BAŞKENT UNIVERSITY
INSTITUTE OF SCIENCE AND ENGINEERING
DEPARTMENT OF DEFENSE TECHNOLOGIES AND SYSTEMS
MASTER'S OF DEFENCE PLATFORMS WITH THESIS

AFTER-SALES OBSOLESCENCE RISK MANAGEMENT IN LONG-LIFE DEFENSE PROJECTS

BY

CEREN KARAGÖZ KATI

MASTER OF SCIENCE THESIS

ANKARA – 2023

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ADVISOR

ASSIST.PROF. ESRA DİNLER

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This study, which was prepared by Ceren KARAGÖZ KATI, for the program of Master's of Defence Platforms with Thesis, has been approved in partial fulfillment of the requirements for the degree of Master of Science in Defense Technologies and Systems Department by the following committee.

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Examining Committee Member	Signature
Assist.Prof. Esra DİNLER (Danışman), Başkent University	…………………
Assist.Prof. Cenk BALÇIK, Başkent University	………………….
Assist.Prof. Ayyüce AYDEMIR KARADAĞ, Gazi University	………………….

APPROVAL

Prof. Dr. Faruk ELALDI

Director, Institute of Science and Engineering

Date: … / … / ……….

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Öğrencinin Adı, Soyadı	: Ceren KARAGÖZ KATI
Öğrencinin Numarası	: 22010465
Anabilim Dalı	: Savunma Teknolojileri ve Sistemleri
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ABSTRACT

Ceren KARAGÖZ KATI

AFTER-SALES OBSOLESCENCE RISK MANAGEMENT IN LONG-LIFE DEFENSE PROJECTS

Başkent University Institute of Science and Engineering

Department of Defense Technologies and Systems

2023

In the defense industry, products are often complex systems developed and maintained with detailed and complicated business processes. Management and planning in such systems are complicated in parts supply or production. The end-of-life phase of products is the final stage of the product life cycle, which begins with product retirement and ends with the expiration of all service contracts. Obsolescence will occur at the end of its useful life, where remanufacturing used or obsolete products can be an alternative source of obtaining spare parts. For this reason, the proper methods should be selected and applied for each stage. This study proposes an obsolescence management model of critical materials to determine in a large-scale defense industry company. By utilizing this proposed model, companies can purchase sufficient products to meet system requirements during its predicted life, reduce costs by optimizing the process and boost the availability of spare parts. This would ultimately improve overall efficiency in managing products within the defense industry. The model would help mitigate the challenges associated with obsolescence and enable the defense industry to manage parts and products more successfully, resulting in better outcomes for all stakeholders involved.

KEYWORDS: Spare Part, Obsolescence, Defense Industry, MCDM, Optimization

ÖZET

Ceren KARAGÖZ KATI

UZUN ÖMÜRLÜ SAVUNMA PROJELERİNDE SATIŞ SONRASI TEMİNSİZLİK RİSK YÖNETİMİ

Başkent Üniversitesi Fen Bilimleri Enstitüsü

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2023

Savunma sanayinde ürünler genellikle ayrıntılı ve karmaşık iş süreçleriyle geliştirilen karmaşık sistemlerdir. Böyle sistemlerde, parça tedariki veya üretimi gibi durumlarda yönetim ve planlama zor ve karmaşıktır. Ürün ömrünün son aşaması, ürün emekliliğiyle başlayan ve tüm hizmet sözleşmelerinin süresinin dolmasıyla sona eren ürün yaşam döngüsünün final aşamasıdır. Kullanım ömrünün sonunda eskime meydana gelecektir ve kullanılmayan veya eskimiş ürünlerin yeniden imalatı yedek parça temininde alternatif bir kaynak olabilir. Bu nedenle, her aşama için uygun yöntemler seçilmeli ve uygulanmalıdır. Bu çalışma, büyük bir savunma sanayi şirketinde belirlenecek kritik malzeme kullanım ömrü yönetimi modeli önermektedir. Önerilen bu modeli kullanarak, firmalar tahmin edilen ömrü boyunca sistem gereksinimlerini karşılamak için yeterli sayıda ürün satın alınabilir, süreci optimize ederek maliyetleri azaltabilir ve yedek parça bulunabilirliğini artırabilir. Bu, nihayetinde savunma sanayisindeki ürünlerin yönetiminde genel verimliliğin artmasına yol açacaktır. Model, eskime ile ilgili zorlukların hafifletilmesine yardımcı olacak ve savunma sanayinin parçaları ve ürünleri daha başarılı bir şekilde yönetmesini sağlayarak ilgili tüm paydaşlar için daha iyi sonuçlara yol açacaktır.

ANAHTAR KELİMELER: Yedek Parça, Teminsizlik, Savunma Sanayi, ÇKKV, Optimizasyon

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LIST OF SYMBOLS AND ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
APS	Active Protection Systems
B	total budget
BoM	Bill of Material
CDM	Collaborative Decision Making
CI	Consistency Index
c_i	the unit cost of component i
CR	Consistency Ratio
COTS	Commercial Off-The-Shelf
d_i	the amount determined to be available from the component i
ELECTRE	Elimination Et Choix Traduisant la Réalité
F	target order frequency
ILS	Integrated Logistics Support
I	set of components, indexed by i
lmax	consistency measure
MAUT/UTA	Multi-Attribute Utility Theory/Utility Additive
MCDM	Multi-Criteria Decision Making
N	number of spare parts
RI	Random Index
r_i	importance coefficient of component i
S	service level
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
u_i	the amount not available from component i
x_i	the quantity to be ordered for component i

1. INTRODUCTION

The production of defense systems is not like that of commercial products. Instead, these systems are designed with highly advanced technology and are produced in limited quantities, making them very expensive. Their product life cycles last 10 to 20 years, but a significant challenge exists in maintaining and sustaining long-life defense projects due to obsolescence. The complexity and broad scope of these projects make maintenance a complicated process, mainly because of the lack of availability of components. Obsolescence of parts can lead to various issues, such as delays in maintenance, reduced system performance, and increased costs. The cost of spare parts accounts for a significant share of the overall life cycle cost of defense systems. The value of spare parts annually consumed by machinery, which may have a lifetime of around 30 years, amounts to nearly 2.5% of the original purchasing price. [1] Therefore, companies need to adopt a structured and systematic approach to managing obsolescence risks in large-scale defense projects to address these challenges. Spare parts are critical in ensuring the product life cycle in these industries, and their availability is crucial for maintaining operational readiness and system performance. The completion of the product life cycles of parts can lead to various issues, creating a need for effective and efficient obsolescence management strategies. Managing obsolescence risk is necessary to ensure the longevity and operational effectiveness of large-scale defense projects.

Keeping an inventory of spare parts is paramount for businesses that rely on equipment to operate. This is because the unavailability of replacement parts can result in equipment downtime, which can be costly and detrimental to the smooth running of business operations. However, obtaining these parts from suppliers on short notice can be challenging, as some parts may require specialized tools for repair. However, while keeping spare parts in inventory can be beneficial, it also comes with risks and costs. Therefore, the amount of maintained inventory must be managed effectively to minimize costs, reduce the risk of parts becoming obsolete and ensure that business operations run smoothly. Although new methods of managing materials aim to reduce inventory levels, it is impossible to eliminate stocks completely as they are a natural result of the flow of materials. In addition, stocks play an important role in the economy and strategies of some businesses. Therefore, balancing the cost of carrying inventory and the potential cost of stockouts is crucial. This involves forecasting future demand, analyzing lead times, and optimizing inventory levels to ensure that the right parts are available at the right time.

In managing obsolescence risks effectively, it is crucial to determine the selection criteria for spare parts that need to be kept as a backup after sales. Decision-makers often consider various criteria, including the part's lead time, the part's cost, the part, failure rate of the part, the need for an export license for parts imported from abroad, and the requirement for complex engineering skills for the parts to be ready-to-use. As the decision-making process for spare parts includes the evaluation of different criteria, it becomes a multi-criteria decision problem. To solve the problem, this study used the AHP and TOPSIS multi-criteria decision-making methods together. The mathematical model developed in this study aims to manage component obsolescence risks in the after-sales phase of a medium-sized project of an armored vehicle manufacturer operating in Turkey.

The company does not have any systematic approach in spare parts management. In the past, when there were fewer projects, the transfer of parts between projects did not cause as many problems. However, due to the recent increase in projects, the company is facing difficulties in meeting customer needs during the after-sales period and is dealing with rising project budgets. Main problems to be addressed in this study can be summarized as follows:

- Unavailability of the necessary part in case of a failure
- Excessive stocking of parts due to the uncertainty of which part will be failure
- Increased project budget due to demand uncertainty
- Insufficient stocking of parts due to the uncertainty of which part will fail

The proposed model can help companies in the Turkish Defense Industry to purchase enough products to meet system requirements during their predicted life cycle time and optimize the process to determine the number of components needed to minimize cost and maximize spare parts availability. The method developed in this study is particularly useful for reducing the unavailability risk and improving decision-making processes for spare parts in the Turkish Defense Industry. By using this model, companies can reduce the potential financial losses caused by incorrect demand prediction during the warranty period and minimize the inventory risk at the end of the warranty period.

In conclusion, obsolescence risk management is a critical issue for large-scale defense projects, and effective spare parts management is essential for ensuring operational readiness and system performance. This study proposes a mathematical model based on the AHP and TOPSIS multi-criteria decision-making methods to manage component obsolescence risks in the after-sales phase of a medium-sized project of an armored vehicle manufacturer operating in Turkey. The proposed method can be used by other companies in the Turkish Defense Industry to reduce unavailability risk and improve decision-making processes for spare parts.

Also, this thesis is structured into several chapters. Firstly, Chapter 1 introduces the problem and offers an overview of the thesis.

Chapter 2 summarizes the review of previous and recent studies in the literature. This review specifically focuses on the specifications of spare part management, Multiple-criteria decision analysis, and spare part cost minimization problems found in the published literature.

Chapter 3 offers a detailed problem description and provides information about the company and the specific problem faced.

Chapter 4 introduces a proposed model for addressing the problem. The model is based on a mathematical approach that utilizes both AHP and TOPSIS multi-criteria decision-making methods. The chapter provides a comprehensive overview of the model's assumptions and detailed information about the parameters, sets, and decision variables involved.

The results and findings are thoroughly interpreted and analyzed in the thesis's final section. This section comprehensively examines and discusses the proposed model's outcomes and application.

2. THEORETICAL BASICS and LITERATURE REVIEW

Spare part management can be defined as managing and optimizing spare parts inventory to ensure the timely and cost-effective availability of the right parts. [2] This is particularly crucial for industries that heavily depend on machinery or equipment for their operations. The effective management of spare parts necessitates careful planning and control of inventory levels. This requires understanding the criticality of each part, estimating demand, and establishing appropriate inventory levels to ensure that the parts are available when needed.

The literature on spare part management provides several approaches to optimizing the management of spare parts. In this section, studies in the literature will be presented.

In our study, a problem was defined by conducting literature research on spare parts and obsolescence. A comprehensive literature review was conducted to identify the key issues and challenges associated with spare part management. The study highlights several critical themes, including the importance of accurate demand forecasting, effective inventory control, and the benefits of adopting a proactive approach to obsolescence management.

Also, in this study, a multivariate decision-making method was selected to optimize spare part management due to the complexity of the problem. For this purpose, a literature review was conducted for the appropriate decision-making method to be successfully executed. The analytic hierarchy process (AHP) and the technique for order of preference by similarity to the ideal solution (TOPSIS) were chosen as the most appropriate methods for the study. Then, these methods will be combined with spare part management to investigate their effectiveness in improving spare part management.

As the study includes optimization methods, research in this area will also be addressed. In this context, previous studies will be examined to optimize the use of AHP and TOPSIS methods in spare parts management. The results of these studies will be utilized to enhance the applicability of the research. As a result, this study will employ a multivariate decision-making method by considering previous research on spare parts management and optimization topics. The study results will offer a practical and helpful solution in this field.

2.1. Spare Parts Management Literature Review

H. Zhang [2] reviews the existing literature on spare parts inventory management, a critical component of supply chain management. The review covers different aspects of spare parts inventory management, including demand forecasting, ordering policies, and inventory control. This study highlights a product or project's life cycle phases, as shown in Figure 2.1. The author identifies several gaps in the existing literature, such as the lack of research on the impact of the circular economy on spare parts inventory management. The paper provides a comprehensive overview of the current state of research on spare parts inventory management and identifies areas for future research.

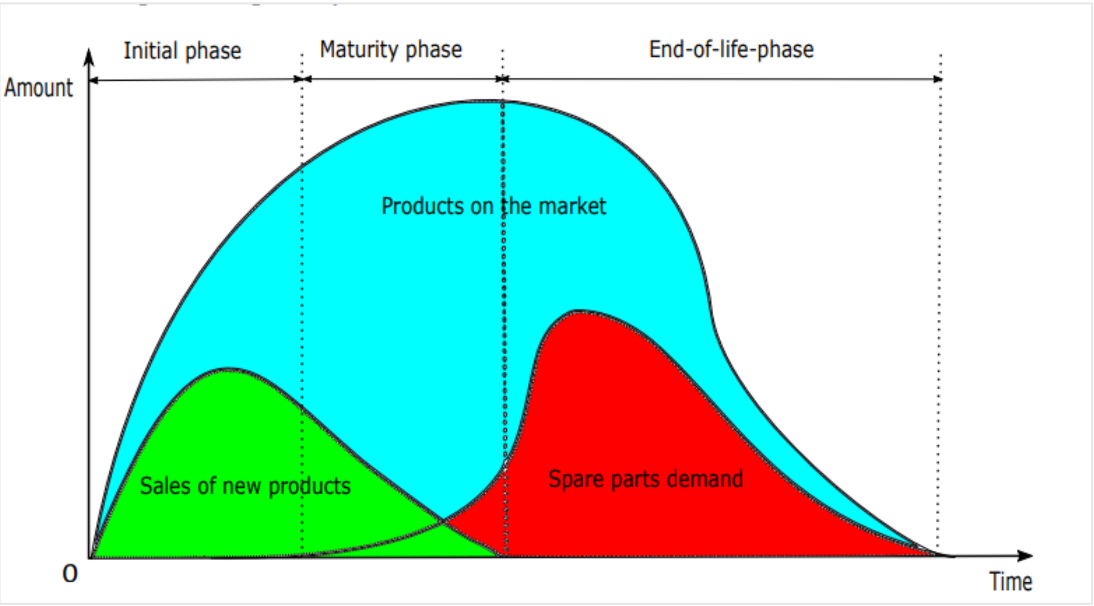


Figure 2.1. Product Life Cycle [2]

Gustafsson and Olsson [3] provide a literature review of spare parts logistics, an essential component of after-sales service operations. The authors identify several key factors that affect spare parts logistics, including demand forecasting, inventory management, transportation, and reverse logistics. The paper also discusses the challenges associated with spare parts logistics, such as the high cost of holding inventory and the need for timely delivery. The authors suggest that future research should focus on developing more integrated models that consider the entire after-sales service process.

Hu et al. [4] conducted a comprehensive review of studies that use operations research in spare parts management, covering the classification of spare parts, demand forecasting, optimization, and supply chain. The authors provide an overview of different OR models used in spare parts management, including inventory models, multi-echelon inventory systems, and demand forecasting models. They also discuss the importance of incorporating uncertainty and demand variability into spare parts management models. In addition, the article highlights the challenges of managing obsolete and slow-moving spare parts and provides insights on how to manage them more effectively. The authors discuss the integration of spare parts management with other areas of supply chain management, such as maintenance and repair operations. Overall, the article emphasizes the importance of OR in improving spare parts management and highlights future research directions. Articles that make spare part classification and their authors are in Figure 2.2 below. This article contributed to the decision of the criteria for classification in our problem.

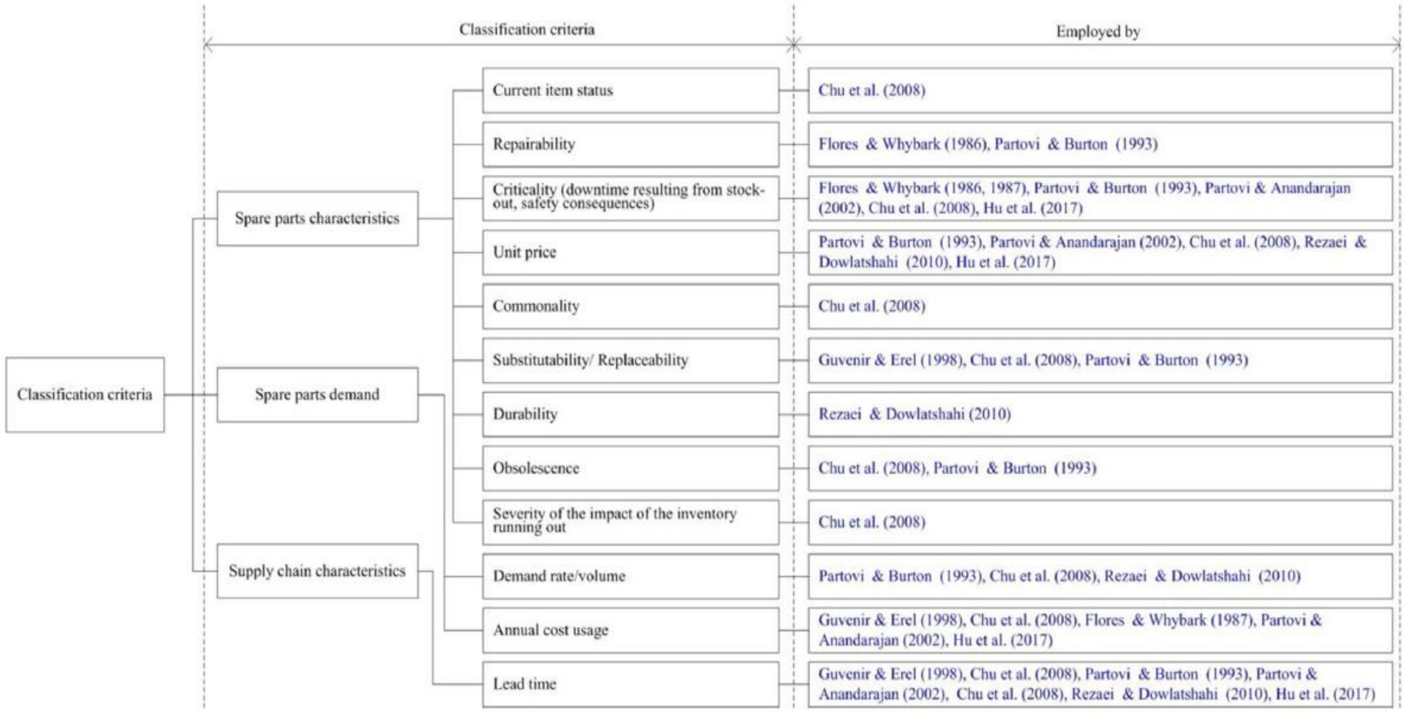


Figure 2.2. Spare Parts Classification Criteria and Articles [4]

Rojo et al. [5] discuss the state-of-the-art and future trends in obsolescence management for long-life contracts. In addition, in this article, the life cycle of a project in the Defense sector is mentioned, and this cycle is included in Figure 2.3 below. The authors emphasize the importance of obsolescence management in ensuring the availability of critical items throughout the life cycle of long-life contracts. They discuss various methods and tools for obsolescence management, including product redesign, lifetime buying, and component and system substitution. The article also highlights the challenges associated with obsolescence management, such as the lack of reliable information and the high cost of implementing obsolescence management strategies. Finally, the authors suggest future directions for research in obsolescence management, such as developing new techniques for predicting obsolescence and integrating obsolescence management into product design and development processes.

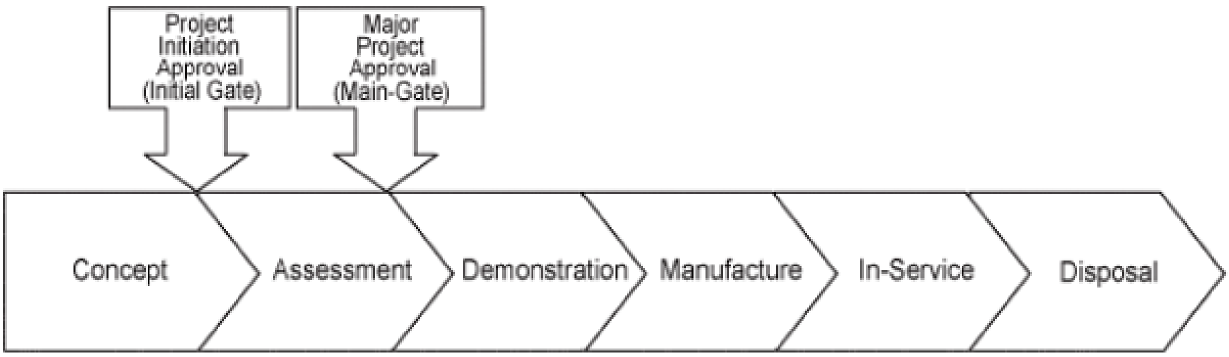


Figure 2.3. The Life Cycle of a Project in The Defense Sector [5]

Rojo et al. [6] proposed a risk assessment methodology for parts in a product's bill of material, which could prevent system maintenance. The obsolescence risk assessment process developed by the authors is given in Figure 2.4. The article discusses the best practices for assessing obsolescence risk in the product development process. Obsolescence risk refers to the likelihood that a product or component will become outdated or unavailable, leading to production delays, increased costs, and reduced competitiveness in this article. The authors propose a systematic approach to assess obsolescence risk, which involves identifying potential sources of obsolescence, evaluating the impact of obsolescence on the product and the company, and developing strategies to mitigate obsolescence risk. They also provide case studies to demonstrate the application of the approach in practice. The article emphasizes the importance of proactive management of obsolescence risk in product development and highlights the benefits of integrating obsolescence management into the overall product life cycle management strategy. This article highlighted that by adopting best practices for obsolescence risk assessment and management, companies could reduce costs, improve product quality and reliability and increase their competitiveness in the marketplace.

Figure 2.4. Obsolescence Risk Assessment Process [6]

Auweaer et al. [7] suggested that information from the current system could impact the demand generation process. The article explores the concept of spare parts management, particularly in the context of multi-echelon supply chains. The authors argue that spare parts are critical components of many products and systems, and managing their availability can significantly impact business performance. They discuss the challenges associated with spare parts management, including demand uncertainty, long lead times, and obsolescence, and propose several strategies to address these challenges. The authors also highlight the importance of collaboration and information sharing between different stakeholders in the supply chain and the use of advanced analytics and technology to improve spare parts management. The article provides valuable insights and practical recommendations for companies seeking to improve spare parts management practices.

Dhakar et al. [8] argued that spare part estimation could be made at a high rate with scheduled and periodic maintenance. Still, a small amount of safety stock is necessary for unexpected failures. Therefore, the authors emphasize a base stock level determination model for critical repairable spares with high cost and low demand. The proposed model aims to minimize the total inventory cost while ensuring critical repairable spares are available. The authors consider various factors, such as lead time, repair time, and demand variability, and develop a mathematical model based on queueing theory and inventory theory. The effectiveness of the proposed model is demonstrated through numerical examples and sensitivity analysis. The results show that the proposed model can help reduce the inventory costs of critical repairable spares without compromising availability.

Braglia et al. [9] focus on implementing a multi-feature classification method for managing spare parts inventory. The complexity and efficiency of spare parts inventory management are the primary concerns addressed in the article. Researchers suggest using a multi-feature classification method as a practical approach to managing spare parts inventory. This method separates the parts into different groups, considering their qualities and requirements. The article provides a detailed description of the multi-feature classification method and proposes a model for its implementation. This model considers the various characteristics of spare parts in the inventory to facilitate the classification process. The ultimate goal is to gain more effective and optimized control over spare parts management, including stock levels, order lead times, and inventory costs. Figure 2.5 includes classification according to “Supply Characteristic,” Figure 2.6 classification according to “Inventory Problem,” Figure 2.7 classification according to “Usage Rate.” All three of these classifications were used to classify the criteria in our problem.

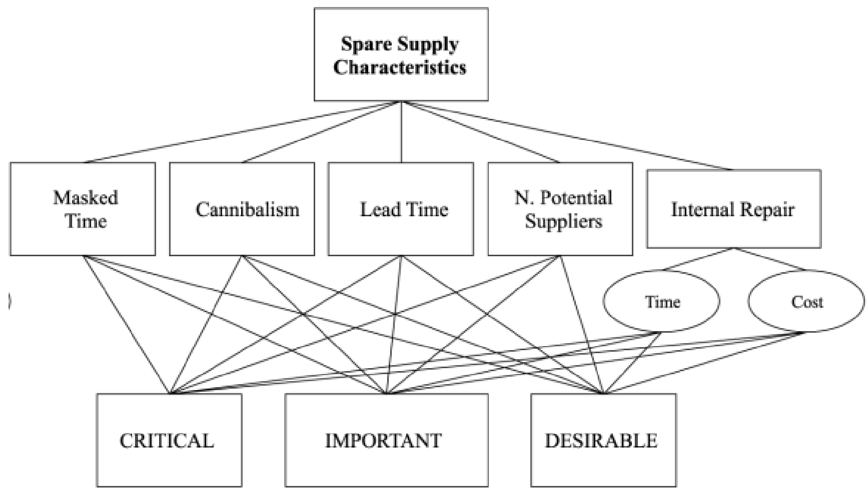


Figure 2.5. Classification by “Supply Characteristic” [9]

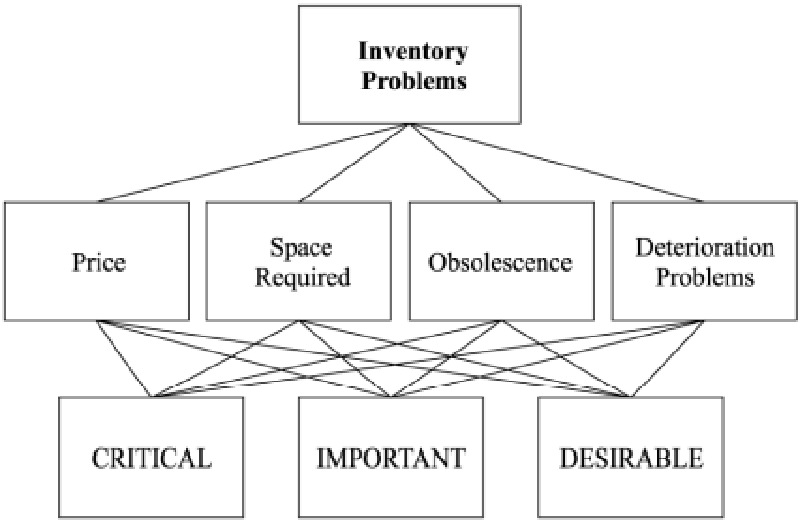


Figure 2.6. Classification by “Inventory Problem” [9]

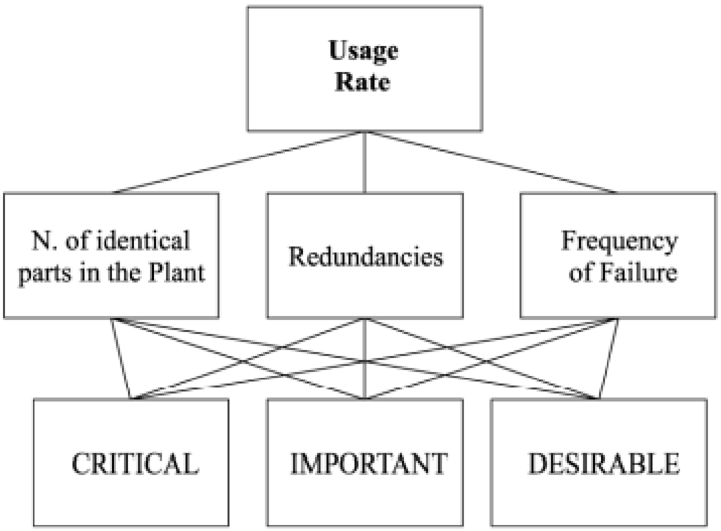


Figure 2.7. Classification by “Usage Rate” [9]

Kasap et al. [10] studied determining critical spare parts used in machinery repair using ABC and optimization methods. The article proposes an inventory management system for critical spare parts used in repairing industrial machines based on a stochastic inventory model. The proposed system aims to minimize the total inventory cost while ensuring the availability of critical spare parts when needed. The authors present a case study to demonstrate the effectiveness of the proposed system in a real-world context. The results show that the proposed approach can lead to significant cost savings and improve the overall performance of the repair process. The basic parameters of the proposed model are as follows:

- Target order frequency (F): The number of orders to restock the spare part.
- Service level (S): A ratio indicating the percentage of demanded spare parts available in stock.
- Number of spare parts (N): The number of critical spare parts used for the machine.
- The unit price of spare part (ci)
- Estimated annual demand for spare part *i* (Di)

Ghare [11] studied the number of failures over time under constant demand using the economic order quantity formula. The paper proposes a mathematical model to analyze inventory systems with exponentially decaying demand. The model assumes that the demand rate follows an exponential distribution and aims to determine the optimal inventory level to minimize total inventory costs. The paper provides numerical examples to illustrate the application of the model and compares the results with other inventory control models. The proposed model effectively minimizes total inventory costs and can be applied in various industries to manage inventory levels.

Bahl et al. [12] present an extensive overview of the research conducted on determining lot sizes and resource requirements. It summarizes significant studies in the field and examines the prevalent methods and techniques employed to tackle these problems. The authors explore various methods for determining lot sizes, including quantity discounts, economic order quantity, safety stock level, and work schedule. Likewise, they also discuss methods utilized to determine resource requirements.

Dhakar et al. [13] argued the difficulty in determining the most suitable base stock levels for repairable spares with high cost, low demand, and criticality. The authors suggest a model that utilizes both ABC analysis and optimization techniques to determine the base stock levels that minimize the total inventory holding costs and ensure a desired level of service. The authors illustrate the proposed model using a case study of a defense organization that handles many repairable spares. The findings indicate that the proposed model can effectively reduce inventory costs and enhance the availability of critical repairable spares. The article provides a valuable framework for decision-makers who are involved in managing repairable spares.

Sandborn [14] focuses on managing supply chain risks during product design, particularly regarding the rapid technological obsolescence of components. The article emphasizes the critical role that obsolescence risk management plays in designing long-lasting and high-value products, particularly in the defense industry. The article discusses various strategies for managing obsolescence risks during product design, including strategic product life cycle management and stock-level planning. “Lifetime Buy Optimization” is one of the strategies discussed in this article. Because Lifetime buy costs play an important role, especially in producing high-cost and long-lasting products. The main elements that make up the lifetime buy costs are shown in Figure 2.8 below.

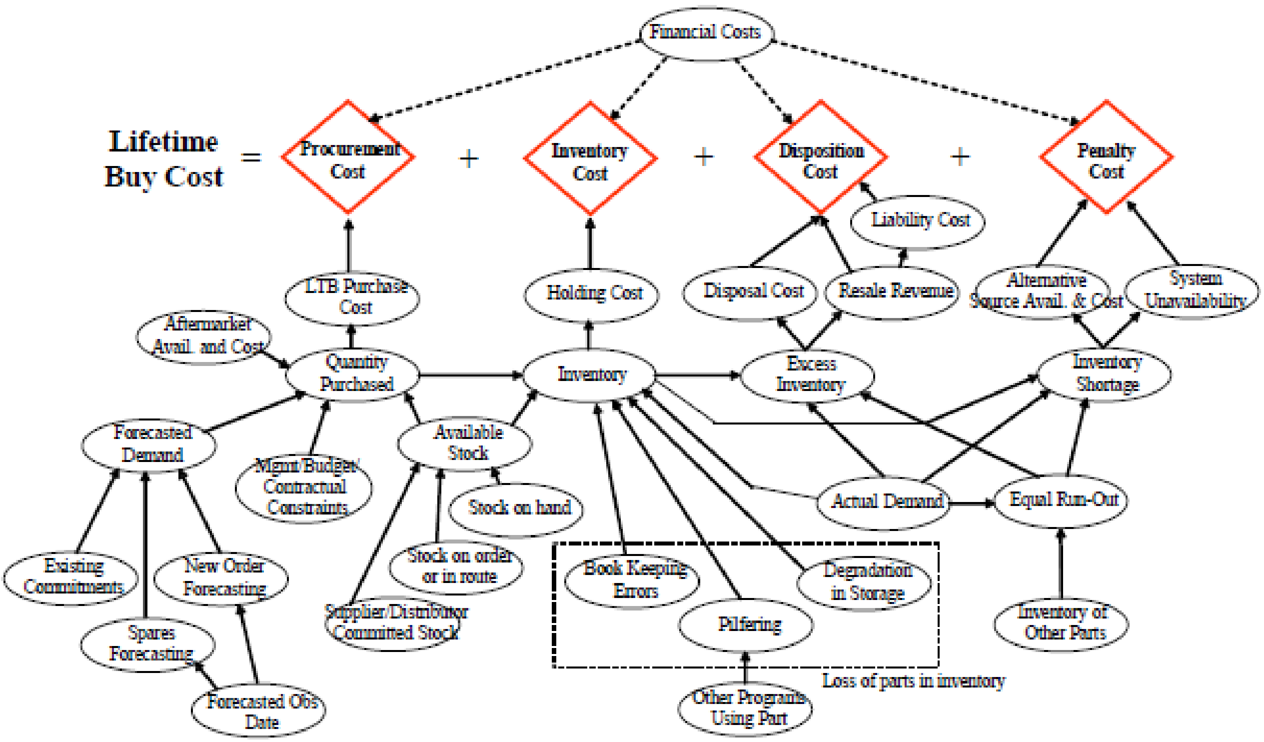


Figure 2.8. Lifetime Buy Costs [14]

2.2. Multi-Criteria Decision Making (MCDM)

Collaborative Decision Making (CDM) can be used for everyday problems. Still, when the problem is based on the more important subjects, the evaluation of criteria is an important issue. Therefore, in these situations, decision-making needs to be based on proper structuring and detailed assessment of all the criteria using the appropriate methods. Practically, MCDM is used to deal with structuring, decision-making, and planning steps when the domain possesses various criteria to reach an optimum solution based on the deciders' preferences. [15] The main involved processes in decision-making consist of situation identification, option generation, evaluation and choice, follow-up, and execution, illustrated in Figure 2.9.

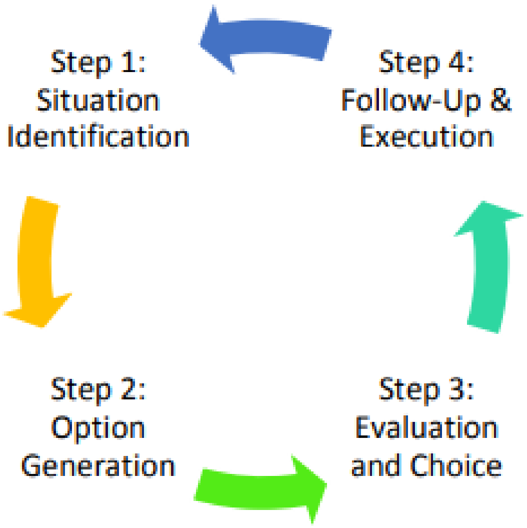


Figure 2.9. Involved Processes in Decision-Making [15]

Multiple-criteria decision methods (MCDM) deal with decision problems that involve multiple criteria. These methods are analytic techniques in which both measurable and immeasurable criteria are evaluated simultaneously. [27] The difficulty and inconsistency encountered in the MCDM process are as follows: while one alternative may be the best in terms of one criterion, it may not be the best in terms of another criterion. Therefore, the goal of MCDM methods is to select the alternative that meets all the existing criteria at the highest level. [28]

In decision-making, the decision-maker selects the alternative with the highest preference value in problems with a single variable. However, real-world decision problems are generally not limited to a single variable and may have multiple variables. This shows that decision problems are more complex and challenging. Decision-making becomes even more complicated, especially when numerous criteria and alternatives exist. Therefore, the Multiple Criteria Decision Making (MCDM) methods are developed to reduce complexity in situations with numerous criteria and alternatives. [29]

One of the most important advantages of the MCDA methods is the ability to evaluate multiple criteria and alternatives simultaneously. Decision-making problems involve multiple criteria that may lead individuals to make different and potentially conflicting choices. The satisfaction of one criterion can sometimes impede the satisfaction of other criteria, or an alternative may not be the best across all criteria. As a result, decision-making becomes more complex and difficult. To achieve consensus among criteria, conflicts among them must be evaluated carefully.

The application of MCDA methods varies depending on the decision problem encountered. The decision maker decides which method is more appropriate for the problem type and structure. Some of the MCDA methods are listed below in Table 2.1. [16].

Table 2.1. Some Multi-Criteria Decision Making (MCDM) Methods [16].

Multi-Criteria Decision-Making (MCDM) Methods	
AHP	PROMETHEE
ANP	TOPSIS
MAUT/UTA	ELECTRE I
MACBETH	Goal Programming

Multi-criteria decision-making (MCDM) methods such as Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are widely used in spare parts and obsolescence management. These methods enable informed decision-making by evaluating and ranking different alternatives while considering multiple criteria such as cost, availability, lead time, and quality. Various studies have applied MCDM methods in spare parts management to determine optimal inventory levels for critical spare parts, select suppliers and determine the most suitable maintenance strategy. Additionally, MCDM methods have been used to address obsolescence management issues, such as identifying and prioritizing obsolete items for replacement and selecting the most suitable replacement options. MCDM methods have shown promising results in improving efficiency and effectiveness in spare parts and obsolescence management by providing decision-makers with a structured approach to evaluate and prioritize alternatives based on multiple criteria.

The problem of determining the priorities of the parts that need to be kept in stock, which constitutes the basis of the study, is a type of MCDA problem. Specifically, a pair of Multi-Criteria Decision Making problem types known as Analytical Hierarchy Process (AHP) and Order Preference Technique by Similarity to Ideal Solution (TOPSIS) were used in this study. In the following sections, these methods will be described in detail for the application phase of the study. Some studies in the literature are given below.

Fazlollahtabar et al. [17] focus on a multi-objective decision-making process for supplier selection and order allocation in a multi-period scheduling problem in an electronic market. The article considers multiple decision criteria, such as supplier selection, order allocation, production planning, and scheduling in an electronic market. The article addresses questions such as selecting the best suppliers from a series of supplier candidates, allocating orders to these suppliers, and when each supplier will fulfill their orders during the predetermined time period. The article also considers multiple objective functions such as supplier performance, order quality, and cost. The article presents a multi-objective decision-making process using the AHP and PROMETHEE methods. The hierarchy of the proposed problem is shown in Figure 2.10.

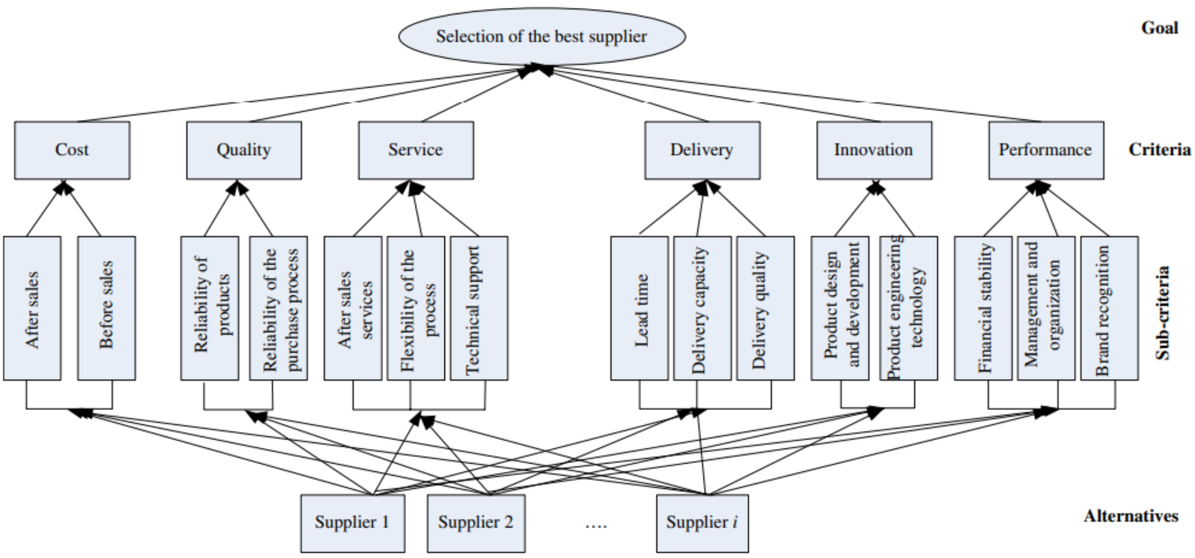


Figure 2.10. Hierarchy of The Proposed Problem [17]

Supçiller and Çapraz [18] developed a multi-criteria decision-making solution to the supplier selection problem using AHP and TOPSIS methods. The article presents a study that proposes a decision-making framework for supplier selection based on integrating the

Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods. The proposed framework aims to provide a comprehensive evaluation of potential suppliers based on multiple criteria, including quality, price, delivery, and environmental factors. The case study presented in the article demonstrates how the proposed method can be applied in a real-world scenario and its effectiveness in enabling informed decision-making in the supplier selection process. In addition, the study provides valuable insights for businesses looking to improve their supplier selection process using a multi-criteria decision-making approach.

3. PROBLEM DEFINITION

3.1. Importance of Spare Part Management for The Defense Industry

The defense industry is crucial in safeguarding a nation's security and sovereignty. It involves the conception, production, and maintenance of intricate and technologically advanced systems. The smooth operation of these systems is contingent upon uninterrupted and effective spare parts management. Therefore, managing spare parts is critical to maintaining sustainable operational excellence within the defense industry. Not only does it ensure operational continuity, but it also directly impacts a country's defense capacity. Moreover, spare parts management is necessary to maintain, repair, and modernize military equipment. Therefore, an effective spare parts management strategy is integral to a nation's defense strategy.

Spare parts management is at the core of the defense industry. Military equipment and vehicles are often operated under challenging conditions, leading to rapid wear and tear or damage to parts. Therefore, a timely and efficient supply of spare parts is vital for the continuous operational readiness of this equipment and vehicles.

The importance of spare parts management in the defense industry is also evident in strategic planning and operational readiness. The availability of spare parts can directly impact the timing and strategy of military operations. This is important both in times of peace and during crises. Therefore, spare parts management should be integral to military planning and preparation.

In the defense industry, spare parts management is also closely related to quality control and safety. Spare parts often serve as critical components of military equipment and can directly impact the reliability and performance of this equipment. Therefore, the quality and reliability of spare parts are vital for the success of military operations. Therefore, good spare parts management should incorporate quality control processes and ensure that spare parts are up to standard.

Moreover, spare parts management is important for supply chain management in the defense industry. Spare parts in the defense industry often come from many suppliers, and these suppliers may be spread out worldwide. Therefore, spare parts management requires coordination and cooperation among suppliers. This can enhance supply chain efficiency and reduce logistic risks.

Also, spare parts management is significant from the perspective of cost control and optimization. Maintaining the correct spare parts inventory can reduce unnecessary stock costs and enhance logistic efficiency. Furthermore, providing spare parts swiftly and effectively in emergency situations ensures uninterrupted operations and the continuous sustainment of defense capabilities.

Additionally, spare parts management must keep pace with the speed of technological innovations and developments in the defense industry. As military technology evolves rapidly, spare parts management must adapt to this fast-paced change. This includes accommodating new technologies and managing spare parts still necessary for older systems. Therefore, spare parts management plays a critical role in managing the complexity and speed of technological transformation.

Spare parts management can provide a competitive advantage in the defense industry. An effective spare parts management strategy can extend the operational life of military equipment and reduce the total cost of ownership. This can enhance a country's defense capacity and give it a strategic advantage. Therefore, spare parts management performs numerous crucial functions in the defense industry. Operational excellence, technological adaptability, supply chain management, and environmental sustainability are the main focus points in this area.

One of the main challenges in spare part management in the defense industry is managing the obsolescence of parts. The life cycle of military equipment is significantly longer than that of commercial equipment, and spare parts often become obsolete before the equipment reaches the end of its life cycle. Therefore, it is crucial to have a proactive approach to spare part management, including identifying and mitigating obsolescence risks, developing robust supply chain strategies, and maintaining an accurate inventory of spare parts. [6]

Another challenge in spare part management is ensuring compliance with regulations and standards. The defense industry is highly regulated, and the procurement of spare parts must meet stringent requirements to ensure safety, quality, and security. This includes complying with military standards and regulations for part quality, traceability, and documentation.

In addition to these challenges, the defense industry faces unique supply chain challenges affecting spare part management. For example, military equipment is often manufactured by a range of domestic and international suppliers, making it challenging to manage the supply chain and ensure the timely delivery of spare parts. Moreover, military equipment is often deployed in remote locations, making it difficult to access spare parts in a timely manner.

Effective spare part management in the defense industry requires a comprehensive approach that involves close collaboration between all stakeholders, including the military, suppliers, manufacturers, and logistics providers. This includes developing robust supply chain strategies that enable the timely and cost-effective delivery of spare parts, developing contingency plans to manage unexpected disruptions in the supply chain, and maintaining an accurate inventory of spare parts to minimize downtime and reduce maintenance costs.

In conclusion, spare parts management plays a critical role in the defense industry. Operational continuity, cost control, risk management, and integration of technological innovations are key elements of spare parts management. Therefore, spare parts management is vital in maintaining efficiency and reliability in the defense industry.

3.2. Company Current Status

The company is a leading Turkish defense company that specializes in the design, development, and production of armored vehicles, weapon systems, and other military equipment. The company was established in 1988 as a joint venture between a Turkish company and an American defense contractor.

With over 30 years of experience in the defense industry, the company has established itself as a major supplier of armored vehicles to the Turkish Armed Forces and other countries worldwide. The company has approximately 1,000 employees.

One of the company's key strengths is its ability to design and develop a wide range of armored vehicles to meet the diverse needs of its customers. As a result, the company has a diverse portfolio of products, which includes various types of armored vehicles, such as tanks, infantry fighting vehicles, and armored personnel carriers. In addition to these vehicles, the company also produces weapon systems, turrets, and other defense-related equipment.

The company's armored vehicles are designed to provide high levels of protection to their occupants while being highly mobile and adaptable to various terrains and combat scenarios. In addition, the company's vehicles are equipped with advanced technologies, such as active protection systems (APS) and situational awareness systems, which help to enhance their survivability and lethality in combat.

In recent years, the company has expanded its presence in international markets and has secured contracts with various countries. The company is committed to continuously improving its products and technologies and investing in research and development to meet the evolving needs of its customers.

Apart from designing and developing armored vehicles and weapon systems, the company also provides various services to its customers, such as product support, maintenance, and training. The company has a highly skilled workforce, including engineers, technicians, and other professionals, who are dedicated to ensuring the success of its customers' missions.

The company has a comprehensive integrated logistics support (ILS) strategy and a professional product support team. Product Support Department's Field Service team offers customer-focused in-service supply support concepts, including and beyond warranty periods which encompasses the product life cycle. The Product Support Department's technical service policy is built on absolute customer satisfaction, based on the high availability of systems to ensure continuous operations.

The company is a highly respected and established player in the global defense industry. The company's diverse portfolio of products and services, highly skilled workforce, and commitment to continuous improvement make it a preferred partner for various countries worldwide.

The company is a leading defense industry company with many projects. With its broad range of products and services, the company offers innovative and advanced solutions to its clients. However, the company has been facing a significant challenge with its spare part management system, which is not being done systematically to include all of its projects. The company, without a systematic approach to spare parts management, has utilized “the minimum 10% spare part inventory strategy” in past projects to ensure appropriate levels of spare part stocks and to facilitate rapid response to customer demands.

One scenario in which the company is experiencing issues with its spare part management system is the production of armored vehicles for a client's military. The company has several projects for this client, each with unique spare part requirements. Despite this, the company's spare part management system does not consider all these projects, leading to several challenges.

The first issue that arises is the lack of coordination between different projects. For instance, a spare part required for one project may not be considered for another project, leading to duplication of efforts and wastage of resources. This increases the production cost and results in a loss of time as the team has to repeat the process.

The second issue is related to the cost of spare parts. With multiple projects underway, the company has to maintain an extensive inventory of spare parts. However, the company often orders spare parts in excess, wasting resources due to the lack of a systematic spare part management system. Additionally, when the company does not have the required spare part in its inventory, it has to order them from external suppliers, which increases the cost of production.

Moreover, the company also faces obsolescence management problems due to its spare part management system's inefficiencies. Some spare parts may become obsolete over time, and the company may not be aware of this until it is too late. In such cases, the company has to spend additional resources to identify an alternative spare part, which delays the production process and increases the overall cost.

The company can also face challenges in its spare part management system regarding maintenance and repair services. For example, suppose a client requires maintenance or repair services for a company’s product. In that case, the company must readily have all the spare parts available to ensure a quick turnaround time. However, due to the lack of a systematic spare part management system, the company may not have the required spare parts in its inventory, leading to a delay in the maintenance or repair process. This can result in delays in repair services, leading to dissatisfied customers and a loss of business for the company.

Another significant challenge that the company may face due to its inefficient spare part management system is the impact on its bottom line. With excessive inventory and duplication of efforts, the company incurs additional costs that could have been avoided with a more efficient system. Additionally, delays in production, maintenance, or repair services due to the unavailability of spare parts can result in a loss of revenue for the company.

To overcome these challenges, the company must adopt a more systematic approach to its spare part management system. The company can start by identifying all its ongoing and upcoming projects and creating a centralized spare part management system that considers all its requirements. Additionally, the company should adopt predictive maintenance and repair services that leverage data and analytics to anticipate spare part requirements, reducing delays and improving efficiency.

In conclusion, the company’s spare part management system's inefficiencies result in several challenges, including excessive inventory, duplication of efforts, delays in production, maintenance, and repair services, and an impact on the company's bottom line. To overcome these challenges, the company must adopt a more systematic approach to its spare part management system that considers all its projects' requirements and leverages data and analytics to improve efficiency.

Having examined Hu et al.'s study [4], we will focus on the third stage of the product's end-of-life, the most critical stage for spare parts management. The third stage is characterized by a decrease in demand for spare parts due to the product's obsolescence and discontinuation, but there is still a need for spare parts among some customers. Therefore, manufacturers need an effective spare parts management strategy during this stage to ensure customer satisfaction and minimize costs. The proposed model in this study will cover the spare parts management practices during the end-of-life period of products, shown in Figure 3.1, the third stage.

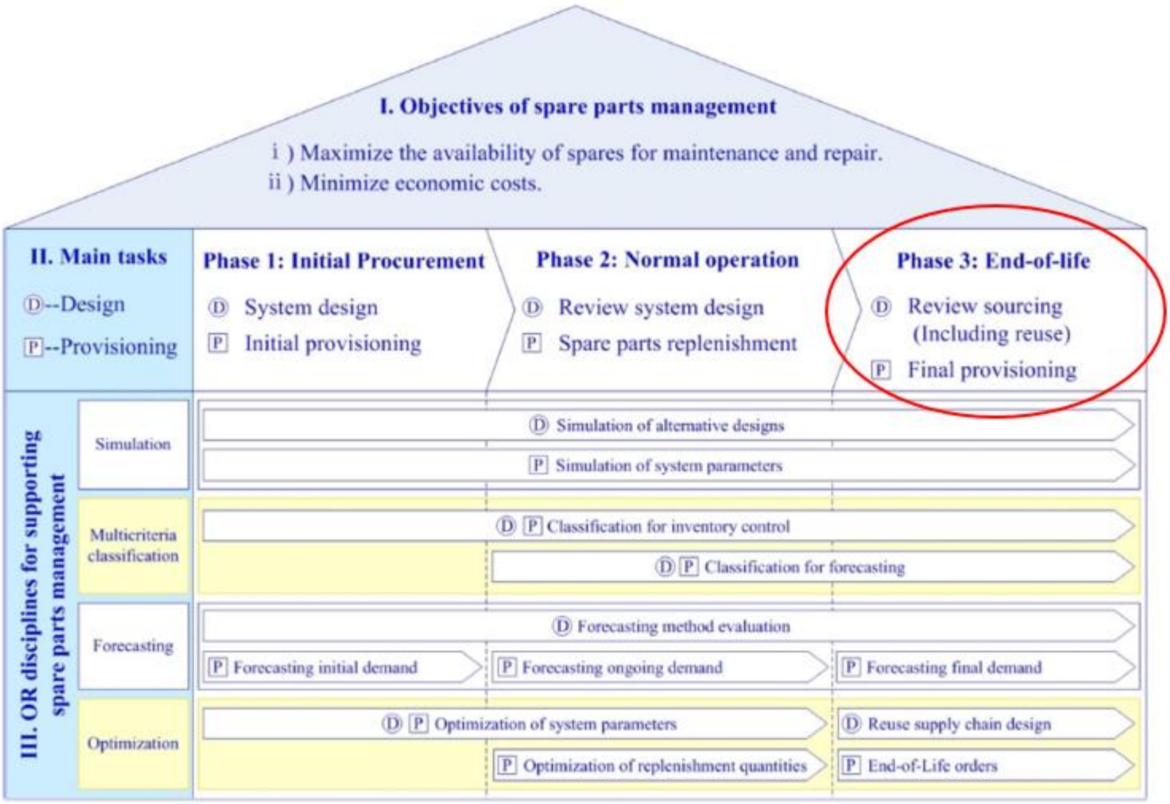
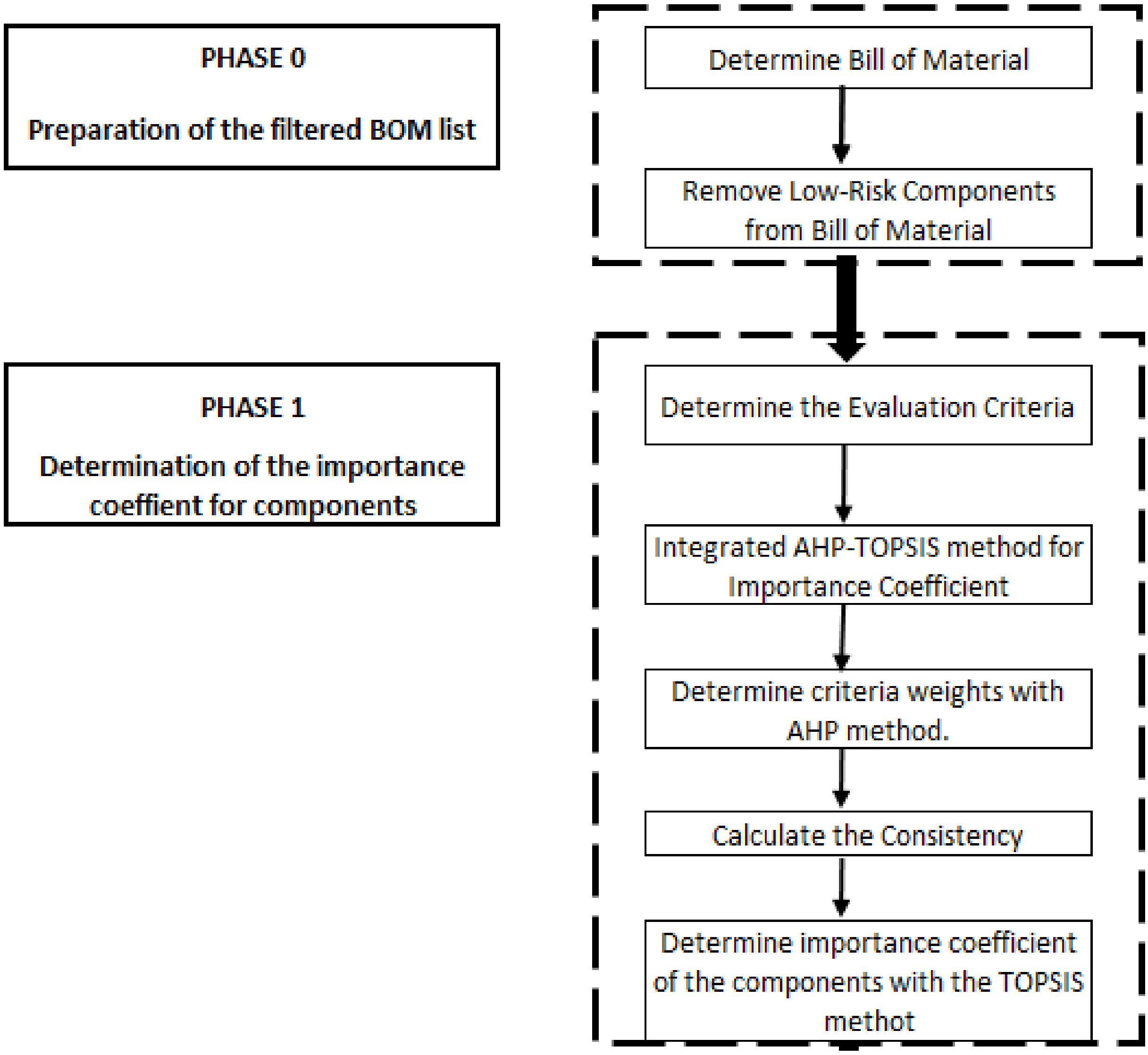


Figure 3.1. Spare Part Management Classification

4. PROPOSED METHOD

In this study, a four-stage method has been implemented. In the first stage, data were obtained. In the next stage, the risk coefficients of the components have been determined by applying the AHP-TOPSIS method. In the third stage, a mathematical model has been developed. And in the final stage, the results have been obtained. The flow chart of the proposed method is given in Figure 4.1.



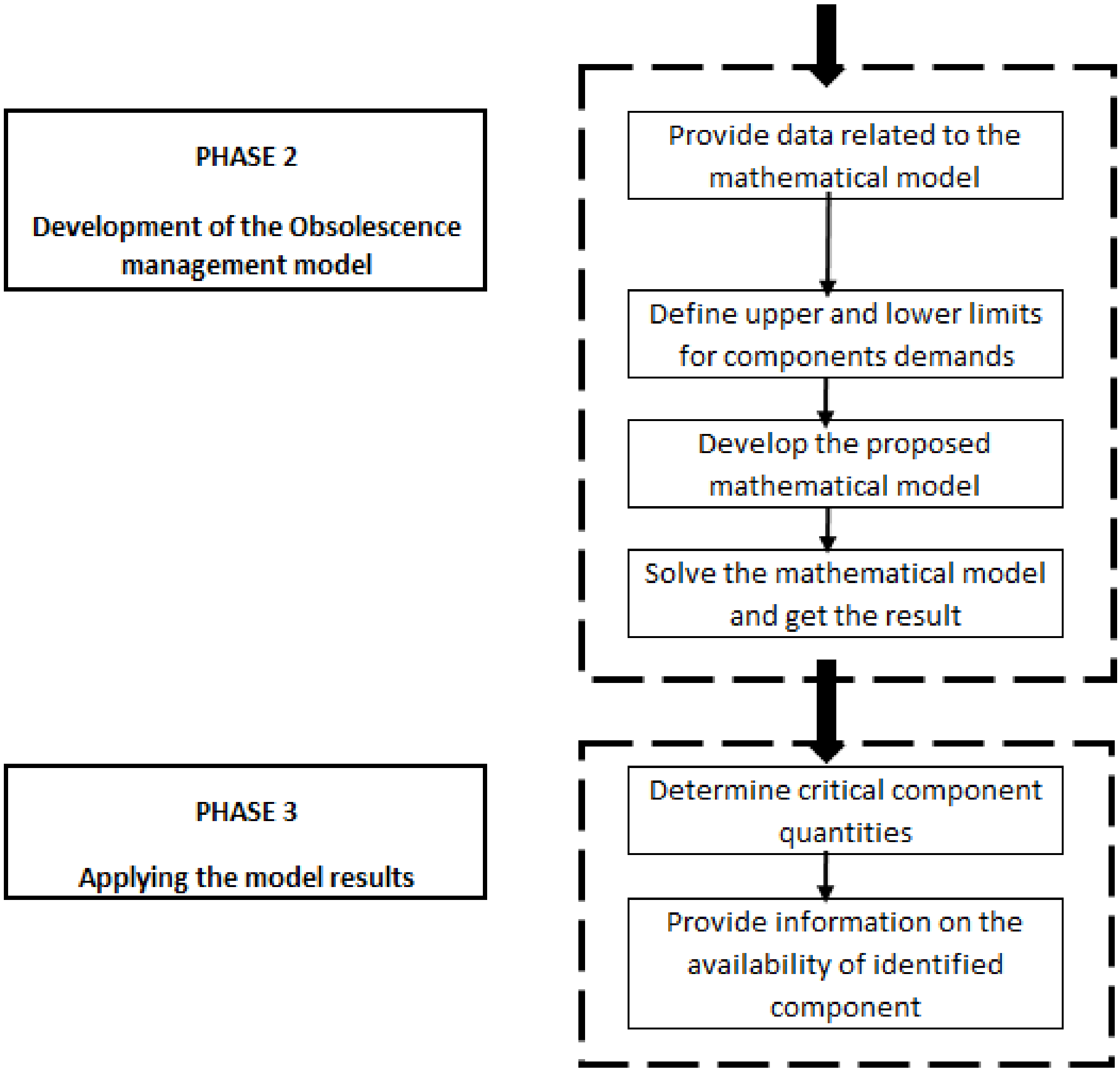


Figure 4.1. The framework of the proposed method

4.1. Preparation Phase

Determine Bill of Material

A Bill of Material (BOM) specifies all the components required for producing a product and the quantities in which they are used. It is crucial to extract the complete BOM from the system or equipment to develop a comprehensive spare parts list. This will provide a detailed list of all components from which the most critical and risk-prone parts can be identified. It is important to use a systematic and thorough approach to identifying these parts to ensure that the spare parts list is as accurate and comprehensive as possible.

In this study, in a project in a defense industry company, spare part risk management is carried out for components. In the focused project, there are about 6387 components in the worked list, the format of which is in Figure 4.2.

1	Line sts	Part No	Descp	Qty	Lt	Inst descp
2009	Onhand	901000-316	ADJUSTABLE 90° MALE ELBOW - METRIC STRAIGHT THREAD	1	62	PNÖMATİK SİSTEMİ MONTAJI
2010	Onhand	901000-316	ADJUSTABLE 90° MALE ELBOW - METRIC STRAIGHT THREAD	1	62	PNÖMATİK SİSTEMİ MONTAJI
2011	Onhand	901000-556	ADJUSTABLE MALE BRANCH TEE - METRIC STRAIGHT THREAD	1	42	FREN SİSTEMİ MONTAJI
2012	Onhand	901000-556	ADJUSTABLE MALE BRANCH TEE - METRIC STRAIGHT THREAD	2	42	FREN SİSTEMİ MONTAJI
2013	Onhand	901000-557	ADJUSTABLE MALE BRANCH TEE - METRIC STRAIGHT THREAD	4	42	FREN SİSTEMİ MONTAJI
2014	Onhand	901000-557	ADJUSTABLE MALE BRANCH TEE - METRIC STRAIGHT THREAD	1	42	FREN SİSTEMİ MONTAJI
2015	Onhand	901000-602	90 UNION ELBOW	6	62	PNÖMATİK SİSTEMİ MONTAJI
2016	Onhand	901000-604	90 UNION ELBOW	4	62	PNÖMATİK SİSTEMİ MONTAJI
2017	Onhand	901000-652	UNION TEE	2	62	PNÖMATİK SİSTEMİ MONTAJI
2018	Onhand	901000-659	UNION TEE	5	62	FREN SİSTEMİ MONTAJI
2019	Onhand	901000-659	UNION TEE	1	62	FREN SİSTEMİ MONTAJI
2020	Onhand	901000-659	UNION TEE	3	62	PNÖMATİK SİSTEMİ MONTAJI
2021	Onhand	901000-727	BULKHEAD UNION	2	42	PNÖMATİK SİSTEMİ MONTAJI
2022	Onhand	901000-729	BULKHEAD UNION	2	42	PNÖMATİK SİSTEMİ MONTAJI
2023	Onhand	901000-729	BULKHEAD UNION	1	42	PNÖMATİK SİSTEMİ MONTAJI
2024	Onhand	901000-778	BULKHEAD LOCKNUT	1	42	PNÖMATİK SİSTEMİ MONTAJI
2025	Onhand	901000-778	BULKHEAD LOCKNUT	1	42	PNÖMATİK SİSTEMİ MONTAJI
2026	Onhand	901000-780	BULKHEAD LOCKNUT	2	62	PNÖMATİK SİSTEMİ MONTAJI
2027	Onhand	901001-104	STRAIGHT CONNECTOR - MALE- MALE - METRIC STRAIGHT THRI	1	62	PNÖMATİK SİSTEMİ MONTAJI
2028	Onhand	901001-203	MALE PLUG	1	62	FREN SİSTEMİ MONTAJI
2029	Onhand	901001-203	MALE PLUG	6	62	FREN SİSTEMİ MONTAJI

Figure 4.2. All Bill of Material List

Remove Low-Risk Components from the Bill of Material

The initial step is to divide the system or equipment into more manageable parts. Creating a spare parts list based on the bill of material (BoM) can be a highly effective approach to managing the risks associated with system or equipment downtime. This approach involves breaking down the BoM into its component parts, with the level of specificity determined by practical considerations, such as the probability of obsolescence or other issues affecting the individual components. Focusing on the most critical components makes it possible to identify and remove low-risk parts that need not be included in the spare parts list.

This BOM-based approach can help ensure the spare parts list is comprehensive and accurate while minimizing the overall inventory costs associated with maintaining many low-risk components. The approach also facilitates effective tracking of spare parts inventory, enabling quick and easy identification of parts that need to be replaced.

Using comprehensive BoM, we must identify and remove low-risk parts. This way, we can avoid unnecessary efforts by conducting a detailed risk assessment for each part on the spare parts list. Low-risk components such as washers, screws, nuts, and clamps should be removed from the spare parts list. It is necessary to use filtered BoM to separate the system or equipment into more manageable parts, determine the level of detail at the most practical level and create a spare parts list specific to the system or equipment. This approach is particularly important for managing spare part management risks that may occur at the component level. By filtering low-risk components and focusing on critical components, we can prevent unnecessary efforts without conducting a detailed risk assessment for each component in BoM. With this approach, the filtered BoM list will include all necessary components and reduce inventory costs by minimizing the number of low-risk components, and it will allow us to critical parts that we need to focus on.

The low-risk components were eliminated from the comprehensive BoM using the method shown in Figure 4.3 of Rojo et al.'s paper [6], resulting in a total component count of 3256. The work continued using the list format shown in Figure 4.4.

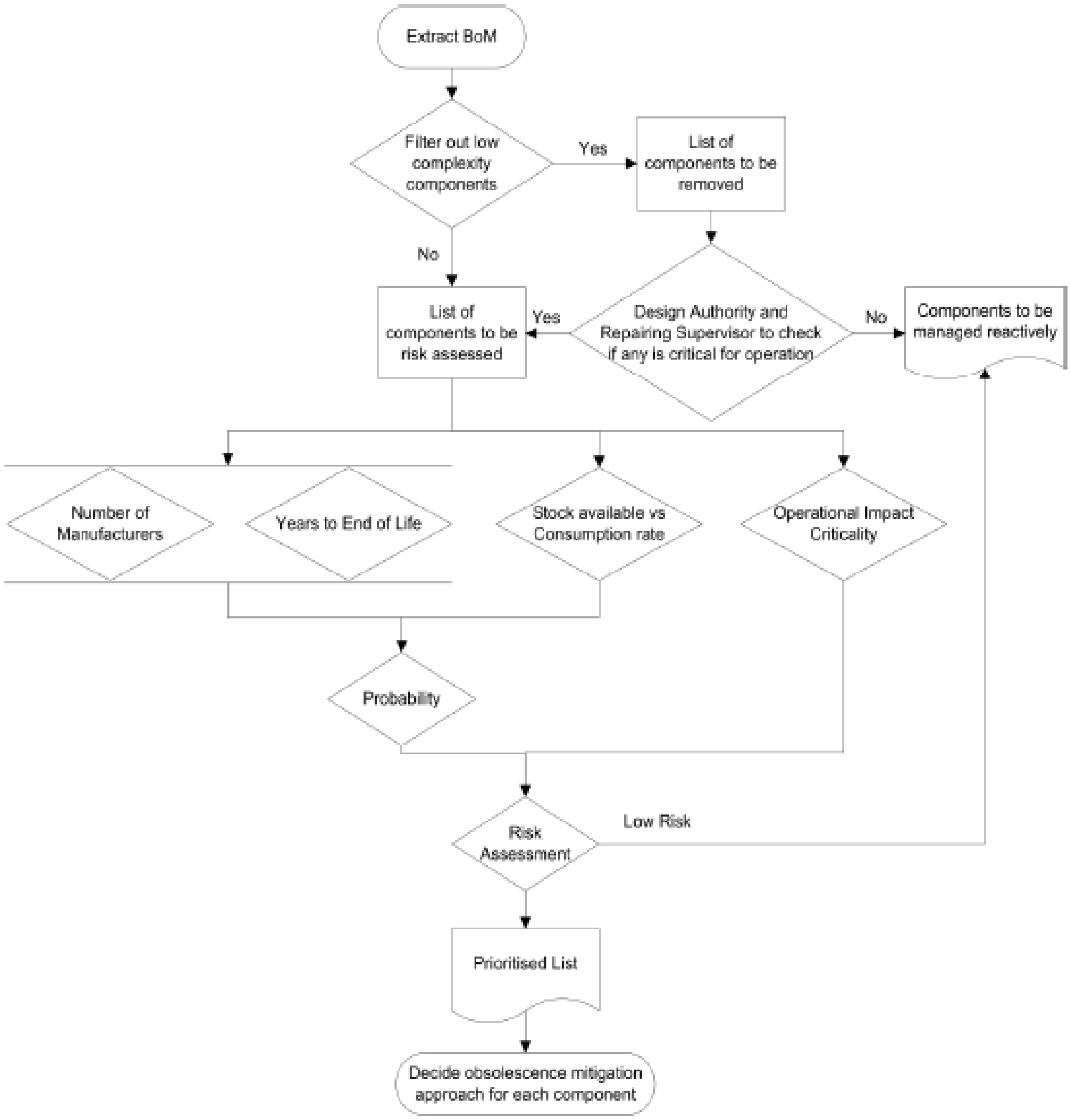


Figure 4.3. Obsolescence Risk Assessment Process Best Practice Core Steps [6]

The filtered list shown in Figure 4.4 contains the parts required to produce an armored vehicle in the focused project and the number of units needed per vehicle.

	A	B	C
1	Sub Part No	Sub Part Descp	Qty Per Assembly
2	826283	BUSHING	1
3	727537	PLATE	1
4	82386381	BLOCK	1
5	12098509	BLOCK	1
6	409892080	BLOCK	1
7	2637621	BLOCK	1
8	11643	BLOCK	1
9	14527574	FRAME	1
10	482682	FRAME	1
11	123678	PLATE	1
12	123678	COAMING PLATE	2
13	123678	PLATE,RAMP	2
14	123678	PLATE,RAMP	1
15	1263382	RETAINER,SEAL,RAMP	1
16	126382	RETAINER,SEAL,RAMP	1
17	23767236	COAMING,RAMP	1

Figure 4.4. Filtered Bill of Material List

4.2. Phase One

Determine the Evaluation Criteria

When a project claim occurs, the customer expects to resolve the issue immediately. In this case, having spare parts on hand is crucial for customer satisfaction because a spare parts inventory enables an immediate response to the customer's needs, resulting in a shorter resolution time for the issues. This, in turn, helps the customer to prevent disruptions to their work and ensures timely completion. It is critical to keep enough products in the system to meet the requirements for the predicted life cycle of the components.

However, even if low-risk components are eliminated from a vehicle's BoM list, it still consists of approximately 3256 components. At this stage, it is necessary to identify the crucial components. It is important to consider specific criteria in determining crucial parts and the order of importance of these criteria. Therefore, this study aims to create a critical spare parts list according to the determined criteria.

Firstly, the difficulty encountered by previous projects in the after-sales period has been examined, and as a result of this examination, which parts are needed more frequently and which parts have difficulty in procurement have been investigated. As a result, it has been observed that the three criteria below have significant importance in terms of spare parts management, and importance coefficients are determined according to these three criteria for the components in this study.

- Subject to Export License
- Lead time
- Whether it is a Commercial Off-The-Shelf (COTS) product or not

Subject to Export License: An export license is a legal regulation that regulates and controls the trade of spare parts between countries. For defense industry firms, an export license is crucial for spare parts management. These firms may need to source many spare parts from abroad and must have the necessary export license.

Proper evaluation of the export license is vital for effective supply chain management. The absence of the license can lead to delays in the supply chain and cause delays in obtaining the necessary spare parts to repair faults. This can be a severe problem for defense industry firms, as delayed procurement of some spare parts can cause defense systems to fail to operate and even prevent vital missions from being carried out.

Obtaining an export license requires effectively managing suppliers and the supply chain. Spare part manufacturers and suppliers must comply with specific legal regulations during export processes. Spare part manufacturers or suppliers who do not comply with these regulations may encounter problems during export processes, causing disruptions in the supply chain.

An export license also gives countries the authority to impose sanctions on defense industry firms. Therefore, all spare parts supply chain parties must ensure they comply with all legal regulations required by the license. Otherwise, the supply chain may be disrupted, causing delays or halting entire projects.

An export license is essential for defense industry firms regarding spare part management. If not managed correctly, delays in the supply chain can occur, resulting in defense systems not functioning correctly. In addition, all parties involved in the spare parts supply chain must ensure they comply with all legal regulations required by the license.

In this study, for each product in the BOM list, it has been investigated whether an export license is required, and this information has been recorded in the format provided in Figure 4.5.

	A	B	C	D
1	Sub Part No	Sub Part Descp	Qty Per Asseml	Var/Yok
2	826283	BUSHING	1	0
3	727537	PLATE	2	0
4	82386381	BLOCK	1	0
5	12098509	BLOCK	5	0
6	409892080	BLOCK	6	0
7	2637621	BLOCK	1	0
8	11643	BLOCK	6	0
9	14527574	FRAME	1	0
10	482682	FRAME	1	0
11	123678	PLATE	5	0
12	123678	COAMING PLATE	6	0
13	123678	PLATE,RAMP	1	0
14	123678	PLATE,RAMP	1	0
15	1263382	RETAINER,SEAL,RAMP	1	0
16	126382	RETAINER,SEAL,RAMP	1	0
17	37398	PNEUMATIC SYSTEM, I	1	0
18	235747	SWS-T48-6-6	1	0
19	594893	BATTERY DISCONNECTO	1	0

Figure 4.5. List of parts subject to export license

Lead Time: Lead time is between placing an order and receiving the corresponding product. When it is considered that defense industry equipment often operates in harsh environments, it is known that failures are inevitable. Therefore, the company must quickly obtain spare parts in the event of any failure. When creating spare part lists, the lead time criterion is crucial. The lead time for projects holds significant importance as it impacts the comprehensive maintenance schedule. Especially for defense industry firms, any delay in obtaining spare parts can significantly affect operational efficiency. These delays can lead to severe consequences, such as a vehicle becoming unusable or a system or machine becoming inoperable.

On the other hand, a short lead time for spare parts ensures that failures are resolved quickly, and customer satisfaction is maintained. Therefore, it is crucial to accurately determine and manage lead time when creating spare part lists. This ensures that the necessary time for repairing failures is reduced and that the company's operations are not interrupted.

In this study, the lead time for each part in the BoM list represents the duration from the supplier to the arrival at the company, and the lead time of the parts has been recorded in the format shown in Figure 4.6.

	A	B	C	D
1	Sub Part No	Sub Part Descp	Qty Per Asseml	Lead Time
2	826283	BUSHING	2	12
3	727537	PLATE	8	16
4	82386381	BLOCK	12	60
5	12098509	BLOCK	7	34
6	409892080	BLOCK	6	16
7	2637621	BLOCK	5	170
8	11643	BLOCK	7	40
9	14527574	FRAME	5	195
10	482682	FRAME	4	176
11	123678	PLATE	10	179
12	123678	COAMING PLATE	4	38
13	123678	PLATE,RAMP	15	93
14	123678	PLATE,RAMP	8	188
15	1263382	RETAINER,SEAL,RAMP	2	67
16	126382	RETAINER,SEAL,RAMP	9	192
17	37398	PNEUMATIC SYSTEM, I	13	22
18	235747	SWS-T48-6-6	8	14

Figure 4.6. Component Lead Time Information

Whether Commercial Off-The-Shelf (COTS) products or not: COTS (Commercial Off-The-Shelf) products are standard off-the-shelf products that can be commercially procured. Regarding spare parts management, COTS products are easier and cheaper to procure than custom-designed products. However, some parts used in vehicles may be specially designed and cannot be procured as COTS products. Therefore, whether spare parts are, COTS products is an important consideration for spare parts management.

When creating a spare parts list for a defense industry company, the availability and compatibility of COTS products should be considered. If a specific part is not available as a COTS product, the company may need to produce or customize the part themselves, which can be time-consuming and expensive. In addition, if a COTS product is used, it may be easier to find replacement parts quickly in case of a failure or breakdown, as the parts are readily available on the market.

In this study, each part in the BOM list has been investigated; class A, B, or C. Class A represents COTS products. This information has been recorded in the format provided in Figure 4.7.

	A	B	C	D	E
1	**Sub Part No**	**Sub Part Descp**	**Qty Per Asseml**	**Class**	**Değer**
2	826283	BUSHING	1	A	1
3	727537	PLATE	2	D	0
4	82386381	BLOCK	1	C	0
5	12098509	BLOCK	5	C	0
6	409892080	BLOCK	6	C	0
7	2637621	BLOCK	1	B	0,5
8	11643	BLOCK	6	D	0
9	14527574	FRAME	1	C	0
10	482682	FRAME	1	C	0
11	123678	PLATE	5	C	0
12	123678	COAMING PLATE	6	C	0
13	123678	PLATE,RAMP	1	C	0
14	123678	PLATE,RAMP	1	A	1
15	1263382	RETAINER,SEAL,RAMP	1	B	0,5
16	126382	RETAINER,SEAL,RAMP	1	C	0
17	37398	PNEUMATIC SYSTEM, I	1	C	0
18	235747	SWS-T48-6-6	1	C	0
19	594893	BATTERY DISCONNECTO	1	C	0

Figure 4.7. Component Class Information

Integrated AHP-TOPSIS Method for Importance Coefficient

In the proposed method, the AHP-TOPSIS method is used to determine the weights of the criteria and the weights of the components according to these criteria. The AHP approach is used to determine the relative relevance levels of the criteria. Afterward, the TOPSIS method for component weights is employed to give more importance to the possession of crucial components based on criteria. Components' importance coefficients determined by AHP-TOPSIS are used as parameters for the objective function in the mathematical model. After determining the importance coefficient of the components, mathematical models and solutions will be obtained.

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making technique developed by T. Saaty in the 1970s. [19] AHP is a method used to solve complex decision-making problems and systematically evaluate the priorities and preferences of decision-makers. AHP and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are multi-criteria decision-making methods commonly used to provide effective results. AHP includes the evaluation of more than one qualitative and quantitative criteria, which is the most crucial factor in its use in the selection process. This method has many applications and is used in many decision-making problems.

On the other hand, TOPSIS (Technique for Order Preferences by Similarity to an Ideal Solution) method, developed by Hwang and Yoon [20], is one of the multi-criteria decision-making techniques that perform the ranking of alternatives according to specified criteria. The optimal alternative is selected by sorting the alternatives according to their closeness to the positive ideal and distance from the negative ideal.

The AHP-TOPSIS method involves first determining the weights of the criteria set by decision-makers using the AHP method. Then, the performance of each alternative for each criterion is measured and compared using the TOPSIS method to determine the best alternative. This method can be used in complex decision-making processes involving multiple factors and uncertainties. [20]

The general steps for applying the AHP-TOPSIS method are as follows: [21]

- Identify the decision problem and criteria to be used in the decision-making process.
- Construct a hierarchy of criteria and sub-criteria based on their importance and relationships.
- Determine the relative weights of the criteria using the AHP method.
- Evaluate the performance of each alternative with respect to each criterion.
- Normalize the evaluation matrix to remove differences in scale.
- Determine the weighted normalized decision matrix.
- Determine the ideal and negative-ideal solutions.
- Calculate the distance of each alternative to the ideal and negative-ideal solutions using the Euclidean distance.
- Calculate the relative closeness to the ideal solution for each alternative.
- Rank the alternatives based on their relative closeness to the ideal solution.

Determine Criteria Weights with AHP Method

First, the objective and the criteria affecting this objective are determined. In the study, the three criteria in Figure 4.8 below have been determined and weighted with the AHP method, and the importance coefficients of the components are determined with the TOPSIS method.

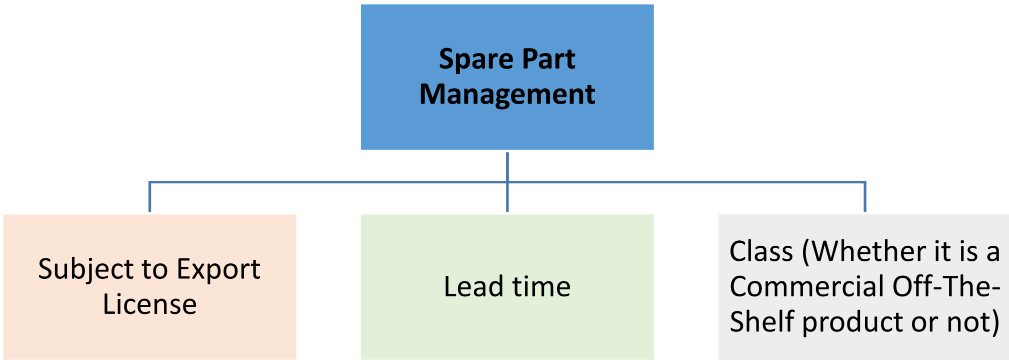


Figure 4.8. Evaluation Criteria

After the criteria are determined, pairwise comparison decision matrices are created to determine the importance of the criteria among themselves. The nine-point scale of importance developed by T. Saaty is used to create these matrices. [22] This scale in Figure 4.9 helps determine the degree of importance between the criteria by evaluating the opinions of the survey or experts.

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation

Figure 4.9. The example scale for comparison [22]

In our study, the criteria weights were determined by taking the judgments of three different decision-makers. These work in the following departments: the logistics department manager, the project manager, and the purchasing department manager. The decision makers' judgments regarding the criteria are given in Table 4.1, Table 4.2. and Table 4.3.

Table 4.1. The judgments of the decision maker 1

Decision Maker 1			
	Export License	Lead Time	Class
Export License	1	3	5
Lead Time	1/3	1	7
Class	1/5	1/7	1

Table 4.2. The judgments of the decision maker 2

Decision Maker 2			
	Export License	Lead Time	Class
Export License	1	3	4
Lead Time	1/3	1	2
Class	1/4	1/2	1

Table 4.3. The judgments of the decision maker 3

Decision Maker 3			
	Export License	Lead Time	Class
Export License	1	2	4
Lead Time	1/2	1	1/3
Class	1/4	3	1

For three decision makers;

- The "Export License" criterion is more important than the other two criteria. Therefore, evaluators consider whether a product is subject to an export license more important than the other two criteria when creating a spare part list.

- Commercial Off-The-Shelf (COTS) products are less important than the other two criteria, indicating that evaluators may find the need to keep these products less important.

- The importance level given to the "Lead Time" criterion is less than the importance level given to the Export License criterion and more than the importance level given to the COTS criterion for decision-makers.

In addition, a more consistent data set was obtained by calculating the geometric averages of the evaluations given in 4.1, Table 4.2. and Table 4.3. As recorded in Table 4.4, the AHP method was applied to these values.

Table 4.4. The Geometric Average for three judgments

Geometric Average			
	Export License	Lead Time	Class
Export License	1	2,620741394	4,30886938
Lead Time	0,381571414	1	1,671099312
Class (COTS)	0,232079442	0,598408481	1

The resulting matrix is normalized after obtaining the evaluator's opinions in the AHP method. The matrix is normalized by summing the numbers in each column. Each entry in the column is then divided by the column total to give its normalized score. The sum of each column is 1. The normalized matrix is in Figure 4.10.

AHP					
	Export License Var/Yok	**Lead Time**	**Class**	**Sum**	**Wi**
Export License Var/Yok	0,619712744	0,621154	0,61732	1,85819	0,6194
Lead Time	0,236464668	0,237015	0,23941	0,71289	0,23763
Class	0,143822588	0,141832	0,14327	0,42892	0,14297

Figure 4.10. Normalizing the Resulting Matrix

After the resulting matrix is normalized, the criteria weights are determined. These weights are given in Table 4.5.

Table 4.5. The criteria weight

Criteria	Weights
Export License	0.619
Lead Time	0.238
Class	0.143

Calculate the Consistency

Since the comparisons are carried out through personal or subjective judgments, some degree of inconsistency may have occurred. Therefore, to guarantee the judgments are consistent, the final operation called consistency verification, which is regarded as one of the most advantages of the AHP, is incorporated to measure the degree of consistency among the pairwise comparisons by computing the consistency ratio [23].

Consistency analysis is performed and interpreted with the help of the following formulas and evaluations in this section. The consistency ratio is a measurement that indicates how much deviates from the consistency. According to Thomas L. Saaty, the consistency ratio should be less or equal to 0.1. So, if the consistency ratio is not less or equal to 0.1, it must revise the judgments. [24]

There are three steps to arrive at the consistency ratio: [25]

- Calculate the consistency measure
- Calculate the consistency index (CI).
- Calculate the consistency ratio (CI/RI where RI is a random index).

Calculate the Consistency Measure: First, the pair-wise comparison values in each column are added together, and each sum is multiplied by the respective weight for that criteria. Then, the average of the values is calculated and recorded as "lmax" in the format Figure 4.11 below.

Consistency Measure					
	Export License Var/Yok	Lead Time	Class	Total	Lmax
Export License Var/Yok	0,619395	0,622769	0,616055	1,858220	
Lead Time	0,236344	0,237631	0,238923	0,712898	3,000029
Class	0,143749	0,142200	0,142974	0,428923	

Figure 4.11. Calculating the consistency measure

Calculate the Consistency Index (CI): The consistency index is calculated as follows, as shown in Formula 4.1:

$$CI = \frac{lmax - n}{n - 1} \qquad (4.1)$$

In our study, n = 3, and lmax is 3,000029. So, we get the consistency index as 0,000015. The consistency index value is recorded in the format Figure 4.12 below.

Consistency Measure						
	Export License Var/Yok	Lead Time	Class	Total	Lmax	Consistency Index
Export License Var/Yok	0,619395	0,622769	0,616055	1,858220		
Lead Time	0,236344	0,237631	0,238923	0,712898	3,000029	0,000015
Class	0,143749	0,142200	0,142974	0,428923		

Figure 4.12. Calculating the Consistency Index

Calculate the Consistency Ratio: The Consistency Ratio (CR) is calculated by dividing the Consistency Index (CI) (from the previous step) by a Random Index (RI), as shown in Formula 4.2, which is determined from a lookup table. The Random Index (RI) in Figure 4.13 is a direct function of the number of criteria or systems being considered. [26]

$$CR = \frac{CI}{RI} \qquad (4.2)$$

Random Index (RI)

n	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Figure 4.13. Random Index (RI) [26]

In this study, the number of items is 3 in the matrix; therefore, our Random Index is 0.58. So, the consistency ratio has been calculated as 0,000028. The consistency ratio value is recorded in the format Figure 4.14 below.

Consistency Measure							
	Export License Var/Yok	Lead Time	Class	Total	Lmax	Consistency Index	Consistency Ratio
Export License Var/Yok	0,619395	0,622769	0,616055	1,858220	3,000029	0,000015	0,000028
Lead Time	0,236344	0,237631	0,238923	0,712898			
Class	0,143749	0,142200	0,142974	0,428923			

Figure 4.14. Calculating the Consistency Ratio

It was observed that the consistency rate was 0,000028, and the consistency is reached because this number is less than 0.1.

Determine the Importance Coefficient of the Components with TOPSIS Method

The relative importance of each criteria is provided by the normalization of this matrix, which is a critical part of using the TOPSIS approach. Both positive and negative ideal solutions are obtained and ordered after the decision matrix of alternatives is normalized and weighted using the relative weights of the AHP approach. The distance between each alternative and the ideal solution is then determined positively and negatively. [30]

Normalize the evaluation matrix to remove differences in scale: Normalized decision matrices; The values of each criterion are found by dividing the square root of the sum of the squares of these criteria as in Formula 4.3.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \forall j \qquad (4.3)$$

The normalized evaluation matrix value was calculated below and recorded in Figure 4.15.

C	D	E	F	G	H	I	J	K	L
Qty Per Assembly	Lead Time	Lead Time^2	Lead T Norı	Var/Yok	Var/Yok^2	Var/Yok Noı	Class Değer	Class Değeı	Class Değer Norm
BUSHING	12	144	0,001673072	0	0	0	0	0	0,000000
PLATE	8	64	0,001115381	0	0	0	0,5	0,25	0,062500
BLOCK	11	121	0,001533649	0	0	0	0,5	0,25	0,062500
BLOCK	13	169	0,001812494	0	0	0	0,5	0,25	0,062500
BLOCK	1	1	0,000139423	0	0	0	1	1	1,000000
BLOCK	5	25	0,000697113	0	0	0	1	1	1,000000
BLOCK	12	144	0,001673072	0	0	0	1	1	1,000000
FRAME	7	49	0,000975958	0	0	0	0	0	0,000000
FRAME	7	49	0,000975958	0	0	0	0	0	0,000000
PLATE	12	144	0,001673072	0	0	0	0	0	0,000000
COAMING PLATE	7	49	0,000975958	0	0	0	1	1	1,000000
PLATE,RAMP	7	49	0,000975958	0	0	0	0	0	0,000000
PLATE,RAMP	1	1	0,000139423	0	0	0	0	0	0,000000
RETAINER,SEAL,RAMP	12	144	0,001673072	0	0	0	0,5	0,25	0,062500

Figure 4.15. Calculating Normalize Evaluation Matrix

<u>Determine the weighted normalized decision matrix:</u> The weighted normalized decision matrix is calculated by multiplying the normalized decision matrix with the weight values given in Table 4.5, determined by the decision maker, and recorded in the format Figure 4.16 below.

			AHP w:	0,237631			AHP w:	0,619395			AHP w:	0,142974
Sub Part Descp	Qty	Lead Tin	Lead Time^2	Lead T Norı	w*LT norn	Exp Li	Exp Lis^2	Var/Yok Noı	w* EL norn	Class Değ	Class Değeı	Class Değer Nor
PLATE ASSY, AUXILIA	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	0	0,000000	0,000000
BAG ASSY, TOOL	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	1	0,250000	0,012922
HOLDER,LEVEL STICK	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	1	0,250000	0,012922
DIODE ZENER 5.1V 20	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	1	0,250000	0,012922
COMMON MODE CHOKE	6	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	1	1,000000	0,025844
PLATE BOTTOM,HULL	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	1	1,000000	0,025844
SUPPORT BLOCK COVER	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	1	1,000000	0,025844
SPALL INSERT INST,	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	0	0,000000	0,000000
PLATE, FLOOR PLATE	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	0	0,000000	0,000000
TAB,CAN	5	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	0	0,000000	0,000000
PLATE, COVER, TOP	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	1	1,000000	0,025844
LOWER HOUSING WELDE	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	0	0,000000	0,000000
COVER,AMMOCAN,7.62	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	0	0,000000	0,000000
PCB, 300W 24V OUT P	1	20	400	0,002788	0,000663	0	0,000000	0,000000	0,000000	1	0,250000	0,012922

Figure 4.16. Calculating Weighted Normalized Decision Matrix

<u>Determine the ideal and negative-ideal solutions:</u> The highest and lowest values in the weighted normalized decision matrix were determined and recorded in Figure 4.17.

		w*LT norm	w* EL norm	w* Class Norm
	V+:	0,014213	0,065290	0,003695
	V-:	0,000663	0,000000	0,000000
Sub Part No	**Sub Part Descp**	**w*LT norm**	**w* EL norm**	**w* Class Norm**
826283	BUSHING	0,000663	0,000000	0,000000
727537	PLATE	0,000663	0,000000	0,001847
82386381	BLOCK	0,000663	0,000000	0,001847
12098509	BLOCK	0,000663	0,000000	0,001847
409892080	BLOCK	0,000663	0,000000	0,003695
2637621	BLOCK	0,000663	0,000000	0,003695
11643	BLOCK	0,000663	0,000000	0,003695
14527574	FRAME	0,000663	0,000000	0,000000
482682	FRAME	0,000663	0,000000	0,000000
123678	PLATE	0,000663	0,000000	0,000000
123678	COAMING PLATE	0,000663	0,000000	0,003695

Figure 4.17. Determine the Ideal and Negative-Ideal Solutions

Calculate the distance of each alternative to the ideal and negative-ideal solutions using the Euclidean distance: The distance between each option and the distance of the n-dimensional option from the positive ideal solution is calculated with the help of the following formulas:

$$S_i^+ = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^+)^2}, i = 1,2,\ldots,m \qquad (4.4)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2}, i = 1,2,\ldots,m \qquad (4.5)$$

The distance of each alternative to the ideal and negative-ideal solutions was calculated and recorded in the following Figure 4.18 format.

	V+:	0,014213	0,065290	0,003695		
	V-:	0,000663	0,000000	0,000000		
Sub Part No	**Sub Part Descp**	**w*LT norm**	**w* EL norm**	**w* Class Norm**	**Si+**	**Si-**
826283	BUSHING	0,000663	0,000000	0,000000	0,066784	0,000000
727537	PLATE	0,000663	0,000000	0,001847	0,066707	0,001847
82386381	BLOCK	0,000663	0,000000	0,001847	0,066707	0,001847
12098509	BLOCK	0,000663	0,000000	0,001847	0,066707	0,001847
409892080	BLOCK	0,000663	0,000000	0,003695	0,066681	0,003695
2637621	BLOCK	0,000663	0,000000	0,003695	0,066681	0,003695
11643	BLOCK	0,000663	0,000000	0,003695	0,066681	0,003695
14527574	FRAME	0,000663	0,000000	0,000000	0,066784	0,000000
482682	FRAME	0,000663	0,000000	0,000000	0,066784	0,000000
123678	PLATE	0,000663	0,000000	0,000000	0,066784	0,000000
123678	COAMING PLATE	0,000663	0,000000	0,003695	0,066681	0,003695

Figure 4.18. Distance of each alternative to the ideal and negative-ideal solutions

Calculate the relative closeness to the ideal solution for each alternative: The relative closeness to the ideal solution was calculated by Formula 6 below and recorded in the format Figure 4.19 below.

$$C_i = \frac{S_i^-}{(S_i^+ + S_i^-)},\ 0<C_i<1,\ i = 1,2,\ldots,m \qquad (4.6)$$

Sub Part No	Sub Part Descp	Si+	Si-	Ci
113397-2	BAR,HANDLE	0,066687	0,001850	0,026995
113433-2	LOWER HOUSING WELDE	0,066763	0,000099	0,001486
MS90728-166	(B1821BH063C250N) S	0,066661	0,003696	0,052536
800374	HARNESS (W124)	0,066763	0,000099	0,001486
113041	M242 25 mm ENHANCED	0,066687	0,001850	0,026995
804266-2	PLATE, AC INLET BOX	0,066687	0,001850	0,026995
GFR08-20F-0-N/M6.0	FLOW REGULATOR, PRE	0,066763	0,000099	0,001486
803225-41	HOSE ASSY	0,066661	0,003696	0,052536
776164-1	KONNEKTOR/CONNECTOR	0,066661	0,003696	0,052536
CA121003-3	KORUMA KAPAGI/PROTE	0,066661	0,003696	0,052536
805101	PLATE, OUTER SIDE	0,066687	0,001850	0,026995
804656	PLATE, EXTERNAL VOL	0,066763	0,000099	0,001486

Figure 4.19. Relative Closeness to The Ideal Solution

Rank the alternatives based on their relative closeness to the ideal solution: The calculated relative of closeness is ordered from largest to smallest. Thus, the risk values assigned to the parts in the mathematical model are calculated.

Thus, during the mathematical modeling process, the assigned risk values are calculated when the components' risk coefficients are examined. The “Ci” value represents the risk coefficient of the parts. Components with high Ci values are evaluated as riskier; similarly, components with low Ci values are considered less risky.

The risk coefficients of the components were determined and recorded in the following Figure 4.20 format.

Sub Part No	Sub Part Descp	Ci
826283	BUSHING	0,000000
727537	PLATE	0,026949
82386381	BLOCK	0,026949
12098509	BLOCK	0,026949
409892080	BLOCK	0,052503
2637621	BLOCK	0,052503
11643	BLOCK	0,052503
14527574	FRAME	0,000000
482682	FRAME	0,000000
123678	PLATE	0,000000
123678	COAMING PLATE	0,052503
123678	PLATE,RAMP	0,000000
117256	COVER,AMMOCAN,7.62	0,000000

Figure 4.20. Risk Coefficients of the Components

4.3. Phase Two

Provide Data Related to The Mathematical Model

Sub Part Unit Cost Data: The spare parts costs are also determined and included in the contract when the project is signed. The unit cost of spare parts is important to a project because these costs can increase project costs, which can cause budget overruns.

The total budget of spare parts is directly related to the unit cost of the parts. Especially high-cost parts can significantly increase the total spare parts budget depending on the number that needs to be backed up. If high-cost parts are backed up, the total budget for spare parts will also be high. This can cause the project to go over budget. Also, backing up unnecessarily costly parts can prevent resources in the project budget from being diverted to other areas. Therefore, each part's cost, criticality, and importance should be considered when developing spare parts management strategies.

The total budget for spare parts for this project, determined at the beginning of the project.

As part of this study, the unit costs of the parts will be considered when identifying the parts that need to be kept in reserve without exceeding the total budget during the mathematical modeling solution. Therefore, the unit price of parts has been taken from the system, and its format is given in Figure 4.21 below.

Sub Part No	Sub Part Descp	Qty Per Assembly	Unit Cost
826283	BUSHING	15	178,00
727537	PLATE	1	154,00
82386381	BLOCK	6	955,00
12098509	BLOCK	1	378,00
409892080	BLOCK	7	373,00
2637621	BLOCK	8	132,00
11643	BLOCK	9	226,00
14527574	FRAME	13	314,00
482682	FRAME	1	379,00
123678	PLATE	12	962,00
123678	COAMING PLATE	12	194,00
123678	PLATE,RAMP	13	667,00
123678	PLATE,RAMP	2	343,00
1263382	RETAINER,SEAL,RAMP	10	781,00

Figure 4.21. Part Unit Cost

Define Upper and Lower Limits for Components Demands

Failure Rate Per Vehicle Data: Understanding and tracking the failure rate of components is crucial for effective spare parts management. It helps optimize inventory management by identifying which parts are more likely to fail and therefore requires higher stock levels. It ensures continuity and efficiency as high failure rates can disrupt operations, making timely availability of spare parts essential. Inadequate stock levels can lead to delayed repairs, compromised business continuity, and decreased workforce productivity. Additionally, knowing the failure rates of parts enables cost control by optimizing the amount of inventory. Excessively stocking parts with high failure rates leads to unnecessary expenses, while the insufficient stock of parts with low failure rates results in costly downtime and expedited procurement. Failure rate data assists in planning and prioritization. Parts with high failure rates can be identified for prioritized maintenance or more frequent inspections, improving resource allocation and overall efficiency. Understanding and monitoring the failure rates of parts plays a vital role in determining appropriate stock levels, ensuring continuity, controlling costs, and enhancing planning processes.

The failure rate per vehicle has been calculated by dividing the number of failures by the usage rate of the part per vehicle. This ratio is multiplied by the number of vehicles in the project, and the number of parts that may be required is calculated in the project. This data will be used with "default minimum 10% spare part inventory" data to determine the minimum and the maximum number of spare parts for parts identified as risky using the AHP-TOPSIS method in this study.

When calculating the minimum number of spare parts to prevent shortages for a component with a high-risk factor, the "Failure Rate Per Vehicle" data and the %10 Spare Part Inventory Data" data will be compared, and the higher value between these two will be used to determine the spare part lower limit. In summary, using the AHP-TOPSIS method, for components identified as high-risk, the lower limit will be determined by comparing the "Failure Rate Per Vehicle" data with the "%10 Spare Part Inventory Data" data, and whichever data is more significant will be used as the basis for setting the lower limit.

As part of this study, the number of failures of parts in previous projects has been requested from the system, and relevant departments, and its format is given in Figure 4.22 below.

Parça no	Parça Açıklaması	Araçtaki Ad	Failure QTY (Araç Başı)	Araç Başı Arıza Or	Yedek Gerek
826283	BUSHING	11	1	9%	2
727537	PLATE	4	3	75%	9
82386381	BLOCK	5	1	20%	3
12098509	BLOCK	5	1	20%	3
409892080	BLOCK	3	6	200%	24
2637621	BLOCK	1	1	100%	12
11643	BLOCK	15	7	47%	6
14527574	FRAME	13	2	15%	2
482682	FRAME	5	2	40%	5

Figure 4.22. Component Failure Rate Information

<u>10% Spare Part Inventory Data:</u> There are various methods for determining spare part inventories. However, the minimum 10% spare part inventory strategy is often preferred. Due to the lack of a systematic approach to after-sales spare parts management, the company has adopted a minimum 10% spare parts inventory strategy in past projects to ensure appropriate spare parts inventory levels and quick customer response. In addition, this strategy can expedite part procurement in emergencies and enable rapid response to customer demands. Nonetheless, certain drawbacks are associated with this approach, particularly, the minimum 10% spare part inventory level may prove insufficient for parts that frequently malfunction, resulting in unnecessary costs for those that do not. Hence,

determining inventory levels should not solely rely on the minimum 10% inventory strategy but must also consider factors such as customer demands, lead times, costs, and part criticality.

When calculating the minimum number of spare parts to prevent shortages for a component with a high-risk factor, the "Failure Rate Per Vehicle" data and the %10 Spare Part Inventory Data" data will be compared, and the higher value between these two will be used to determine the spare part lower limit. In summary, using the AHP-TOPSIS method, for components identified as high-risk, the lower limit will be determined by comparing the "Failure Rate Per Vehicle" data with the "%10 Spare Part Inventory Data" data, and whichever data is more significant will be used as the basis for setting the lower limit.

In the format given in Figure 4.23 below, these data will be used with " Failure Rate Per Vehicle " data to determine the minimum and maximum number of spare parts for parts identified as risky using the AHP-TOPSIS method in this study.

Sub Part No	Sub Part Descp	Qty Per Assem	Toplam Projede Kullanım	%10 Yedek Tutulması
826283	BUSHING	1	12	2
727537	PLATE	2	24	3
82386381	BLOCK	1	12	2
12098509	BLOCK	5	60	6
409892080	BLOCK	6	72	8
2637621	BLOCK	1	12	2
11643	BLOCK	6	72	8
14527574	FRAME	1	12	2
482682	FRAME	1	12	2
123678	PLATE	5	60	6

Figure 4.23. %10 Spare Part Inventory Data

Develop the Proposed Mathematical Model

Optimization with a mathematical model in spare parts management is the key to reducing costs while increasing service levels and supply chain efficiency. Mathematical modeling helps accurately and efficiently manage spare part inventories, thus optimizing business processes and supply chain efficiency. Keeping spare parts stocks at optimal is a significant challenge considering uncertain demands and high costs. In this case, mathematical modeling reduces costs and improves service levels by improving demand forecasting and accurately managing stock levels. Excess stock leads to unnecessary costs and waste, while insufficient stock reduces customer service levels and threatens business continuity. Therefore, mathematical models can be critical for determining spare part procurement and stocking strategies. Additionally, considering the complexity and uncertainty of the supply chain, mathematical modeling and optimization can be the key to more effectively managing supply chain planning and operational resources. This directly impacts both the financial performance of the business and customer satisfaction.

The importance of mathematical modeling and optimization in spare parts management becomes more pronounced in specific industries, particularly in sectors with high-cost parts and severe consequences, such as the automotive, aviation, and defense industries. In these sectors, the failure of a part or the absence of a specific part can halt production processes, cancel flights, or render vehicles non-operational. Therefore, a business must have the right part in the right place at the right time. Hence, mathematical modeling is used for optimizing spare parts stocks. These models typically consider a set of variables, such as part failure rates, supply lead times, stock costs, and service level requirements. Using this information, a business can determine the ideal stock levels, plan when to order which parts, and optimize overall supply chain efficiency.

Mathematical programming models can simulate various scenarios and analyze the results of these scenarios. This can help managers make the right decision in the decision-making process. In addition, mathematical programming models can be used for different optimization objectives. For example, models can be created to minimize costs, maximize customer service levels, or increase stock turnover.

In addition, mathematical programming models can also solve complex problems with multiple constraints. For example, problems with constraints such as minimum spare part stock levels, high customer service levels, and storage space limitations can be solved using these models.

The constraint and objective functions in our study are explained in detail below.

The proposed study presents a mathematical model that can effectively manage the potential risk of obsolescence. The model aims to reduce the overall level of risk by prioritizing the procurement of components with high importance coefficients in situations where the required components are unavailable. The sets, parameters, and decision variables used in the model have been carefully selected and determined to ensure that the risk management approach applied is as effective as possible. This approach will enable businesses to manage their resources better and minimize potential losses due to obsolescence.

The sets, parameters, and decision variables are as follows:

Sets

I Set of components, indexed by i

Parameters

c_i: the unit cost of component i

d_i: the amount determined to be available from the component i

B: Total budget

r_i: importance coefficient of component i

Decision Variables

x_i: the quantity to be ordered for component i

u_i: the amount not available from component i

The obsolescence risk management model is below.

$$Minimize \sum_{i=1}^{I} r_i u_i \tag{4.7}$$

$subject\ to$

$$x_i + u_i = d_i \quad ,\forall i \tag{4.8}$$

$$\sum_{i=1}^{I} c_i x_i \leq B \tag{4.9}$$

$$x_i, u_i \geq 0\ and\ integer \quad ,\forall i \tag{4.10}$$

Eq. (7) is to minimize the total risk if the required components are not available. With Constraints (8), the number of unavailable components is determined. Constraint (9) ensures that the total budget is not exceeded. Constraints (10) are non-integrality constraints. With this model, the number of components that should be purchased is determined in a way that does not exceed the total budget and minimizes the risk by considering the number of components determined.

In this study, the amount determined to be obtained from the (d_i) component is obtained from the last year's fault records or 10% of the total number of uses. If any component has a no-fault record, these two numbers are compared and taken as lower. If the stone is risky, the higher one is taken. The importance coefficient values (r_i), another parameter is the values determined by the AHP-TOPSIS method. The total budget parameter (B) is the budget allocated for the current project. A mathematical model for the project's 3256 components is developed using the defined parameters and decision variables. The developed mathematical model was solved in the CPLEX 22.1.1 and the algorithm was run in the background to find the optimal result for the objective function and the results are obtained.

5. RESULTS AND ANALYSIS

This study aimed to optimize spare part risk management by examining spare part stocks in a large-scale defense industry company. With the proposed method, it is aimed to find solutions to the following problems encountered in the company.

- Purchasing a sufficient number of products to meet the requirements for the system's projected lifecycle
- Optimizing the process to determine the number of parts needed to minimize cost
- Maximizing spare parts availability

In order to achieve the targeted, the criteria for selecting spare parts by conducting a literature review and consulting with experts were determined. The Analytical Hierarchy Process (AHP) method was used to determine the relative importance of the criteria. By giving weights according to their importance in the decision-making process, it has been revealed that the “Export License” criterion has the highest weighted AHP score of 0.619, as seen in Figure 5.1. This highlights the vital role of export regulations in the defense industry.

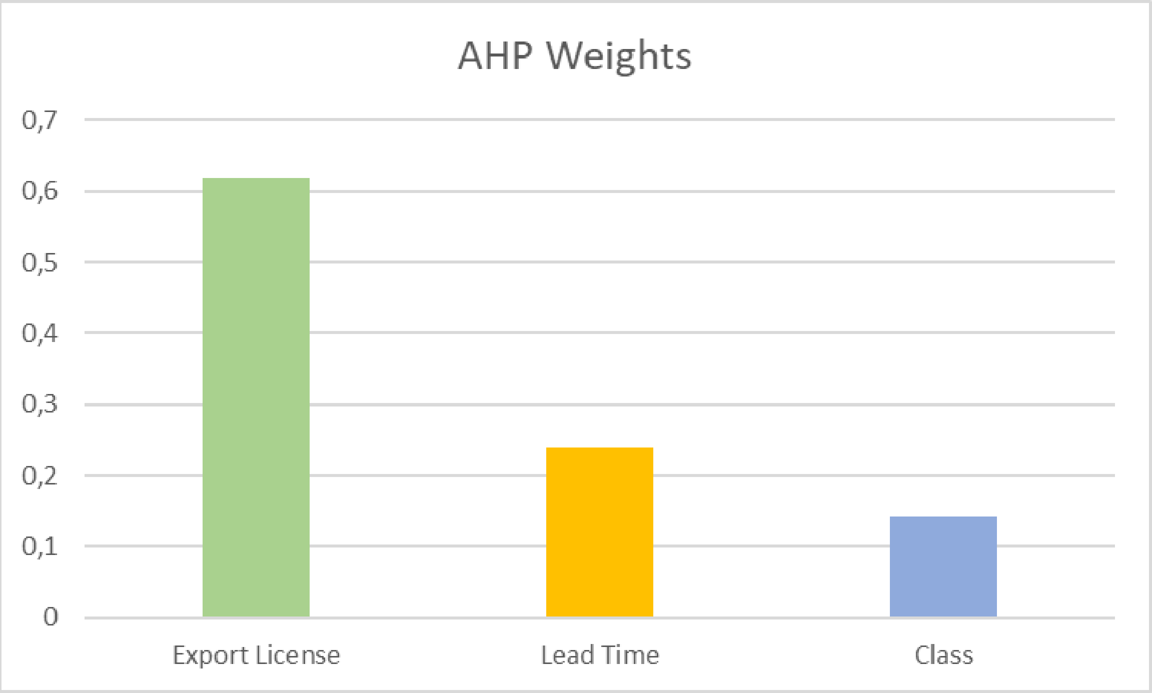


Figure 5.1. Criteria Weights

The AHP-TOPSIS method was integrated to identify critical spare parts according to the established criteria. Then, risk coefficients are assigned to each part according to the criteria. Each part has a unique part number and resides within the system. Analysis of the risk coefficients obtained by the TOPSIS method showed that they aggregated in the score of 0.05, as shown in Figure 5.2. For this reason, parts with risk coefficients above 0.05 were determined as "risky components." This corresponds to a total of 386 risky items in our BoM list.

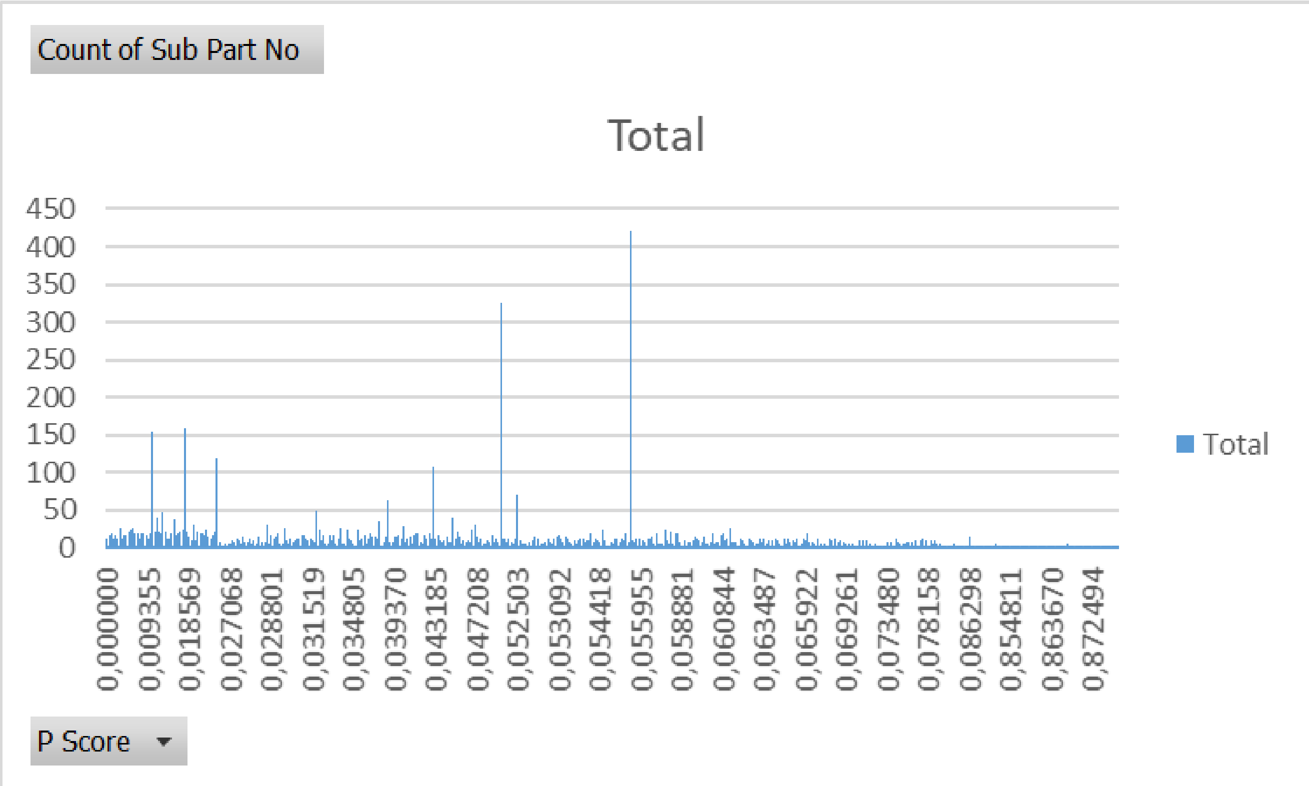


Figure 5.2. P Score & Part Amount Analysis

By multiplying the number of uses per vehicle of the parts considered risky and the total number of vehicles in the project, the number of units required in the total project was calculated, and a value was obtained by taking 10% of this number. In addition, by examining the fault records of that part in past projects, the failure rate of the part was determined. Then another value was obtained by multiplying the usage amount per vehicle and the total number of vehicles in the project. These two values were compared for risky parts, and the higher value was used as the minimum demand for these parts. For risk-free parts, whichever value is lower, minimum demand is determined as that number. For example, in Figure 5.3, the risk coefficient of part number 807911 in the TOPSIS method was found to be 0.86614, and the part was considered risky. Since the total usage in the project is 40 units, if it is desired to keep 10% spare, four units should be kept in stock since the error rate is 0.05. Considering the error rate, two units should be kept. Since the part is risky, the minimum demand is determined as four units.

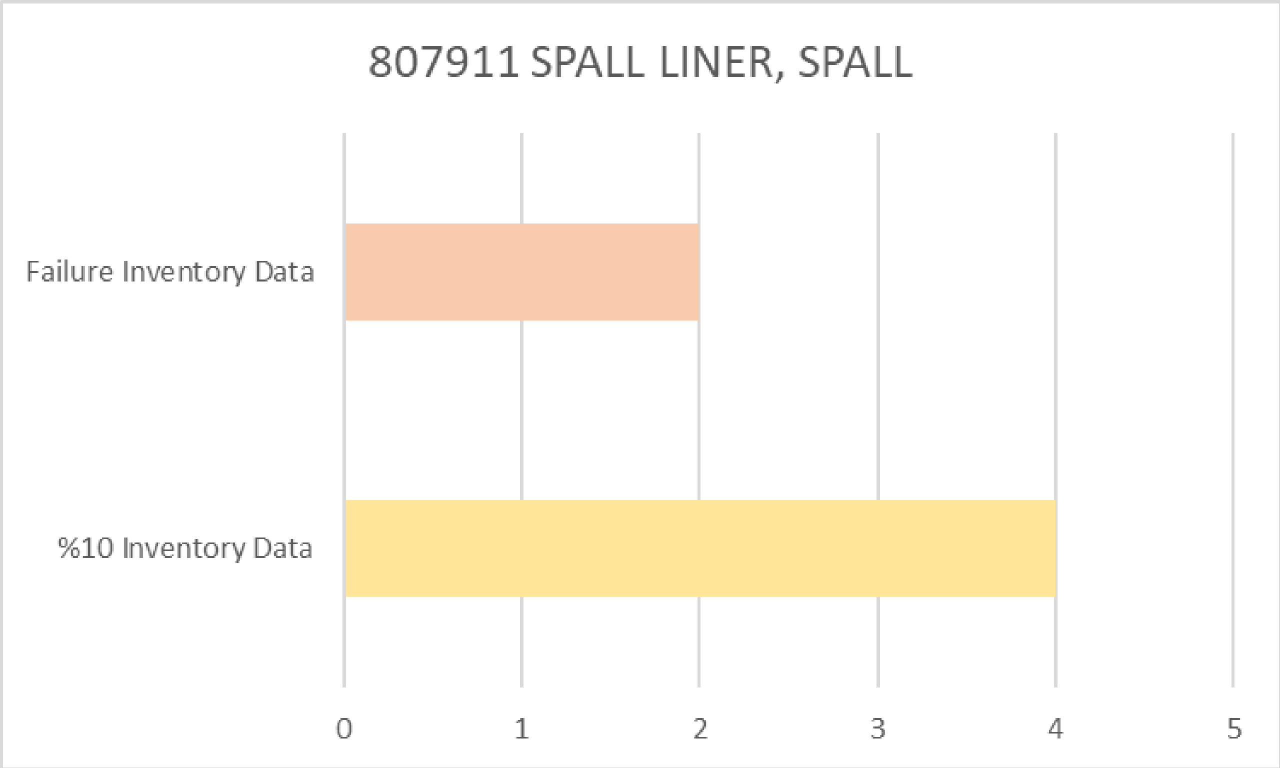


Figure 5.3. Minimum demand for “807911 spall liner” part

In the developed mathematical model, since the objective function is formulated to minimize the total risk if the necessary components are not available, the formula will force to reduce the number of not available components since the amount not available from the component is a decision variable since the parts with high risk are fixed value. In addition, while doing these, the budget constraint of the project was considered, and an optimization was made for both risky and costly parts.

After the mathematical model solved in the CPLEX 22.1.1, the results of the components not available due to the mathematical model are given in Appendix 1. The demands of the components other than those in this table have been met. According to the results in Appendix 1, it is seen that the demands of the components with low importance coefficient and high unit cost are mostly not met.

In addition, the comparison of the unit cost and importance coefficient of the unavailable components is given in the graph in Figure 5.4. Figure 5.4 shows that density is observed in components with a low importance coefficient.

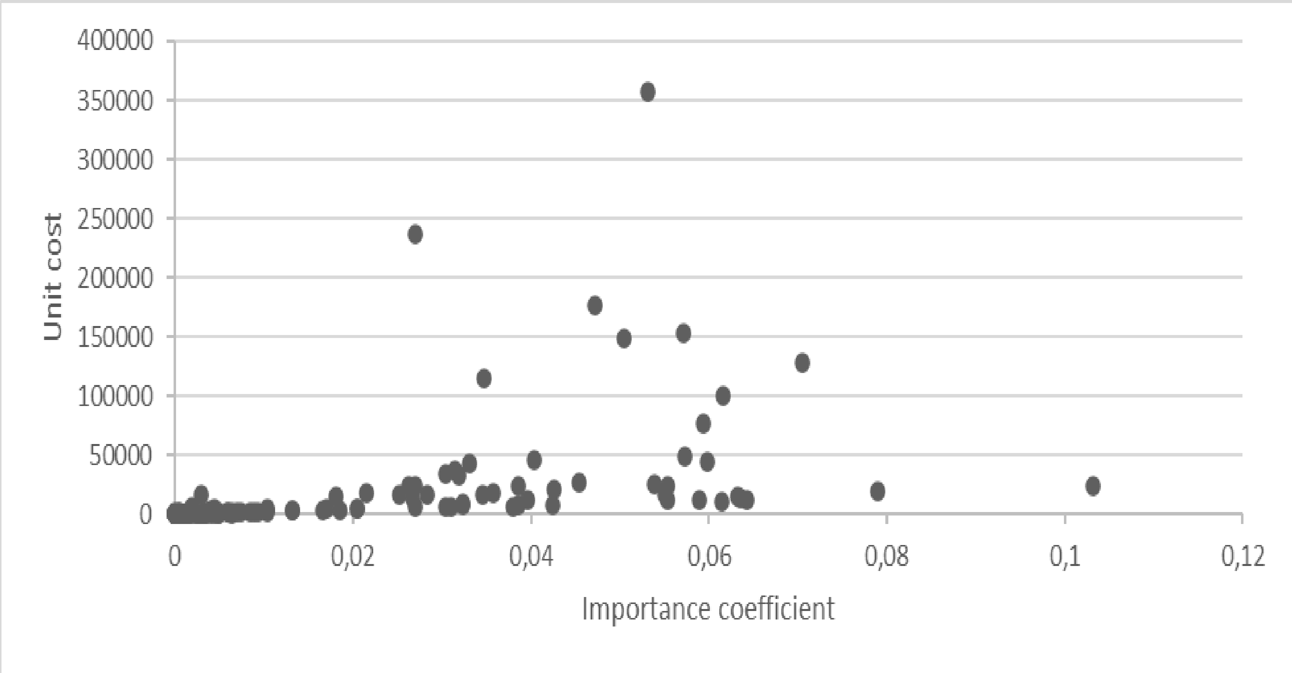


Figure 5.4. Unit cost vs. Importance coefficient for unavailable products

In conclusion, very low-importance parts (washers, bolts, etc.) were removed from our BoM list of 6384 parts, leaving 3256 parts to be focused on. The TOPSIS method was applied to these parts, and 386 parts were determined as risky. When solved in the CPLEX 22.1.1., the mathematical model, which takes into account budget and risk constraints, has determined that not meeting the demand for 171 parts is less risky The proposed model recommends keeping 215 parts as spares for this project. When these components are examined, it is observed that they are critical components of the project. The model did not only focus on the risk of the parts but also optimized the risk management of the parts when there were risky but over-budget parts.

6. CONCLUSION

Spare parts management is a crucial issue in many industries and sectors. Spare part costs, especially in the defense industry, constitute a considerable part of the project costs. Appropriate spare parts management can significantly reduce operational costs, ensure production continuity and increase customer satisfaction. The development and maintenance of products in the defense industry can involve sophisticated systems that require complex business procedures. Managing and planning these systems can be difficult and complex, particularly in part supply or production situations.

The product life cycle starts with product retirement and ends with the expiration of all service contracts, including an end-of-life phase that signifies the end of that life cycle. Remanufacturing used or obsolete products can be an alternative method for obtaining spare parts when obsolescence occurs at the end of their useful life. However, spare parts stocking strategies pose many challenges in decision-making, requiring appropriate techniques at each stage. For instance, deciding which spare parts to keep in stock and at what level can be challenging.

Therefore, this study proposes using mathematical programming models for spare parts management. These models can optimize the amount and cost of spare parts inventories, simulate various scenarios and analyze the consequences of these scenarios to aid decision-making. They can also be used for different optimization goals, such as minimizing costs, maximizing customer service levels, or increasing inventory turnover. However, mathematical programming models alone may not be sufficient for decision-making, as spare parts management is a multi-criteria decision-making process.

Therefore, this study also includes multi-criteria decision-making techniques such as AHP and TOPSIS to reduce uncertainty in the decision-making process. These techniques provide managers with a systematic approach to decision-making and minimize the impact of the human factor by making the decision-making process more objective. However, using AHP and TOPSIS techniques may also entail some difficulties, such as subjectivity in identifying the relationships between criteria.

This study adopted the geometric mean of the decisions made by the decision-makers and evaluated these values as a comparison matrix to obtain a more consistent result. Additionally, the fact that the data used in this study is real project data and that the developed method has been implemented within the company indicates that the proposed approach is applicable.

In summary, this study proposes a suitable method for obsolescence management, which can be applied by armored vehicle producers in this industry to reduce the risk of spare part shortages and enhance decision-making.

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APPENDIX

APPENDIX 1: THE RESULTS FOR THE COMPONENT NOT AVAILABLE

Component	Score	Unit cost
1	0	37,59456
8	0	222,1698
9	0	47,73522
10	0	1,464041
12	0	1206
13	0	327
15	0	0,915567
16	0	397
19	0	2,1044
20	0	7,429627
24	0	202,632
25	0,000496	117,35
30	0,000496	214
31	0,000496	1881
33	0,000496	143,9316
34	0,000496	406
36	0,000496	107,3312
45	0,000496	784
47	0,000496	2207
52	0,000496	430,4264
56	0,000991	419,1864
59	0,000991	512
77	0,000991	327
78	0,000991	678,2408
79	0,000991	641
81	0,001486	1020
86	0,001486	609
88	0,001486	262,2568
89	0,026995	236947,3
100	0,001486	584
103	0,001486	688
110	0,001981	969
119	0,001981	6102
134	0,002475	452,6001
136	0,027068	23312
141	0,002475	652
144	0,002475	507,8689
151	0,027068	6303,837
158	0,002969	16320,57

Component	Score	Unit cost
163	0,002969	1026
184	0,002969	858
193	0,003463	1112
195	0,003463	1645,956
206	0,003463	726
219	0,003463	728,8557
221	0,003956	1017,794
232	0,003956	2889
274	0,004449	4495
285	0,004449	918
303	0,004941	969
314	0,004941	1212,375
320	0,004941	899
380	0,005925	1893
381	0,005925	1187
435	0,006416	1877
450	0,006416	1180,542
468	0,006907	2341
508	0,007397	1804,07
568	0,008377	1589
592	0,028328	16455
600	0,008866	2637
637	0,009355	1646
739	0,010331	2922
754	0,010331	4205
763	0,010331	1724
1121	0,013251	3732
1141	0,013251	3377
1192	0,030355	5948
1321	0,031037	6167
1387	0,016640	3105
1415	0,031519	36675,54
1454	0,055065	16507,6
1456	0,017123	4595
1655	0,055348	11970
1673	0,018087	14743,07
1701	0,018569	3293,592
1766	0,033083	43202
1854	0,020490	5197
1943	0,021449	18759
1978	0,034508	17017

Component	Score	Unit cost
2063	0,057140	153183,2
2088	0,035718	18214
2118	0,057322	48554,16
2550	0,025268	16403
2606	0,026219	23603,36
2660	0,026694	13089,02
2728	0,038627	7408,593
2742	0,038627	24529
2856	0,039646	11625
2918	0,030479	33563
3059	0,031892	32090
3101	0,032362	8351,062
3109	0,032362	9717
3160	0,042461	8025
3161	0,061543	100368
3290	0,034708	115628
3420	0,063255	15857
3450	0,063508	14344
3510	0,037975	6719
3764	0,040298	45740
3938	0,042611	21674
4179	0,045374	27294
4299	0,047208	176578
4306	0,053867	25637,71
4411	0,070440	127981
4562	0,050404	149494
4872	0,053128	357457,8
5048	0,055388	23503,69
5073	0,061464	10313,94
5332	0,058984	12040
5355	0,059431	76891
5397	0,059879	44328
5449	0,078909	19495
5522	0,064333	12689,45
5655	0,103221	23487,74
161	0,002969	486
1889	0,020490	4461,73