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A Review of Simulation Modelling Approaches in Aviation Spare Parts Inventory Optimisation

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Abstract

Aviation spare parts are expensive and are being kept as a buffer for unscheduled and scheduled maintenance activities. Apart from cash flow being locked in the inventory, spare parts for aircraft or helicopters are also critical in the continuous operations of air assets. In addition, the holding cost is roughly 20 per cent of the total inventory value. Holding costs are costs such as insurance, utilities and manpower. Minimising the total inventory value could be done by adopting a lower inventory count through various methods, such as the provision of spare parts, which can be done either by forecasting the failure of components or by using new maintenance methodologies, such as predictive maintenance. The methods have been used widely in the aviation industry for a long time. The upward trend of papers published from 1963 to 2023 shows that aviation spare parts optimisation is still being discussed. This paper reviews the simulation modelling approaches to optimise aviation spare inventory. 221 papers were reviewed from Scopus and Web of Science (WoS) literature databases, and 17 papers from 1982 to 2023 were chosen based on the simulation modelling approach, such as System Dynamics and Discrete-Event Simulation. The papers were classified according to simulation modelling techniques, spare parts and operations classification, and challenges and opportunities.

Keywords: simulation modelling approach; aviation spare parts; inventory management; review paper;

1. Introduction

The definition of “stock” is goods being held, and “inventory” is a register of items kept in stock. At the same time, “Inventory Management” is an act to control the stocks within an establishment. In the context of this paper, the stocks are aviation spare parts. The stock cycle consists of suppliers and customers. Purchased spare parts are procured from the supplier before the supplier delivers the spare parts and are kept in stock. Meanwhile, customers could be within the same organisation, depending on the operation type. For example, an airline keeps an inventory of spare parts to be supplied to the aircraft, commonly ordered by maintenance personnel.

Spare parts are expensive. However, due to their importance in supporting the operations within an aviation organisation, spare parts are still being kept. The yearly inventory holding costs are roughly 20 % of the total inventory value. For example, if the total inventory value is 10 million, the holding costs are 2 million dollars annually. Holding costs consist of costs such as rental, utilities, insurance and manpower. Therefore, keeping spare parts at a minimum is essential to keep costs down while ensuring that overall operations are maintained.

There are various methods of inventory optimisation. The commonly used method is mathematical optimisation, which is comprised of demand forecasting methods to predict the failures of components. However, aviation operations are becoming more complex, with many variables affecting the operations. There is a need to find a solution to capture the complex scenarios of aviation operations. In this paper, the various simulation modelling approaches are reviewed and evaluated. Chapters 2 and 3 present the review methodology and the spare parts classifications. While Chapter 4 introduces the type of operations, Chapter 5 discusses the challenges and opportunities.

2. Review Methodology

Fig. 1 shows the systematic review methodology conducted. This review paper uses Scopus and Web of Science (WoS) databases to search for publications and articles. The search string for Scopus was done by using the search within the article title, abstract, keywords, (aircraft OR helicopter) AND (spare) AND (inventory), with 190 papers. While for WoS, the search string was (((((ALL=(aircraft OR helicopter)) AND ALL=(spare)) AND ALL=(inventory)) AND

TS=(aircraft OR helicopter)) AND TS=(spare)) AND TS=(inventory), resulting with 103 papers. Some papers that are duplicated are removed from the list.

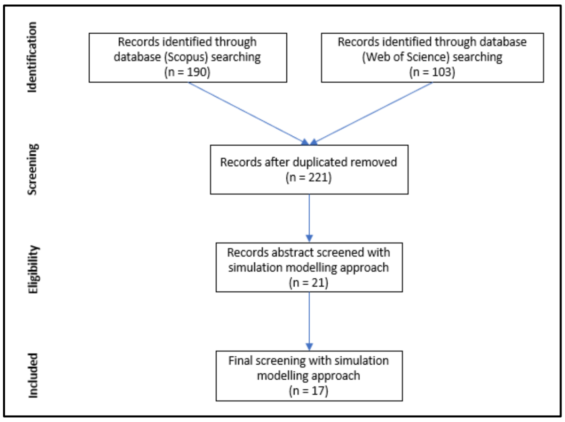

Fig. 1. Systematic Review Methodology.

The initial search produced 221 papers from 1963 to 2023. The inclusion criteria comprised papers using simulation modelling techniques to optimise aviation spare inventory, such as System Dynamics, Discrete-Event Simulation and Agent-Based Simulation. The exclusion criteria encompassed papers using other optimisation techniques, including Monte Carlo Simulation.

All the abstracts of the 221 papers were reviewed. In total, 21 papers discuss the simulation modelling approach, with 4 papers looking into Monte Carlo Simulation as the technique was removed. Only 17 papers have been reviewed using the simulation modelling approach of System Dynamics and Discrete-Event Simulation.

3. Simulation Modelling Techniques

A simulation model is an imitation of a facility, system and operation of a real-world process over time [1] [2] [3]. They are used to understand and analyse complex systems and are comprised of Discrete-Event Simulation (DES), System Dynamics (SD) and Agent-Based Simulation (ABS) [3]. Simulation models are simulated iteratively and analysed using numerical rather than analytical methods.

Table 1 shows the simulation modelling approach and the software, language or tool name adopted by seventeen research papers to optimise the inventory for aviation spare parts.

Table 1. Simulation Modelling Techniques, Discrete-Event Simulation and System Dynamics, and the Language/Software used by the research papers.

Simulation Modelling Techniques	Count	Language/ Software	Count
Discrete-Event Simulation	16	ARENA	4
		FORTRAN	2
		Java-based	1
		Python-based	1
		MATLAB	1
		SHOAM	2
		Flexsim	1
		ExtendSim	1
		Not Mentioned	3
System Dynamics	1	Vensim	1

Table 1 shows that DES has more research papers than SD. The overview from the table sets the stage for a closer review in the next chapter.

Compared to other optimisation approaches, the advantages of a simulation modelling approach are due to the versatility of representing complex real-world systems in a virtual environment with the ability to create various scenarios without compromising safety and putting the operations at risk. Fig. 2 depicts the cycle of the simulation model as a way of carrying out experiments or what-if analysis.

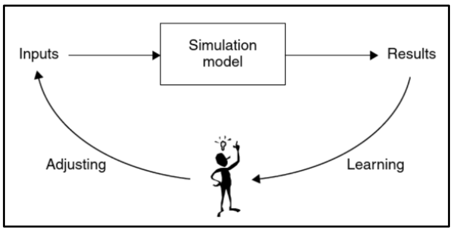

Fig. 2. Experimentation or what-if analysis with simulation [3]

Upon obtaining the results from running the simulation model, the user would be able to learn and then adjust the inputs to see the outcome of the changes being made.

A simulation model is also able to test and validate other optimisation methods depending on the spare parts classification, which will be discussed in Chapter 4

3.1. Discrete-Event Simulation (DES)

Discrete-Event Simulation (DES) is a simulation modelling technique used mainly in manufacturing, healthcare and many other fields. DES was introduced by an IBM engineer, Geoffrey Gordon, in

1961. The technique considers a complex system as a process [4]. As shown by Table 1, sixteen papers use DES to optimise the spare inventory, making it the most used method compared to others.

Five types of software, programming languages, and tools are used. The earlier papers [5] and [6] were built using the FORTRAN programming language. Meanwhile, [7] and [8] used a Python Java-based programming language, even though they were published in 2013 and 2014. Four papers were built on a simulation software environment named ARENA [9] [10] [11] [12], one on Flexsim [13], one on ExtendSim [14] and one on MATLAB [15].

The advantage of using a software environment is that it comes with graphical user interfaces, animation, and visualisation tools, providing users with better tools. Two papers used a company-developed simulation modelling tool by Boeing company. It is named as System Health Operations Analysis Model (SHOAM). According to Banks [2], adopting a simulation software environment reduces the time to learn the programming language and comes with features such as model debugging and input and output analyser.

3.2. System Dynamics (SD)

System Dynamics was founded on Jay W. Forrester's control theory and the modern concept of nonlinear dynamics. The technique provides perspective and conceptual tools that enable an understanding of a complex system's structure and dynamics [16].

Ghadge et al. [17] uses the SD simulation modelling technique to assess the impact of implementing Additive Manufacturing (AM) within an aircraft supply chain network. The aircraft supply chain network consists of multiple Regional Distribution Centers (RDCs) and Service Locations (SLs) based in the United States. The SD model developed compares the supply chain performance, aggregate inventory level, and inventory holding costs between AM and Conventional Manufacturing (CM). The AM system's aggregate inventory level and holding costs are better than those of the CM systems.

The study's results presented an overview of supply chain performance without providing much insight into the performance of each RDCs and SLs, reflecting the abstraction level that an SD model could capture. However, a micro-level understanding of each RDCs and SLs inventory level and holding cost would also be beneficial.

4. Spare Parts Systematic Classification

4.1. Type of Spare Parts

According to the International Air Transport Association (IATA) [18], aviation spare parts are classified as rotable, repairable and expendable. The classifications are based on three distinctive characteristics of the spare parts: scrap rate, financial and lifecycle. Table 2 describes the characteristics based on the three classifications.

Table 2. Spare Parts Classification and Characteristics.

Classification	Scrap Rate	Financial	Life Cycle
Rotable	Low or Negligible	Asset	Indefinite
Repairable	Between 0% to 100%	Asset	Continued usage until scraped
Expendable	100% scrapped	Consumed	Consumed

Generally, managing rotatable and repairable spare parts is much more complex than managing expendable spare parts. For example, an engine consists of multiple modules and sub-components with their own lifecycle. They are being monitored on a sub-component basis, and once they are unserviceable, the main component will also be unserviceable. This adds to the complexity of managing rotable and repairable components.

Also, rotable and repairable spare parts must be tracked financially and compliant throughout their lifecycle. The tracking includes whenever the spare parts are installed on the aircraft, stored in the inventory, or out for repair and overhaul. Besides tracking the spare parts of rotable and repairable, the supply sources could include suppliers and Maintenance, Repair and Overhaul (MRO) organisations carrying out repairs or overhauls. Thus, metrics like repair turnaround time (TAT) are included.

Rotable and repairable are high value [7] [19] [20] assets. The demand for most rotable and repairable is slow-moving, intermittent and lumpy [14]. These characteristics are challenging to forecast and could also have long lead times.

The papers are further classified based on their spare parts classification and spare part names, as shown in Table 3.

Even though Table 2 highlights the classification of spare parts into three classifications, the actual classification, especially for rotable and repairable in the industry, is not as straightforward. According to the International Air Transport Association (IATA) [18], airlines define rotable and repairable through their economic analysis. Sometimes, they do not have a repairable inventory classification but only rotable and expendable.

This is also the case with the papers included in this review paper, where some only state the spare part name without classifying the classification. In this instance, the author classified the spare parts into the classification based on the author's understanding of the three characteristics: scrap rate, financial and life cycle.

Table 3. The spare parts classification and spare part name.

Spare Types	Count	Spare Part Name	Count
Rotable/Repairable	5	Engine	5
Repairable	9	Avionics	2
Expendable (non-repairable)	2	Nose Landing Gear Tire	1
Not mentioned	1	Complex Duct Flange	1
		Structures	1
		Environment Control Systems	1
		Not mentioned	9

4.1.1. Rotable/Repairable

Five papers cover a mixture of rotable and repairable in the study. As specified by the International Air Transport Association (IATA) [18], rotable consists of multiple repairable and expendable items. All five papers review engines and their subcomponents. Engines are considered rotable, where the life cycle of this highly valued asset is almost as long as the air asset. Engine sub-components are considered repairable because their scrap rate exceeds an engine's.

Engines and the sub-components are subject to scheduled maintenance to ensure airworthiness. Depending on the task, they would be required to be inspected on-wing or removed, sent to an authorised MRO to be overhauled, inspected, repaired if necessary and returned to service. Due to unforeseen events, they are also subject to unscheduled maintenance. The repair could be done on-wing or require more in-depth repair within a repair shop environment.

Considering the complex nature and challenging task, it is important to make a spare engine and the sub-components available for scheduled and unscheduled maintenance to ensure continuous operations. Two papers within a supply chain optimisation category propose an integrated life cycle maintenance modelling framework covering the whole process of an engine life cycle [15]. Ramirez-Hernandez et al. [7] suggests an engine and sub-components ownership planning at the operator level for an airline. While Hausman et al. [5] evaluates various priority scheduling rules for an engine repair shop with modules and components used by commercial and military.

Two other papers review enabling technologies, Condition-Based Maintenance [13] and the Theory of Constraint (TOC) with Integrated Vehicle Health Management (IVHM) [21]. Both technologies monitor the engine and sub-components, providing the condition and health information for better decision-making and ensuring better operational metrics.

4.1.2. Repairable

Compared to rotable, repairable spare parts are similar but with a higher scrap rate. Depending on the spare parts, the repair lead time is long, requiring operators to place a replacement unit if a component requires to be changed and sent for repair. However, various factors and parameters need to be considered, such as the utilisation of the air assets, demand for spare parts through transactional data, the suggested Mean Time before Removal (MTBR), or Mean Time Before Unscheduled Removal (MTBUR). These are only a few variables, and many more are to be considered.

In this chapter, nine papers cover repairable spare parts in their research. Bradley et al. [14] reviews three forecasting techniques, engineering estimates, statistical, and Bayesian, to optimise inventory. 239 unique repairable parts are being looked at, with the nose landing gear tire being one of them. The forecasting technique differs from the life cycle of a newly built air asset to be in operation for a couple of years.

Two papers presented an inventory optimisation using Vari-Metric [9], the Applied Repairable Item Inventory Planning Method [19] and MRO Inventory Level Optimisation considering customer-owned stock [20]. Three papers suggested a supply chain optimisation by applying spare parts consolidation with two military nations and a logistics strategy by adopting a faster mode of transport to reduce logistics lead time [10]. Mcgee et al. [11] reviews logistic strategy to reduce cost by reviewing less truckload, full truckload, and mode of transport varying in the lead time. Two papers examine process improvement. Tracht et al. [19] uses TOC to examine the process, identifying and improving the bottlenecks, while Iwata et al. [8] reviews maintenance and logistics improvement. The complex nature of the repairable spare parts within their life cycle requires extensive optimisation methods, as shown by the research.

Ghadge et al. [17] presented an enabling technology by using additive manufacturing to manufacture complex duct flange at Service Locations (SLs) on demand. As the spare parts are produced nearer to the demand location, lead time is greatly reduced, with no inventory on hold by the OEM and only safe stock by the airline due to the production times. The technology is promising, but ensuring the quality standards of every piece produced would be challenging, especially for critical components.

4.1.3. Expendable (non-repairable)

Two papers are investigating expendable (non-repairable) spare parts [22] and [12]. The inclusion of non-repairable is due to the papers including non-repairable within the paper title.

Both papers use an Economic Order Quantity (EOQ), continuous review inventory policy, (R, Q) Model as a baseline and compare it with an inventory model based on Prognostics Health Monitoring (PHM). Rodrigues et al. [22] study one item with a fixed lead time while Vandawaker [12] review 20 items with a variable lead time.

The EOQ model consists of a formula where Q is the spare parts to be purchased when a new order is placed. D is the average demand per unit of time, K is the administrative cost of placing an order, H is the holding cost per unit per unit of time held in inventory, and P is the stockout cost per unit per unit of time [22]

4.1.4. Not mentioned

One paper could not be classified into any of the three classifications as there is no information about the spare part characteristics [6]. The paper looks at an OEM spares department with five international warehouses comprised of 120,000 stocked part numbers. The paper reviews the effect of adjusting a performance control parameter (service level) and compares the changes in the inventory. In the two scenarios, the difference between average stock value and maximum average holding time could be compared between a low-performance setting of 90 per cent service level and a high-performance setting of 99.5 per cent service level.

The 9.5 per cent difference in service level between low-performance settings vs high-performance settings increases the Average Stock Value to more than 800,000 dollars, Maximum Stock Value of more than 1,800,000 dollars and 99.5 days in Average Holding Time. These differences in values enable the decision-makers to understand the extent to which a change in one variable changes another variable.

5. Operation Classification

5.1. Type of Operations

Table 4. The operation types are Operators, MRO, and spare parts supplier.

Operation Types	Count
Operators	**9**
Airline	1
AAM	2
Defense	4
Coast Guard	1
Not Mentioned	1
MRO	**6**
Spare Parts Supplier	**2**

Within the life cycle of a spare part, it is either installed on an air asset, stored, or repaired. How it is handled at various life cycle stages also differs from its ownership status. In this chapter, we review the type of operations covered by each paper using a simulation modelling method. Table 4 shows the operation types divided into operators, MROs, and spare parts suppliers. Overall, nine research papers are about operators, six are MROs, and two are about spare parts suppliers. Simulation modelling approaches differ from operation to operation.

5.1.1. Operators

From an airline or AAM perspective, the various operations could be seen as flying based on a schedule from either one base or multiple bases and flying to multiple airports. Airlines and AAMs' business model will then dictate the inventory model required to support it. From a defense perspective, fighter jets or helicopters fly based on sorties to achieve activities such as training, support missions, etc. Another factor to consider is the type of air asset being used. An operator could use one type or multiple types, increasing the complexity of operations, including maintenance and supply chain. Supporting operations such as an airline and defense in spare parts is vital because the air assets won't achieve their scheduled flight or mission if the spare parts are unavailable. The metrics to see this performance are aircraft availability and operational availability (Ao) [9], [11]. Furthermore, other metrics such as shipping costs, customer wait times, and abort rates are also considered [11].

5.1.2. MRO

Even though the operations of Maintenance, Repair, and Overhaul (MRO) organisations are vital in supporting airlines or defense operations, spare parts requirements are not as high as those for airlines and defense operations. However, if certain spare parts are not available to support the repair of a component like an engine during overhaul, the turn-around time (TAT) would be affected. TAT is vital to achieving the required service level to support customers from airlines, AAMs, and defense. Other metrics, such as inventory levels and total costs, are also monitored to evaluate the performance.

5.1.3. Spare Parts Supplier

Depending on the type of services they provide, a spare parts supplier generally handles hundreds of thousands of spare parts in their inventory. Like MRO, spare parts are not as critical for the organisation but are essential for their customers if they need the item to get their fleet in service again. So, the most important element within the operations is understanding the customers' requirements, which will usually be written in the contract with certain metrics such as Service Level and Lead Time. However, without historical and forecast data from the customers, it would be difficult for the spare parts supplier to plan their inventory to support the customers.

6. Challenges and Opportunities

Due to the lack of operational data, representative data was used instead by Rodrigues et al. [10]. Meanwhile, Ghadge et al. [17] had to make reasonable and rational assumptions due to a lack of highly specific real-life data. In addition to the lack of data, data accuracy is also an important element. Therefore, Rodrigues et al. [10] suggested that spare parts be tracked and monitored closely to ensure accurate data. Historical data also provides an opportunity to validate the simulation model's results [6].

Another aspect mentioned by Bradley et al. [14], most of the captured data are flight hours (FH) each month for each aircraft and specific spare parts demand data such as order date and quantity. However, more could be done by capturing data from when a spare part is installed on a particular air asset to when there is a demand for the same spare part for the aircraft. This newly captured data would provide an improved representation of the demand and increase the accuracy of the demand prediction.

Open-source simulation modelling programming languages are readily available without any issue with licenses. However, the learning curve is higher and less user-friendly than commercial simulation modelling software [8].

Integrating existing production software, such as statistical analysis, allows a better decision-making tool [6]. Simulation modelling enables the users to build cost-benefit models to determine the effectiveness of certain technologies, forecasting techniques [14] and optimisation methods, such as Prognostic Health and Monitoring (PHM) [22] [12] and Vari-Metric [9]. Also, simulation modelling provides a platform to predict and understand the effect of certain decisions on performance metrics such as service levels, inventory levels and operating costs [6].

7. Conclusion and Future Research

This paper provides insights into the researchers' simulation modelling approaches to optimising aviation spare inventory. Each approach has specific advantages and disadvantages. For example, DES looks at complex systems as a process, while ABM can interact with multiple agents and capture the history of the interactions. As highlighted in Chapter 6, where the time stamp is used to indicate when the spare parts are installed on the aircraft tail registration and when a demand for the same spare part is required for the same aircraft registration, ABM could capture the required data. Future research could better represent complex systems by combining the two approaches, known as hybrid or multimethod simulation modelling.

While building the simulation model from scratch will be a good learning opportunity, adopting a simulation model through a simulation software environment will reduce the learning curve and provide the tools to focus on ensuring the robustness of the model.

Even though many researchers have looked at the rotable and repairable compared to expendable, the characteristics of rotable and repairable spare parts are vast, difficult to manage, and require a specific inventory model based on the objectives of operations. In addition, using a simulation modelling approach, there are opportunities to include inventory optimisation, process improvement and enabling technologies into the rotable and repairable spare parts.

The papers reviewing the operators cover a wider spectrum of operations that include operations of air assets, which includes flying, maintenance and supply chain. Reviewing and assessing these wider functions ensures a better understanding of the varying parameters affecting the various performance metrics.

Nevertheless, the wider functions do not necessarily mean a macro-level review of the functions. Micro-level representation of the main functions will ensure robustness, consistency and complexity of real-world aviation business operations.

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