Spare Parts Inventory Management: A Literature Review of Mathematical Model and Further Research Direction

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***Abstract*— This paper aim to analyse mathematical models in a spare parts inventory management problem for supporting future research direction that have the potential for significant future contribution in the field. The result showed that studies in a past decade adopt stochastic settings in mathematical model according to uncertainty demand during lead time. The model in reviewed literature mostly focused on minimizing inventory cost. However, there were some differences in details because a repair network may consist of multiple echelon levels. Although the manager may consider addressing a spare parts inventory management problem in a single echelon system. Smart spare parts inventory management requires synchronizing each echelon level together. Subsequently, various solution methods were proposed to solving spare parts inventory management problem. Noteworthy, heuristic and meta-heuristic methods were most widely used to handle the complexity of a spare parts inventory problem due to uncertainty of demand during lead time. Hence, a robust solution method should be developed further. In addition, demand distribution during time between failure should be recognized to handling the uncertainty and unpredictability demand. Moreover, a framework for smart supply chain of spare parts collaboration was presented herein.**

Keywords—spare parts, inventory management, literature review, mathematical model, smart supply chain

I. Introduction

Maintenance, repair, and operations (MRO) are crucial for manufacturing-based industries that heavily rely on machinery operations. The efficiency of the operating machines is naturally decreased over time. In order to achieve the highest continuous production performance, machinery maintenance and repair work must be done in parallel with factories' operations. Replacing spare parts after the machine has already broken down can cause a significant operation downtime which leads to higher overall production costs. For this reason, a reasonable spare parts warehousing management plan must be carefully implemented and evaluated. This is one of the important functions in the value chain process and also one of the activities in the inbound logistics management scheme. Having an effective spare parts warehousing system can help the company to reduce the cost of spare parts storage as well as help make the production lines run smoothly. Also, in the case of increasing service level in the production pipeline, the management of spare parts inventory is critically important for prompt and continuous maintenance to be undertaken. The challenge comes when the factories' operators need to decide on choosing the right strategy for managing the spare parts inventory and the depot space. Unlike other typical warehousing systems for other inventory, such as raw material, work in process (WIP), finished goods, etc., these types of spare parts parcels are waiting for the recipients or customers to pick them up from the storage ground. Normally, the parcel will be produced and then circulated from the warehouse at all times. However, spare parts inventory will circulate slower when the machines do not need any maintenance or the wear level is still low. Together with the factor of uncertainty in determining the time when machines might fail. These two reasons make the estimation of demand becomes very challenging. because of high uncertainty and unpredictability of demand during time between failure.

In this context, a natural question that arises is: "How to manage inventories for spare parts being stocked in maintenance facilities?". Hence, this work aims to investigate for answers to the aforementioned specific research question to be a guideline for handling the high uncertainty and unpredictability of demand during the time between failure of spare parts inventory. Indeed, developing mathematical models to answer this question has both theoretical and practical values. To accomplish the mission, we adopted systematic reviews as a preliminary study to justify formulating mathematical models and solving methods. This allowed us to present results by combining and analyzing research results from various studies conducted on similar research topics. After the presentation of the research background (Section I) and the methodology used for the study (Section II), Section III presents the answer to the research question. Section IV, presents the details of further research direction. Finally, we conclude with lessons learned and an outlook on developing spare parts inventory managing guidelines in Section V.

II. Methodology

This systematic literature review adopted the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) statement [1]. The PRISMA flow diagram of this work was shown in Fig. 1. The review included articles from different sources such as international journals, conferences, book chapters, and Ph.D. theses during the period 2012–2022 which are related to spare parts inventory problems with solution methods as a whole. A total of 329 records were obtained after executing the search strategies, and 5 records from subsequent snowballing. After duplicates were removed, 177 records remained. From these remaining 177 records, 133 of them were excluded because they might be not researched articles since the word "Review" "Survey" "State of the art" or "Overview" existed in the title, abstract, or keywords. Since we focus on spare parts inventory management in a warehouse, after reviewing the abstracts, 15 articles were excluded from the remaining 44 records because they did not mention solving spare parts inventory problems in the abstract, leaving 29 articles for the final screening. 18 articles were excluded in the third round because they are not related to our specific question is within the scope of this study. In total, 11 articles were included in the analysis.

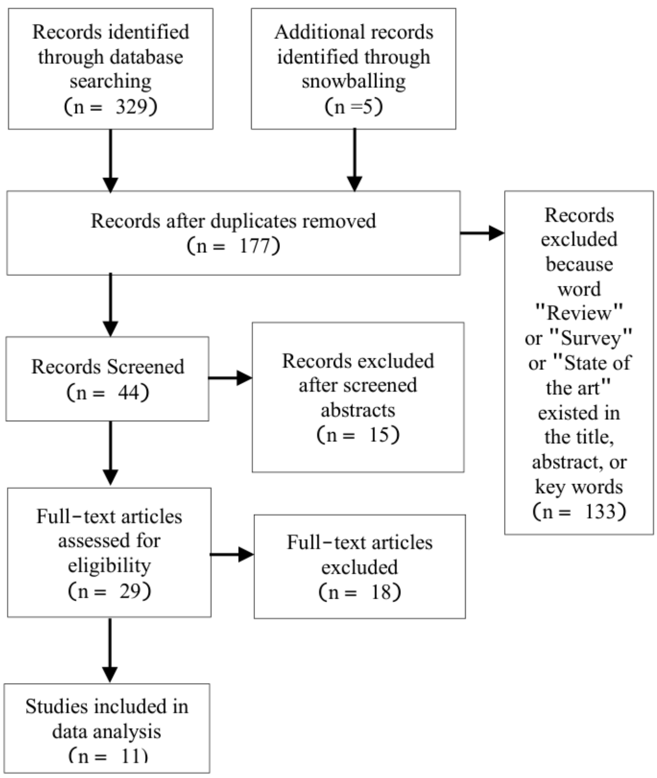

Fig. 1. PRISMA flow diagram

III. Literature Analysis

In this section, 11 studies using prescriptive analytics are examined and divided into three topics: (*A*) Model setting, (*B*) Model Objective, and (*C*) Solution Method.

A. Model setting

Based on the model setting consideration, in this case, if a model assumes spare part demand is uncertain, we classify it as using a stochastic model setting. Instead, if the demand is assumed to be known in advance, we classify it as using a deterministic model setting. As shown in the third column of Table I, all 11 studies adopt stochastic settings, indicating that stochastic settings are basically in this field.

B. Model Objective

Generally, mathematical models of spare parts inventory management usually focus on optimizing inventory cost and service level regarding economic order quantity and reorder point. However, there were some differences in terms of cost in each model. The expected cost could be included with a few terms, for example, holding and shortage cost [2], holding and ordering cost [3, 4], and overhaul and procurement costs [5]. On the other hand, several terms of cost in spare parts inventory were taken in the objective function of a model. [6] considered the expected operating cost of the system in their objective function associated with unit cost, holding cost, shipping cost, replenishment cost, and penalty cost of downtime. [7] included the disposal cost of allocation business, the disposal cost of an inward and outward warehousing business, the transportation cost of spare parts when allocating each other, and the storage cost and the loss cost of shortage in the inventory cost.

In addition, minimizing backorders subject to budget constraint was the one of interesting objectives when the spare part was very critical [8, 9]. Besides inventory cost, [10] formulated a model to minimize stock level by considering service levels.

C. Solution Method

The 11 studies propose various methods to solve the problems, including exact methods, heuristic methods, and meta-heuristic methods. Exact methods can find optimal solutions or bounds on optimal solutions to optimization problems. Large-scale optimization methods such as Branch-and-Bound, Benders Decomposition, and Lagrangian Relaxation were also considered as exact methods. Heuristic and Meta-heuristic methods were used when the problems have high computational complexity. The computational time was reduced but optimal solutions cannot be guaranteed. The studies adopting different solution methods are summarized in the last column of Table I and Fig.2. It should be noted that in some studies, multiple solution methods were proposed.

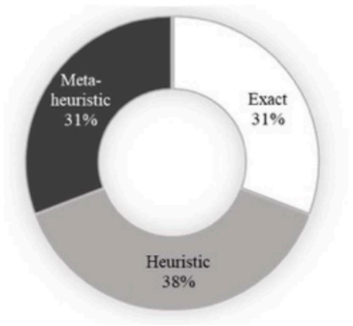

Fig. 2. Solution Method in spare parts inventory models

According to the results in Fig.2, we can see that heuristic and meta-heuristic methods were most widely used in the reviewed literature.

TABLE I. SOLUTION METHOD USED IN SPARE PARTS INVENTORY PROBLEMS

Article	Objective	Uncertainty Demand	Solution Method		
			Exact	*Heuristic*	*Meta-heuristic*
[8]	Min Backorders s.t. budget constraints	√		√	
[2]	Min Cost	√	√		
[9]	Min Backorders s.t. budget constraints	√			√ (GP)
[6]	Min Cost	√			√ (GA)
[3]	Min Cost of Stock Level	√		√	√ (SA)
[4]	Min Cost of Stock Level	√		√	
[11]	Min Cost	√		√	
[12]	Min Cost with Location Problem	√			√ (Adaptive GA)
[5]	Min Cost	√	√		
[7]	Min Cost	√	√		
[10]	Min Stock Level	√	√	√	

Note:
GP = Genetic Programming, GA = Genetic Algorithm, SA = Simulated Annealing

IV. FURTHER RESEARCH DIRECTION

Based on the literature survey, there are some common issues for the spare parts storage, which are, overstock, understock, and the negligence of implementing effective inventory control and management plan. All these issues lead to cost and opportunity loss as well as causing a significant downtime in the production line. Even though there might be no the best solution to solve the issue, this work aims to be one of the real-world case studies and one of the solutions for such areas. Thus, a general picture of the systematic research direction for spare parts inventory management is provided herein. Fig. 3 shows a four steps approach for a further research direction for spare parts inventory management in the context of optimization.

- **In Step 1**, the problem statement should be identified and respect the different features of complex systems. A system may contain tens or hundreds of assemblies, and probably, hundreds or thousands of parts that were organized into multiple indenture levels as shown in Fig.3.

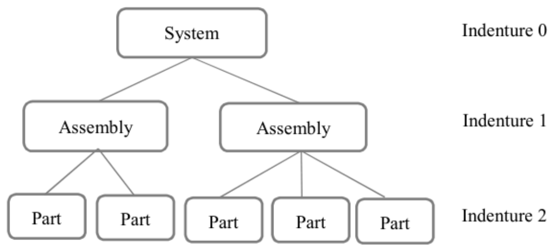

Fig. 3. multiple indenture levels

However, different systems may have parts in common. Therefore, either part in common can be stocked separately for each system or they can be destined to a single system, thus reducing inventory costs. Moreover, systems may require differentiated availability levels. The service differentiation can be seen as a cost-saving opportunity when it is possible to allocate more resources only to the most critical systems.

Besides, a repair network may consist of multiple echelon levels. If a component is repaired, it should also be decided where to do that in the multi-echelon repair network. A depiction of a multi-echelon repair network is shown in Fig.4.

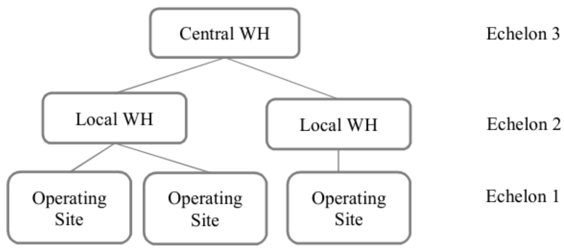

Fig. 4. multiple echlon levels

Since a manufacturing supply chain can consist of central and local warehouses (WH), where central warehouses replenish the stock of local ones. Spare parts allocation should consider stock availability both for the central depot and local sites. In other words, real-world systems are characterized by a multi-echelon repair network. Although the manager may consider addressing a spare parts inventory management problem in a single echelon system. Smart spare parts inventory management requires synchronizing each echelon level together.

- **In step 2**, the interesting spare parts inventory problems should be formulated in mathematical modeling with specific objectives and all of the constraints. Noteworthy, the objective of the model should be to respond to the needs of a decision maker. As a result, in section III, minimizing inventory cost is a common interested objective. However, each model's components of inventory cost may be different according to particular problems.

- **In Step 3**, a robust solution method should be developed to handle the complexity of a spare parts inventory problem due to uncertainty of demand during lead time. Although an optimal solution could be obtained by the exact method, high computational time may be consumed. Thus, heuristic and meta-heuristic methods are the most widely used. Subsequently, the complexity of the algorithm should be considered according to the trade-off feature between solution quality and computational time. Therefore, we call on more research with recently developed algorithms for solving problems in this area to provide high-quality solutions in a reasonable solution time. However, the developed algorithm should be evaluated on the target application to ensure its robustness. In addition, demand distribution during time between failure should be recognized to handling the uncertainty and unpredictability demand. Althoug some studies proposed a methodology base on demand distribution fit for slow and fast moving spare parts [3, 4]. However, either fast or slow moving was judged regrading with a specific number of demand frequency. Consequenty, this may lead to a bias judgement. Hence, there are opportunities to improve and extend the current research.

- **In Step 4**, Recently, the biggest change that is occurring in maintenance is the introduction of the Internet. This has potential to change the relationships between the equipment user and the equipment supplier. The Internet provides better communication between the supplier and user to be more greater frequency and more faster communication [13]. Since the data might influence the decision-making of each participant, the collaboration in supply chain of spare parts is an important goal to achieve. Fig. 5 illustrates a framework for smart supply chain of spare parts collaboration.

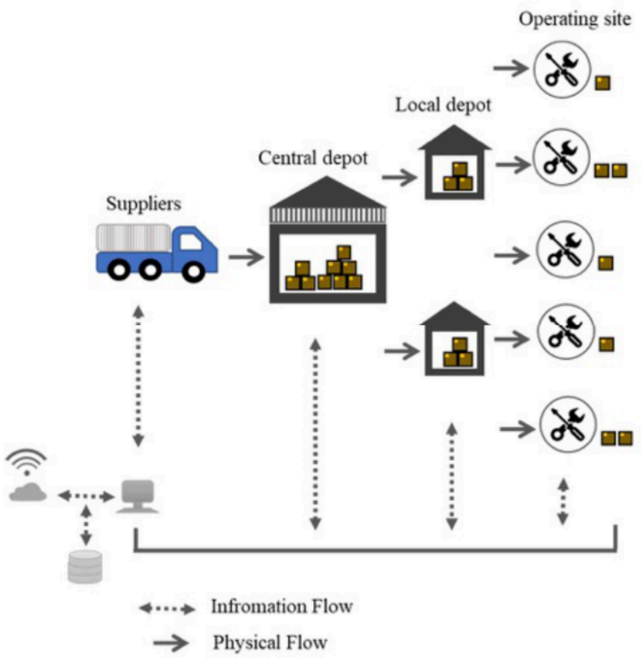

Fig. 5. A framework for smart supply chain of spare parts collaboration

In Fig.5, two or more chain members working together to create a competitive advantage through sharing information. This electronic communication allows all equipment users to predict more accurately their need for replacement parts and consumable items. Thus, a catastrophic breakdown of a critical component can be rapidly replaced. Besides, smart supply chain could be identified as a human-like operation form embedded in emerging technologies such as big data, blockchain and artificial intelligence to achieve efficient collaboration throughout the supply chain through intelligent decision-making, digital management, and automated operation [14]. Consequently, the "smart" characteristics of a framework for smart supply chain of spare parts collaboration are embodied in emerging technologies, digital processes and ecological organizations. Therefore, more work needs to be done in these areas. For example, [15] implement the blockchain-based system, executed under a decentralised ledger mechanism, to improve the quality of traceability data and reliable information sharing within the spare parts supply chain.

V. CONCLUTION AND DISCUSSION

Evaluating a proper amount of spare parts inventory is one of the essential aspects of manufacturing product maintenance. Performing suitable system maintenance can help reduce production downtime and extend the lifetime of machinery within the manufacturing pipeline. The suitable number of spare parts that needed to be kept in the warehouse or storage space is important. According to the reason that there is high cost of keeping a large number of part items, at the same time, the needs of customers and repair requests from the production line must also be satisfied.

This article presents a literature review of mathematical model and further research direction on spare parts inventory management. The result indicated that stochastic settings in mathematical model were basically in this field according to uncertainty demand during lead time. The model in reviewed literature mostly focused on minimizing inventory cost. However, there were some differences in details because a repair network may consist of multiple echelon levels. Thus, the expected cost could be included with a few terms in a dock terminal when single echelon was considered. In contrast, if researchers dealing with multiple echelon problem, the cost may be included additional terms outside a dock terminal such as shipping cost or transportation etc. Although the manager may consider addressing a spare parts inventory management problem in a single echelon system. Smart spare parts inventory management requires synchronizing each echelon level together. In reviewed literature, various solution methods were proposed. Although an optimal solution could be obtained by the exact method, high computational time may be consumed. Thus, heuristic and meta-heuristic methods are the most widely used. Hence, a robust solution method should be developed further.

Furthermore, modern technology makes a supply chain of spare parts feasible and able to develop suitable business models. Therefore, a supply chain of spare parts to be a smart system should be enhanced by emphasized using electronic communication trougout supply chain of spare parts inventory. A competitive advantage from sharing information could be created when the chain members working together.

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