17)$$

Example t = 5:

$$SI(5)+ER(5)-TOD(5)< SS(5) \Rightarrow (2.8+0-50.9)<0, \text{ so } RR(5) = 155.$$

This function can only be processed if the lead-time permits.

- Purchasing Requisition (PR) is the moment that the purchase order is sent to the supplier. It can be expressed:

$$PR(t) = RR(x+Lt) \quad (18)$$

Where Lt is lead time. In this example Lt = 4.

Example for t = 1

$$PR(1) = RR(1+4) = R(5) = 155$$

The sequence of the events in a year or in week time frame 1–5 is in Table 7.

Table 7. MMRP of Part A

		Year	y-1	y				
Part A		Week Number	52	1	2	3	4	5
Lead Time (Lt)	4	Total Demand (TOD)		50.9	50.9	50.9	50.9	50.9
		Ending Requisition (ER)			155			
Lot Size (LS)	155	Starting Inventory (SI)		51.4	0.5	104.6	53.7	2.8
Safety Stock (SS)	0	Ending Inventory (EI)	51.4	0.5	104.6	53.7	2.8	106.9
EOQ	155	Receiving Requisition (RR)		0	0	0	0	155
		Purchasing Requisition (PR)		155				

Methodology

This section presents the research question with hypotheses and describes the experiment designed to answer the question.

The purpose of this experiment is to test a new collaboration model between maintenance supply chain elements, to match inventory to maintenance requirements and to decrease inventory cost. This research is important because the result tries to reduce uncertainty and consequently, to decrease cost and increase the availability of the equipment.

This investigation applies information processing theoretical approach to analyzing the integration of information between the elements of the maintenance supply chain. It expands the idea that with the new technology and techniques (e.g., ERP), that if the new model connects the elements of supply chain, then it can increase the capacity of information processing and consequently decrease uncertainty and costs. The specific research question addressed in this chapter is

Does Maintenance Enterprise Resource Planning (MERP) decrease inventory costs compared with the EOQ model?

To answer this question, the experiment will test seven hypotheses:

H-1: There is significant difference between different inventory models and quantities of maintenance on inventory cost.

H-2 to H-7 (to each level of maintenance): Inventory cost is lower using MERP than the EOQ model with different quantities of maintenance.

Independent Variable

Inventory Model: represents the rule that managers can use to decrease the costs associated with maintaining an inventory and meeting customer demand (Hillier & Lieberman, 1980). There are two nominal levels for this variable.

1. Maintenance Enterprise Resource Planning (MERP)—represents a model that increases the capacity to process information by connecting the elements of the supply chain to work as a system. The model was explained in the preceding section.
2. Economic Order Quantity (EOQ)—Harris (1913) created a model that seeks to minimize the order cost and holding costs (Harris, 1913). This is one of earliest and most well-known inventories (Silver et al., 1998).

EOQ model uses the following formula:

$$EOQ\sqrt{\frac{2KD}{H}} \quad (19)$$

EOQ = order sizes in units, D = total demand in unit period, H = cost to hold a unit per period of time, K = accounts for when an order is placed (Simchi-Levi, Kaminsky, & Simchi-Levi, 2007, p. 33).

In this experiment, the demand will be sum of demand in one year before the period of planning.

This model represent a continuous review policy (Q,R), whenever inventory levels fall to reorder level (ROP) an order for Q units is placed (Simchi-Levi et al., 2007). The ROP has two factors: First is the average of demand ( ) during lead-time (Lt), and second is the safety stock (SS), which is the "amount of inventory that the distributor needs to keep at the warehouse to protect against deviations from the average demand during lead time" (Simchi-Levi et al., 2007, p. 42).

$$ROP = Lt^{*}\overline{D} + z^{*}STD^{*}\sqrt{Lt} \quad (20)$$

z is a constant associated service level and STD is standard deviation of average demand in the period.

Quantity of Maintenance: represents a quantity of maintenance that will be performed in a period.

The maintenance can be measured by frequency or elapsed time. This experiment will use the quantity of maintenance by elapsed time (e.g., aircraft maintenance occurs after 100 hours flown, Generator TBO occurs after 3000 hours flown).

To change the quantity of maintenance in this experiment, manipulate the quantity of hours per month that an aircraft flies. The range of this variable uses equal interval scales that will vary from very low to high. High represents when an aircraft flies internationally; on average it represents 12 hours per day. Generally, airplane flies six days a week (48 hours), and monthly (192 hours). So the research starts the range (very low) with 5 hours monthly, and increases with interval of 40 hours until reaching 205 hours. The range can be seen in the in Table 8.

Table 8. Level of Quantity of Maintenance

Range	Quantity
High-H	205
Medium High-MH	165
Medium-M	125
Low Medium-LM	85
Low-L	45
Very Low-VL	5

The research will simulate the inventory cost of each model having high or low maintenance. The intention is to check how the models affect the inventory cost with high or low material consumption in an uncertain maintenance environment.

This way, no matter which reparable or material consumption used, the importance is with the range of the amount of maintenance and the behavior that the stock will have. Thus, the experiment is intended to cover the full range of maintenance and material consumption possible and analyze it in each inventory model.

Dependent Variable

Inventory Cost: the dependent variable is inventory cost. To calculate the inventory cost, this research uses three components: holding cost, fixed cost and shortage cost.

1. Fixed cost: K is accounted, every time that it is placed an order;

$$Ck = K*N \tag{21}$$

N quantity of order in a period.

2. Holding Cost(h), also referred to as a inventory carrying cost, “is accumulated per unit held in inventory per day that the unit is held” (Simchi-Levi et al., 2007). Ballou (2007) affirms that 80% holding costs is referred to as a capital cost (Ballou & Srivastava, 2007, p. 348). Cost of capital can vary from 5% to 35%. Others variable costs compose the holding cost such as insurance, shelf life limitations and operating cost involved storing inventory or cost of operating warehouse facility (Vollmann et al., 2005, p. 138). In this research will use annual Holding Cost Per Unit:

$$Ch = C * H \text{ (in \$/item in inv./year)} \tag{22}$$

3. Shortage Cost occurs when demand exceeds the available inventory for an item. It is related to the level of customer service that the organization wants to reach. It can be like a missed chance of profit, which is called the opportunity cost. In this research, this cost is the quantity missed (S) of item in period times the price of the item (P):

$$Cs = P * S \tag{23}$$

4. Total cost (TC) is the sum of the there components: fixed, holding and shortage cost. It is represented in the following formula:

$$TC = Ck + Ch + Cs = > TC = K*N + H*Q + P*S \tag{24}$$

An example of the calculation is in Table 9.

Table 9. Total Cost Calculate

	Sum of qty negative stock in a period	qty ordered in a period	Sum of qty positive stock after in a period
Qty	**100**	**39.00**	**21,360.10**
Parameters	**P=21.6**	**K=54**	**h=0.4**
Total Cost	**Shortage Cost**	**Order Cost**	**Holding Cost**
12,810.04	**2,160.00**	**2,106.00**	**8,544.04**

The factorial design 2x6 of the experiment is represented in Table 10.

Table 10. Factorial Design of Experiment

Independent Variable	Inventory Models	
Quantity of Maintenance	EOQ	MERP
High	Inventory Cost	Inventory Cost
Medium-High	Inventory Cost	Inventory Cost
Medium	Inventory Cost	Inventory Cost
Low-Medium	Inventory Cost	Inventory Cost
Low	Inventory Cost	Inventory Cost
Very Low	Inventory Cost	Inventory Cost

Simulation Experiment

To compare the effect of the models over inventory cost, this research will do a simulation experiment with empirical data. This empirical experiment controls all internal threats and seeks to study the relations “under a pure and uncontaminated condition” (Kerlinger & Lee, 1999, p. 581).

The result of the experiment will be compared and analyzed to support the hypotheses, or not. The experiment design is as follows:

Situation A_1^n ---------------X(EOQ)-----------------------O

Situation A_1^n---------------X(MERP)----------------------O

n is the number of sample per quadrant in factory design.

Basically the purpose of the simulation experiment is to test the hypotheses derived from the theory. The weakness of generalizing the hypotheses is compensated for per strong internal validity (Kerlinger & Lee, 1999). The simulation represents the reality of an environment. The simulation manipulates the independent variables and records the dependent variable to analyze. This kind of experiment allows for “all of the roles of the research scientist without having to contend with the time-consuming process of data collection” (Benedict & Butts, 1981).

The time of the experiment is of 4 years, (y-2, y-1, y, y+1). In each year, it will set up the weekly average usage to process the quantity of maintenance. In y-2 and y-1, it will calculate the demand of corrective and preventive maintenance, the spare part consumption of the maintenance, and the weekly average. For the y, and y+1 are simulated 52 events for year with total 104 events for sample. Then, the result experiment is recorded.

The simulator was programmed using Visual Basic for Application along with Microsoft Excel. The Excel is used to produce a useful and comfortable tool (Hihn, Lewicki, & Wilkinson, 2009) . It permits easy testability and repetition of the experiment. The simulation was programmed to produce 50 samples in each quadrant of the factorial design. The simulation ultimately creates 600 samples.

The simulator utilizes a lot of Excel worksheets to process, record and analyze the information. The first step is to fill in the variable and fix parameters. With this information, the quantity of PM and CM per year (MOP function) are calculated. Based on the weekly average of maintenance, the simulator creates a random Poisson number/quantity of maintenance per week to represent the uncertainty.

For an EOQ simulation, the material consumption used in maintenance is processed and calculated for the EOQ (EOQ Demand is the sum of 52 week -1 year-old demand before of actual period week of calculation; ROP uses the average of demand in this period). With EOQ and ROP data, the experiment simulates 2 years of consumption and replacement of stock. To decrease the stock weekly and increase uncertainty, the simulation uses a random Poisson distribution to calculate the consumption of material. In the end, simulator records the EOQ costs.

For MERP, it is uses the same data of maintenance (MOP) and generate a MPS with the quantity of PM and CM. Afterwards, it generates the spare parts to purchase based on MMRP. To decrease the weekly stock and increase uncertainty, the simulation uses a random Poisson distribution to calculate consumption of material.

At the end of each procedure, the EQO and MERP cost and quantities are recorded and the simulator repeats the experiment 50 times with random maintenance and consumption of material. After recording 50 samples, the simulator changes the parameters and processes again until finishing the last parameter. The procedure is in Figure 3.

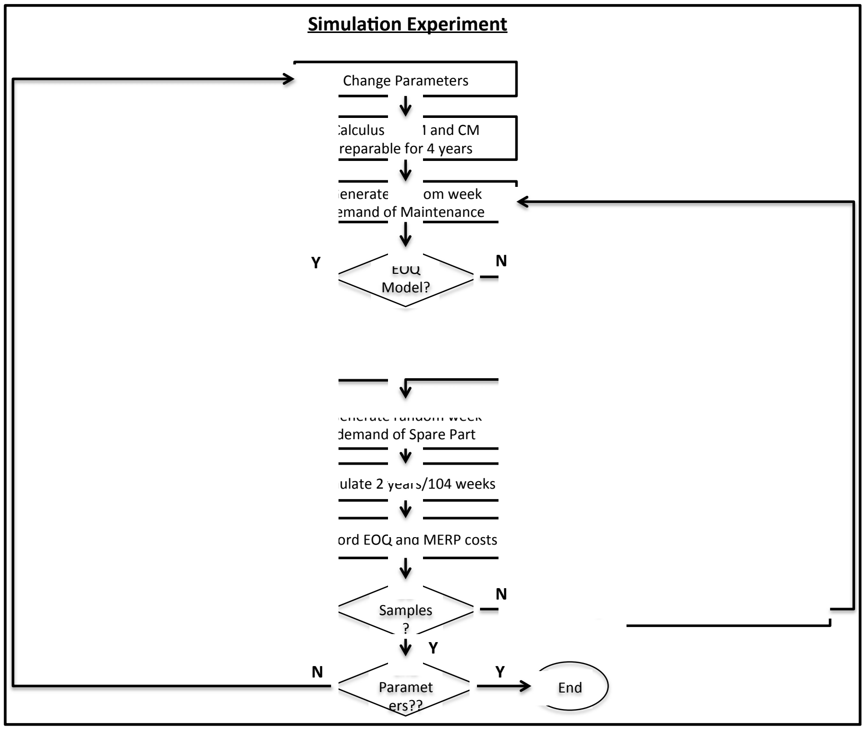

Figure 3. Simulation Procedure

For the H-1, the samples are statically tested with an analysis of the variance (ANOVA) to support the hypothesis that there is a significance difference between the two models. For H-2 to H-7, because the samples are paired, (i.e., simulation uses the same parameters to produce different results in EOQ and MERP), it will use depend t-test to check the hypotheses.

Assumption and Fixed Parameters of the Simulation

Assumptions for MERP:

1. The simulation will calculate the requirements at the beginning of period.
2. The simulation tries to meet requirements for future periods;
3. The decisions will occur weekly.
4. The cost does not change significantly with time.

5. Supplier delivers the requirement on time; delivers don't have uncertainty.
6. The experiment put uncertainty only requirement demand (requirement for more or less than planned using Random Poisson distribution)

Assumption for EOQ:

1. It uses a continuous review policy for purchases.
2. ROP and EOQ use historic demand for 1 year.

Fixed parameters were put with based in Silver et al. (1998) experiment. (Silver et al., 1998). The parameters are at Table 11.

Table 11. Fixed Parameters

Fix Parameter	Value
Fixed Cost (K)	$54.00
Item Price	$20.00
Tax Annual Holding Cost(H)	$22%a.a
Number of Aircraft X	300
QPA of Generator in Aircraft X	2
QPA of Part A in Preventive maintenance of Generator	QPA=10 Probability of change=100%
QPA of Part A in Corrective maintenance=10	QPA=10 Probability of change=80%
Service Level	0.90
Lead Time Spare Part	4 weeks
Frame Time of Experiment	52 week/year

Results

Hypothesis 1—There is significant difference between MERP and EOQ inventory models, and different quantities of maintenance on inventory costs.

To test this experiment, the simulation generates 50 results to each quadrant of a factorial design. Analysis of variance (ANOVA) was used to compare the systematics variance in the data to the amount of unsystematic variance and presents the result at Table 12.

Table 12. Result of Experiment After Simulation

Independent Variable	Inventory Models	
Quantity of Maintenance	EOQ	MERP
High	5,604.73	3,845.59
Medium-High	5,250.52	3,451.92
Medium	4,371.84	2,996.56
Low-Medium	3,711.36	2,489.34
Low	2,686.83	1,833.45
Very Low	1,265.09	685.99

ANOVA produces an F-statistic or F-ratio to support that the means of the experiments are equal or not. The significance level tested is 95%. The test is at Table 13.

Table 13. ANOVA Table

Source	SS	df	MS	F	p-value
Models	972,559,674	5	194,511,934	470.26	9.32E-203
Qty Maintenance	239,876,513	1	239,876,513	579.94	1.11E-89
Interaction	29,570,294	5	5,914,058	14.30	3.18E-13
Error	243,210,640	588	413,623		
Total	1,485,217,122	599			

After analyzing the results, researchers can infer that

- There is a significant main effect of the type of inventory model on inventory cost, F(5,588) = 470.26, p<0.001, ω^2 = 0.78.
- There is a significant main effect of the quantity of maintenance on inventory cost, F(1,588) = 579.94, p<0.001, ω^2 = 0.19.
- There is a significant interaction effect between inventory models and quantity of maintenance on the inventory cost, F(5,588) = 14.30, p<0.001, ω^2 = 0.02. This indicates that EOQ and MERP models are affected differently by quantity of maintenance.

ω^2 represents the variance estimate for the effect divided by the total variance (Field, 2009, p. 446).

The result supports Hypothesis 1 that there is significant difference between the two inventory models, and quantity of maintenance on inventory cost.

H-2 to H-7 (to each level of maintenance): Inventory cost is lower using MERP than the EOQ model with different quantity of maintenance.

After Simulator produced 50 samples to each level of maintenance, it was done a dependent t-test to $p \leq 5\%$. With the results of Table 14, researchers can infer that on average the experiment present that the inventory cost is significant lower using MERP than the EOQ model with different quantity of maintenance according Table 14.

Table 14. H-2-H-7-Dependent t-Test

Maintenance Qty	Parameters	EOQ	MERP
High	Mean	5,604.73	3,845.59
	Std. Error Mean	150.51	18.89
	mean difference (MERP - EOQ)	1,759.14	
	std. dev.	1,091.74	
	std. error	154.40	
	t-test	11.39	
	p-value (one-tailed, lower)	1.11E-15	
	r (effect size)	0.85	
	confidence interval 95.% lower	1,448.87	
	confidence interval 95.% upper	2,069.41	
	margin of error	310.27	
Medium-High	Mean	5,250.52	3,451.92
	Std. Error Mean	178.77	16.71
	mean difference (MERP - EOQ)	1,798.60	
	std. dev.	1,283.77	
	std. error	181.55	
	t-test	9.91	
	p-value (one-tailed, lower)	1.37E-13	

Maintenance Qty	Parameters	EOQ	MERP
	r (effect size)	0.82	
	confidence interval 95.% lower	1,433.76	
	confidence interval 95.% upper	2,163.45	
	margin of error	364.84	
Medium	Mean	4,371.84	2,996.56
	Std. Error Mean	135.19	14.03
	mean difference (MERP - EOQ)	1,375.27	
	std. dev.	967.83	
	std. error	136.87	
	t-test	10.05	
	p-value (one-tailed, lower)	8.59E-14	
	r (effect size)	0.82	
	confidence interval 95.% lower	1,100.22	
	confidence interval 95.% upper	1,650.33	
	margin of error	275.06	
Low-Medium	Mean	3,711.36	2,489.34
	Std. Error Mean	112.47	10.79
	mean difference (MERP - EOQ)	1,222.02	
	std. dev.	800.92	
	std. error	113.27	
	t-test	10.79	
	p-value (one-tailed, lower)	7.62E-15	
	r (effect size)	0.84	
	confidence interval 95.% lower	994.40	
	confidence interval 95.% upper	1,449.64	
	margin of error	227.62	
Low	Mean	2,686.83	1,833.45
	Std. Error Mean	79.35	8.42
	mean difference (MERP - EOQ)	853.38	
	std. dev.	559.40	
	std. error	79.11	
	t-test	10.79	
	p-value (one-tailed, lower)	7.67E-15	
	r (effect size)	0.84	
	confidence interval 95.% lower	694.40	
	confidence interval 95.% upper	1,012.36	
	margin of error	158.98	
Very Low	Mean	1,265.09	685.99
	Std. Error Mean	79.82	6.69
	mean difference (MERP - EOQ)	579.10	
	std. dev.	562.68	
	std. error	79.57	
	t-test	7.28	
	p-value (one-tailed, lower)	1.23E-09	
	r (effect size)	0.72	
	confidence interval 95.% lower	419.18	
	confidence interval 95.% upper	739.01	
	margin of error	159.91	

Effect size (r) is “simply an objective and (usually) standardized measure of the magnitude of observed effect” (Field, 2009, p. 56). The formula to calculate the effect size is:.

$$r = \sqrt{\frac{t^2}{t^2 + df}} \quad (25)$$

Discussion

The study tests a new collaboration model between maintenance supply chain elements. It matches inventory to maintenance requirements in order to decrease inventory costs. We compare the new model with the traditional inventory model and at different quantities of maintenance. The research question is supported by the result of seven hypotheses.

The first hypothesis shows that there are strong differences in inventory costs using models with different quantities of maintenance. Models, quantities of maintenance and their interactions have a significant effect on inventory cost. Although the experiment demonstrates that both models purchase almost the same quantity of material, inventory cost is different between the models when different quantities of maintenance are applied.

The second through the seventh hypotheses are supported by the dependent statistic t-test. The t-test supports that when MERP is used to manage inventory, the cost is lower than with EOQ. Therefore, we can infer that there is strong evidence that Maintenance Enterprise Resource Planning (MERP) model decreases inventory costs when compared to the EOQ model.

This research extends the use of information processing theory to supply chain management by creating a model that integrates information within and across the supply chain. Because of the complexity of the maintenance environment, the model organizes, shares and integrates information among the elements of the supply chain (e.g., MTBUR, BOM, hours of flight). MERP framework increases the integration capability, and consequently, can increase supply chain performance. So, the model extends the Galbraich (1973) proposal where with high uncertainty, there is more need for processing information. This model increases the lateral and vertical integration providing a great increase in cost performance in supply chains. Posey & Bary (2009) propose a framework to supply chain but didn't test the framework. This experiment complements the study of Posey & Bary (2009) by showing results that are proposed in their framework.

This research adds a new scientific approach to MRP by adding a new theory on the use of MRP. In the early days, "MRP was neglected in academic curricula in favor of intellectually challenging statistical and mathematical techniques. Academics considered the study of MRP vocational rather than scientific" (Ptak & Smith, 2011, p. 375). This experiment uses the principle of information-processing theory to integrate lateral relation and increase vertical information to decision makers, a principle of MRP. Using MRP techniques, this model can increase the capacity of information processing and decrease uncertainty in the maintenance supply chain.

Further, this model brings a new framework to the maintenance supply chain. A literature review shows scarce research about models that attend to this environment. This model brings a new management dimension to maintenance supply chain. With it, MRO organizations can integrate the use of equipment, predict maintenance and material, and consequently, decrease inventory costs. This framework fits well in organizations that specialize in management maintenance and service supply chain.

Reducing inventory costs can now be explained. The integration of information decreases the degree of separate information, so that there is both a reduction in uncertainty and an increased information processing capacity. "Traditional inventory management, in the pre-computer days, could not process and integrate the information because of limitations imposed by the information-processing tools." Almost all those approaches suffered from this imperfection causing development of elaborate mathematics models working in isolation, such as with the EOQ and ROP models (Ptak & Smith, 2011, pp. 377–378).

The new model decreases the volume of uncertainty by putting the maintenance demand as a mitigating factor. So, demand forecasting mitigates uncertainty and consequently the quantity of the stock needed to attend the maintenance is lower than the buffer class in EOQ.

This simulation controls the unbiased variables and manipulates the independent variables to measure the dependent variables. This model studies only an aircraft, a generator and a spare part, but the pattern observed in this experiment can be applied to any reparables or spare parts. Only the basic parameters change, yet the results are the same because the models tested the high and low quantities of maintenance demand. So the spare parts have to follow the same pattern for any reparable. This model can be used for all items of an aircraft, and results will be the same. By putting all reparables and spare parts in MERP models, managers can simulate the fleet usage and can adjust the quantity to fit their budget. Nowadays, the only limitations are the processing capacity, which, is easily overcome with the improved capacity of new computers and networks.

This model can also bring new approaches to manage maintenance. For example, car dealers have to maintain a high inventory to attend to corrective and preventive maintenance. If cars now have technologies such as machine-to-machine (M2M) that transmit mileage, MERP can calculate and forecast maintenance and material requirements and decrease the materials inventory for shop maintenance. All companies doing maintenance can use this framework to improve their supply chain.

This research uses uncertainty in demand only. For future research, it is suggested to put uncertainty into lead time, and to study new buffers against such uncertainty such as Demand-Driven MRP (Ptak & Smith, 2011). Other useful research would include testing this model in a real environment to record the data and compare it across the simulations performed.

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