QATAR UNIVERSITY

COLLEGE OF ENGINEERING

SUPPLY CHAIN MODELING OF ADDITIVELY MANUFACTURED VERSUS CNC-PRODUCED SPARE PARTS

BY

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ABSTRACT

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Title: Supply chain modeling of additively manufactured versus CNC-produced spare parts.

This research proposes a generic BLOC-ICE-based framework that considers multiple aspects of the adoption of additive manufacturing (AM) in the spare part supply chain. It proposes also a multi-period multiple parts mixed-integer linear programming optimization model for the trade-off analysis spare parts supply through computer numerical control (CNC) manufacturing and AM. The multiple spare parts have different characteristics including volume, shape size, and geometry complexity. The model focuses on minimizing lead times and thus reducing downtime costs. Scenario analyses are developed for some parameters to test the robustness of the model. The analysis shows that the mix between AM-based spare parts and CNC-based spare parts is sensitive to changes in demand. For the given data, the findings demonstrate that AM is cost-effective with spare parts having high geometry complexity while CNC-based manufacturing is economically feasible for spare parts with low geometry complexity and large sizes. The proposed model can support decision-makers in selecting the optimal manufacturing method for multiple spare parts having different characteristics and attributes.

DEDICATION

I would like to dedicate this work to my parents, my siblings, and my friends who believed in me, helped me to put all pieces together and supported me throughout this journey.

ACKNOWLEDGMENTS

I would like to express my sincere thanks and gratitude to my supervisors Prof. Faris Tarlochan and Prof. Shaligram Pokharel for their guidance, support, and advice throughout the journey.

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CHAPTER 1 INTRODUCTION

Additive Manufacturing (AM), also known as 3D Printing or Digital Manufacturing, is recently gaining the interest of researchers from both academia and industry (Yılmaz, 2020). It is defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer” as per the definition by the American Society for Testing and Materials (ASTM, 2015). The 3D printing technology was first developed in 1986 by Charles Hull through a process that is known as stereolithography (SLA), which was later followed by subsequent developments inducing powder bed fusion, fused deposition modeling, inkjet printing, and contour crafting (Ngo et al., 2018).

Additive manufacturing applications have evolved from rapid prototyping and tooling earlier in the 90’s to industrial manufacturing technology nowadays which many industries rely on (Cardeal et al., 2021; Montero et al., 2020). AM was adopted in various industries such as aerospace, defense, and military operations, the automotive industry, the medical sector, and the construction industry. However, the adoption of AM in the oil and gas industry is still under exploration and it is only used for rapid prototyping purposes (Vendra & Achanta, 2020). This technology has proved its efficiency in the aviation sector since it contributes to a 64% weight reduction of the hinge bracket of Airbus A320 compared to the original part (Knofius et al., 2019). Furthermore, AM is widely used in medical applications in order to produce patient-specific solutions on a large scale like hearing aids, orthopedic implants, and prosthetics (Knofius et al., 2019).

A variety of materials are utilized in 3d printing processes namely metals and alloys, polymers and composites, ceramics, and concrete (Ngo et al., 2018). Each material is utilized for different purposes. Metals and alloys are utilized in the aerospace, automotive, and military industries. Polymers are used in sports, toys, and architecture applications. Ceramics are used for biomedical and chemical industries and concrete is utilized in the infrastructure and construction sector.

The market of metal additive manufacturing is growing rapidly as the number of companies that sell AM systems increased from 49 in 2014 to 97 in 2016 with 49% involved with metal additive manufacturing (Wohlers, 2017). Metal additive manufacturing made it possible to produce metallic functional parts and components through 3D printing enabling Direct Digital Manufacturing (Kerbrat et al., 2011). Indeed, metal additive manufacturing is used currently in demanding industries such as aerospace, energy, defense, and biomedical (Jiménez et al., 2021). Figure 1.1 represents the classification of metal 3D printing techniques (Deradjat & Minshall, 2018).

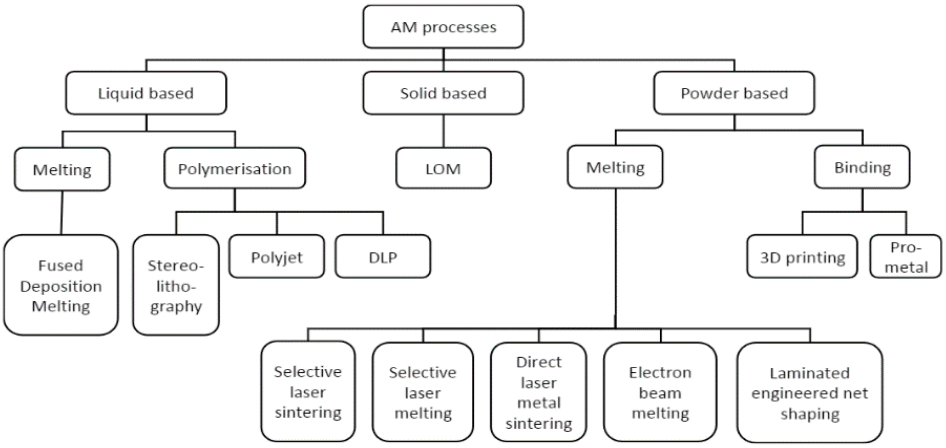

Figure 1.1 Classification of metal AM techniques based on Deradjat and Minshall

Direct Metal Laser Sintering (DMLS) is a technique that belongs to the category of powder bed fusion process where a laser beam fuses and melts powder particles layer by layer. It is considered an extension of the selective laser melting (SLM) process providing higher sintered magnitudes and energy distribution through varying laser power and scan velocity (Sumanth & Srinivasan, 2022). DMLS is widely used to produce functional units because of its good accuracy and quality of surface finish among many industries including aerospace, automotive, and biomedical. For example, the industrial manufacturing company siemens has utilized DMLS technology to manufacture gas turbine blades that will be used in power generation (Di & Yang, 2020).

The recent advancement of additive manufacturing technologies has shown its advantages over conventional manufacturing methods. Additive manufacturing produces less waste and material scraping. It also allows customization and freedom in parts design which makes it able to additively manufacture parts with internal cavities and complex geometries that are impossible to produce via traditional methods. Furthermore, the carbon footprint of AM processes is low compared to other manufacturing methods as AM can have a near-optimal buy-to-fly ratio (Deppe & Koch, 2014). Whereas conventional manufacturing ratios vary from 5 to 20 (Portolés et al., 2016).

One potential area of additive manufacturing technology application is spare parts businesses (Knofius et al., 2019). Intermittent and uncertain demand, material supply capacity, and long lead times are some factors that impose high stock of spare parts. Therefore, the introduction of AM into spare parts supply chains would effectively contribute to cutting lead times, reducing inventory costs, eliminating physical storage of spares, and allowing on-site and on-demand production, especially in offshore and remote locations. AM has a great impact on changing the structure of supply chains and spare parts inventory management systems reducing resupply time, and inventory costs.

1.1 Spare parts Supply Chain

Spare part management is an important aspect of many capital-intensive businesses which has a direct impact on the availability of high-value capital assets. Lifecycles of advanced capital goods usually last decades. More than 60% of the total lifecycle costs of capital goods are related to spare part management. The main contributor to the total cost is the downtime cost which can exceed tens of thousands of units per hour (Knofius et al., 2016). The unavailability of a replacement part when it is needed might result in long downtime affecting the company's profit. The main critical issues that spare parts management may face are the high uncertainty of demand, and demand quantity which is derived from the failure rate. In the spare part business, the uncertainty of the demand, high costs of downtime, and long lead times impose high stocks of spare parts associated with high costs (Knofius et al., 2019). Therefore, the implementation of AM in spare part supply chains is potentially profitable, especially in industries where the cost of downtime is high or those which get penalties due to late deliveries (Frandsen et al., 2020). The technology of three-dimensional printing enables the manufacturing of a variety of products with a high level of customization which leads to reduced production cost, lead times, raw materials, and supply chain complexity (Caldas et al., 2019). Additive manufacturing has the potential to change the spare parts industry because it helps in reducing cost and production time which boosts the supply chain robustness. AM can reduce the inventory of raw materials and the associated cost with it as well, such as ordering costs, transportation costs, and inventory costs. Instead of storing a high inventory of physical spare parts, AM raw material is stored which requires less space and enables producing a wide range of products. Therefore, whenever a part is demanded, it can be printed immediately in a shorter lead time rather than ordering it from an external supplier and waiting for its delivery (lead time). However, AM raw materials are usually expensive, and AM suppliers are still not very widespread (Kunovjanek et al., 2020). Therefore, a trade-off between the raw material parameters (inventory, order frequency, and demand quantity) is required in order to justify the inclusion of AM into the spare parts supply chain. This explains why companies keep a high level of inventory which results in high inventory holding costs (Chekurov et al., 2018).

1.2 Problem Statement

Large-scale applications, like that in the oil and gas industry, require a continuous supply of spare parts. There are two types of spare parts that should be considered by procurement managers: spare parts that are obtained on a periodic basis or a need basis. Spare parts come in different shapes and sizes and may be needed on an immediate basis. The current method of obtaining spare parts from the original equipment manufacturers (OEM) or third-party suppliers may take a higher lead time and costs. The regularity of the production of high-velocity spare parts is also costly due to the cost of ordering, packaging, and transportation. One suggestion is to get the spare parts in inventory, which is one of the solutions currently adopted in many companies.

However, this requires handling costs. Although it might be easier to mass produce the fast-moving parts through the conventional manufacturing processes in the upstream, due to long lead times and supply disruptions, it may create problems in the continuity of the operations. There are opportunities to produce such parts, specifically the slow-moving spare parts (due to emergency requirements) through AM. In some cases, it might also be more attractive to produce, at least partially, the fast-moving parts to counter the disruption and high lead times. However, the analysis of the trade-off on the spare parts through supplier based conventional manufacturing and AM-based local manufacturing (within the company requiring the spare parts) is dependent on the type of spares, the volume of requirements, supply capacity, and the type of material. The research seems to lack this type of comprehensive analysis for optimizing the spare parts supply process by considering different supply chain aspects. Therefore, this research provides the answer to the question of optimal design for the spare parts acquisition or development process.

1.3 Research questions and objectives

Research Questions

RQ1: How supply chains are designed to address additive manufacturing requirements?

RQ2: What supply chain differences exist between conventional manufacturing and additive manufacturing?

RQ3: What framework is available for considering and analyzing supply chains for additive manufacturing?

RQ4: What quantitative model is suitable to assess the trade-off between AM and CNC-based manufacturing?

The following are the research objectives for this thesis. Each of the research objectives is addressed by research questions which have been mentioned below:

Research Objectives

1. To understand the current development of AM in supply chains compared to conventional manufacturing. (RQ1 and RQ2)
2. To develop a generic framework to support the adoption of AM in supply chains. (RQ3)
3. To develop a mathematical model for the trade-off analysis between AM and CNC manufacturing through the generic framework. (RQ3 and RQ4)

1.4 Thesis Contribution and Outcomes

The thesis contributes by developing a generic framework for AM and CNC-based spare parts acquisition and development. A deterministic discrete multi-period mixed integer linear programming (MILP) for multiple spare parts supply chains is proposed to analyze the problem and solutions are developed through an IBM CPLEX OPL platform.

One journal paper has been published as an outcome of the thesis:

- A comprehensive review of the AM and CNC-based processes and modeling techniques. This part has been published in Applied Statistics journal.

  Mecheter, A.; Pokharel, S.; Tarlochan, F. (2022). Additive Manufacturing Technology for Spare Parts Application: A Systematic Review on Supply Chain Management. Appl. Sci. 2022, 12, 4160. https://doi.org/10.3390/app12094160

- A second paper on the theoretical framework and analysis is being prepared for publication.

1.5 Thesis outline

This thesis contains five chapters. Chapter 1 provides an overview of the main related topics to the thesis and presents the problem statement, objectives, and research questions. Chapter 2 includes a systematic review of the literature and research gaps. Chapter 3 presents the adopted methodology of the work along with the mathematical problem formulation and data collection. A multi-period multiple parts mixed integer linear programming analyzing the trade-off between AM and CNC is proposed. In Chapter 4, the outcome and numerical experiments of the model, scenario analysis, discussion, and managerial model insights are included. Finally, in Chapter 5, a summary of the whole work, limitations of the study, and future work are provided.

CHAPTER 2 LITTERATURE REVIEW

In this chapter, a literature survey that reviews the research work on different topics related to this thesis is presented. This chapter is going to fulfill the first objective, which is about understanding the current development in AM supply chains compared to CNC manufacturing. The main covered topics of interest are:

1) Additive manufacturing in the spare parts supply chain.
2) Quantitative modeling of AM and conventional[1] manufacturing in supply chains.
3) Optimization modeling of additive manufacturing and conventional manufacturing in supply chains.

2.1 Additive Manufacturing in Spare Parts Supply Chain

The adoption of additive manufacturing in spare parts management can be described as a supply chain process based on the BLOC-ICE system conceptual framework proposed by Pokharel (2022). As shown in the BLOC-ICE diagram in Figure 2.1, the supply chain process is divided into the following: inputs, process, constraints, and outputs. All aspects of the framework including inputs, processes, constraints, and output are discussed in detail in (Mecheter et al., 2022). However, in this section, only the process aspect, which is shown in red color, will be discussed.

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[1] It is to note that the terms conventional manufacturing and CNC are interchangeably used. CNC is a type of conventional manufacturing methods. The terms additive manufacturing (AM) and 3D printing are interchangeably used as well.

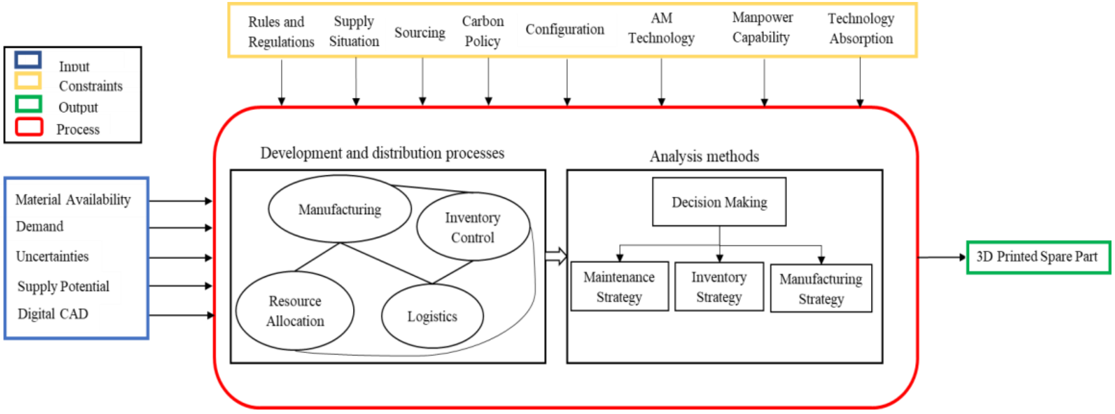

Figure 2.1 Supply chain process adopting AM in spare parts management (Mecheter et al., 2022)

The inputs take into account the demand of spare parts, uncertainty factors, material availability, supply potential, and digital files that transmit the necessary information in order to manufacture the 3D-printed spare parts using the system process.

The input raw materials are scheduled to be replenished from the supplier with a specified quantity in a certain period. The demand for spare parts is usually intermittent and difficult to be predicted, which explains the presence of uncertainty in the input aspect. The supply potential is associated with the supply capacity.

Initially, the raw material should be available in order, to begin with, the processing stage. The material is then processed in the AM-based supply chain system to undergo several processes including decisions-making. Allocation of material and resources, manufacturing, storage, and transportation of spare parts are involved in the processing stage. Resources including 3D printers, spare parts, and raw materials should be optimally allocated to minimize the cost and increase the efficiency production system.

The inventory control depends on the available space for storage, raw materials quantity, spare parts demand, production capacity, and capability of logistics for packaging and transportation. Parts can be transported either directly by the company to the service location or through agents (such as third-party logistics providers or freight forwarders).

The management of the AM-based supply chains (SC) is supported by decision-making in which inventory, manufacturing, and maintenance strategies of the company are considered. The optimal manufacturing strategy could be with the partial adoption of traditional methods instead of total dependence on additive manufacturing methods. Maintenance strategies can be implemented with several types such as preventive maintenance, condition-based maintenance, corrective maintenance, and predictive maintenance. The company should decide on the maintenance strategy that matches the assets and business the most. Consequently, the spare parts production system focuses as well on the maintenance approaches adopted by the organization. In fact, a combination of multiple maintenance strategies can be adopted by companies (Deighton 2016). Inventory strategy also becomes important to balance the production and storage, lead time to meet the demand through internal production or purchase of spare parts, service efficiency, and cost of handling and operation. Therefore, the decision to produce spare parts needs multi-level analysis.

The output of the AM-based supply chain process is 3D-printed spare parts. It is to note that all spare parts are developed by strictly adhering to the 3D digital computer-aided design (CAD) input file.

Several constraints and limitations govern the conversion of inputs to the intended outputs. Various constraints were identified in the literature. Policies, rules and regulations, and other factors, such as the type of AM technology adopted in the industry, the impact of the adoption, and the use of AM in the company. Policies and rules of various entities such as original equipment manufacturers, supplies, distributors, and customers control the supply chain process. Moreover, the SC process is controlled by the SC configuration, supply potential, and sourcing strategy.

Other requirements which are essential to driving the system are the level of technology absorption of the company and the capability to utilize and maintain a certain type of AM technology. Carbon policy through carbon tax can facilitate the SC process for AM as well. With a carbon taxation policy, the carbon footprint of the AM process is low compared to other manufacturing approaches. It is expected to be reduced more when the buy-to-fly ratio is considered. AM can have values of nearly close to one concerning the buy-to-fly ratio, whereas traditional manufacturing processes ratios vary from 5 to 20. Thus, waste can be avoided due to the almost optimal buy-to-fly ratio of additive manufacturing technology (Deppe & Koch, 2014),(Portolés et al., 2016).

2.1.1 Development and distribution processes

Based on extracted the content from the literature, research on AM supply chain process can be divided into two main categories: (i) industry-based processes and (ii) decision-making processes. The discussion of each sub-process is provided below.

- ***Manufacturing***

According to Kretzschmar et al. (2018), there are opportunities for the development of digital spare parts when three aspects are taken into account: demand production, manufacturing speed in comparison to CM, and digital storage. The authors declare some challenges to the industry's adoption of AM, including the limited types of 3D printers, the volume of production, the integration of the IT system, and post-processing issues.

In order to analyze the costs associated with an operator, machine, and material, Zhang et al. (2019) have evaluated the operational details of AM process. The authors have observed that the spare part size impacts the AM operation where in some cases they could not be able to compete financially with traditional methods of parts supply.

According to Cestana et al. (2019), the long setup times required for CM have resulted in improved performance of AM. Therefore, when there is a continuous need for spare parts, the CM may be more advantageous in terms of setup time alone. However, there are other factors which are involved including spare parts inventory requirements, the ease in obtaining and storing raw materials, and easier production of available digital files for the parts.

The analysis of Delic et al. (2019) of the adoption of AM in the automotive industry looked at many aspects of SC integration, performance, and firm performance. According to the authors, the implementation of AM enhances SC and firm performance. However, the authors pointed out that adopting AM technology alone would not create this improvement; instead, it will focus on how AM might be integrated into already-existing SC activities.

Salmi et al. (2020) offer an analysis of the use of AM in COVID-19-related healthcare. According to the authors' analysis of the costs associated with 3D printers, printer maintenance, labor, raw materials, overhead, and sterilization, most healthcare products can be manufactured with AM using available equipment in the market.

A review of the literature reveals opportunities for AM, but there may be issues with its wider adoption because it needs a constant flow of demand in order to develop spare parts continuously. Investments in AM may not increase cost efficiency if the spare parts are more durable, but they will shorten lead times and boost production efficiency.

- ***Inventory Control***

Muir and Haddud (2018) has looked into how AM affected the performance of the inventory. The adoption of AM, according to the author, might lower supply risk and improve inventory management and performance.

In order to evaluate the inventory for an AM-based production system, Zhang et al. (2019) have developed a discrete event simulation model that focuses on spare parts backordering, inventory replenishment, and order evaluation. The proposed model takes into account the costs related to inventory-carrying, replenishment shipping, ordering, warehouse, penalty, and operator costs.

Cestana et al. (2019) developed a minimization problem and mentioned that comparing the inventory performance of AM is better than that of CM because of the lower stock level with AM. As there is already a facility to produce spare parts with AM, the stock levels in AM are lower than those in the CM.

Westerweel et al. (2020) studied the on-site inventory level taking into account the cost and inventory for implementing AM for spare parts manufacturing in remote sites. In order to decide when to print a part and when to wait for its planned replenishment, the author proposed an optimal inventory policy.

The review demonstrates the importance of inventory and warehousing in managing the supply of spare parts. However, the use of AM can result in lower inventories and less need for large volume storage, and manpower to manage such inventory, thus lowering costs.

- ***Logistics***

The review has obtained only a few studies that deal with the logistics aspect of AM. The adoption of AM may make some of the logistics related to production management and some transportation parts redundant. AM adoption might eliminate some parts of the SC, thus making the network shorter and with fewer players.

An analytical hierarchy process was used by Knofius et al. (2016) to rank the spare parts in terms of their value by focusing on attributes such as demand rate, safety stock costs, resupply lead time, number of supply options, and supply risks. The study has focused on the modeling of service logistics with AM. The potential for value improvement was analyzed in terms of reduction in costs such as manufacturing, ordering, direct parts use, safe stocks, and supply disruption. The author stated that the development of such a rank could help the company in creating a better after-sales service.

Caldas et al. (2019) investigated the configuration of SCs for AM in various facilities. The authors developed a simulation model that simulates the installation of 3D printers in an organization's internal facilities, changing different SC designs between model runs. The following key performance metrics were used to measure the performance of SC centers: production, service level, inventory level, stockouts, and supply costs, and lead times. The proposed model can test the effects of eliminating and adding internal facilities, external suppliers, and SC products in addition to testing the impacts of AM.

Yılmaz (2020) had investigated an integrated job and vehicle scheduling problem, minimizing the makespan in AM SC using best-fit heuristics. The best-fit capacity utilization-based selection algorithm, according to the author, improves the make span more than other techniques.

Similarly, He et al. (2021) studied the integration of AM with JIT delivery systems intending to minimize delivery times and transportation costs. The authors used a branch and price-based methodology for integrated machine and vehicle transportation scheduling problems. A location-dependent cost minimization SC optimization model was developed by taking into account the total cost of production, transportation, and inventory. According to the author, companies can save costs by integrating production and transportation.

- ***Resource Allocation***

The allocation of materials and 3D printers can be considered for resource allocation. In the context of AM, some studies have looked into 3D printer allocation in sites and facilities (Caldas et al., 2019; Ivan & Yin, 2018).

Ott et al. (2019) have developed a multi-stage process model serving as a decision support tool for spare parts allocation in order to quantify the cost and classification of spare parts. The emphasis was on various spare part allocation strategies, such as stockpiling, traditional spare production, and AM strategy. The preprocessing and postprocessing costs for AM, setup and preparation costs, building job assembly costs, and part building costs were all included in the proposed cost modeling for spare parts allocation strategies.

Through a location-dependent model followed by a cost-minimization supply model, Bonnín et al. (2019) studied how to determine the optimal location and number of manufacturing facilities and investigated the trade-offs between the cost of production, transportation, and inventory. The authors have determined that the decentralized configuration was only appropriate for low-volume products after applying the suggested methodology to an aviation case study.

Brito et al. (2021) used the classical p-median, location-allocation modeling, and mixed-integer linear programming to study the optimal installation of 3D printers in various facilities for the production of spare parts. The model was put to the test for the optimal scenario using a case study on elevator maintenance that involved nine production facilities, each of which had a 3D printer. This kind of optimal analysis will assist businesses in managing difficulties at various locations where AM is adopted.

A real green time allocation and scheduling architecture was proposed by Darwish et al. (2020) for large-scale distributed AM task allocation for medical spare parts and personal protective equipment (PPE). The failure of the global SCs, which caused a significant shortage of PPE and spare parts, motivated the design of the proposed architecture. The workload between 3D printers was balanced, and the authors discovered that the 3D printer usage had improved. According to the study, it is important to allocate 3D printers, raw materials, and human resources in a way that ensures AM's effectiveness and efficiency.

2.1.2 Decision Making

The research on different strategies of analysis methods in decision-making for AM is covered in the section below. Decision-making is focused on three main strategies: inventory, manufacturing, and maintenance.

- ***Inventory Strategy***

Liu et al. (2014) have stated that the focus of the inventory strategy with AM is to reduce the safety stock levels of spare parts in the SC. Any increase in safety stock can result in a significant increase in the cost of SCs because of the high value of the products in the aircraft industry. The production of slow-moving parts in one location and the consolidation of demand for the utilization of AM capacity, as well as the deployment of AM in service locations to lower the cost of transportation and inventory, were the two scenarios that the authors examined to understand their impact on inventory. According to the authors, if a company chooses the centralized method, its objective would be to establish an inventory based on historical demand, which would reduce the level of customer service.

Togwe et al. (2019) examined how different percentages of AM spares could be added to the inventory mix in order to shorten the total system lead time. The authors demonstrated that AM increases agility and reduces lead times for replenishing spare parts, which results in less capital tied up in spare parts inventory.

Based on models and concepts of inventory management, Heinen et al. (2019) evaluated the transition from conventional manufacturing of slow-moving spare parts to additive manufacturing. The findings revealed that the switch to AM technology would result in a 6.4% decrease in overall system costs using the empirical dataset they examined. The authors looked at the possibilities for digitizing spare parts and how it would affect inventory control and after-sale services.

- ***Manufacturing Strategy***

Deppe and Koch (2016) created a decision tool to assist the decision-making process for aircraft maintenance, repair, and operations (MRO) activities. It assesses the costs of using AM, conventional technologies, and purchasing a new part from the original equipment manufacturer. This tool can help in the choice of a manufacturing strategy.

The proposed multi-attribute decision analysis approach considered the technology's cost, time, and quality. A different decision-support tool, on the other hand, was suggested to assist decision-makers in choosing the most practical AM technology class and material in a remote manufacturing environment (Meisel et al., 2016).

A scoring technique that takes into account the eligibility of spare parts for AM was proposed by Knofius et al. (2016). The methodology used by the authors helps to increase the efficacy and efficiency of selecting promising facilities for logistics related to after-sales services.

Adopting a lifecycle cost model, Westerweel et al. (2018) et al. have compared the production of components using AM and traditional manufacturing. It was discovered that AM is more advantageous for after-sales logistics. In the early design process, break-even characteristics allow the original equipment manufacturer to decide on the design option to adopt.

A simulation model was developed by Caldas et al. (2019) in order to study AM spare parts for elevators. The authors have mentioned that the model could support choosing a manufacturing strategy in a SC based on the total cost, lead time, and service level. The performance of SC simulations was evaluated using the following key performance metrics: service level, inventory level, and cost, production time and cost, lead time, stock-outs number and costs, and supply costs. The authors have emphasized that while AM may be advantageous for producing small batches with a low volume, it also has the capacity to produce products with a high level of customization. To explore the use of AM spare parts in elevators, a simulation model was created. The authors have mentioned that the model may enable selecting a production approach in a SC based on overall cost, lead time, and service level.

Similarly, Marek et al. (2020) created a web-based software tool that performs an AM feasibility assessment identifying the components that can be manufactured by AM in order to choose an appropriate 3D printer service provider.

The decision support system identified and used the objectives and constraints of each of the processes, equipment, parts, materials, environment, and logistics. The analysis demonstrates that researchers took into account analytical tools to assist the industry in choosing AM and traditional manufacturing. Decisions regarding AM capacity, AM facility allocation, and demand-based production methods were also taken into consideration.

- ***Maintenance Strategy***

The use of AM in maintenance has been shown to support both corrective maintenance and preventive maintenance techniques, according to Togwe et al. (2019). Adopting AM would increase agility and positively impact lead times for replenishing spare parts.

A sustainable method model for airplane maintenance has been used by Cardeal et al. (2020). The impacts of switching from conventional maintenance, repair, and overhaul activities to AM were examined by the authors. The authors demonstrated that adopting distributed manufacturing of spare parts provides the opportunity for optimizing spare parts' weight from a maintenance perspective.

Cardeal et al. (2021) proposed a process-based model to investigate the potential of AM in maintenance activities, emphasizing the significance of AM's capability to lower maintenance costs and increase machine lifetimes.

A hybrid simulation model was utilized by Xu et al. (2021) to compare SC configurations and to determine how AM capabilities affected increases in operational effectiveness and maintenance effectiveness. However, the authors did not examine the resource management aspect of maintenance operations, which will allow for more rational decisions in the deployment of manufacturing resources, such as maintenance equipment and maintenance technicians.

The review shows that studies have demonstrated that the maintenance strategy can impact the choice of AM and that lead time, service effectiveness, and agility can be some of the factors which can support AM. However, it is important to keep in mind that lead time, service effectiveness, and maintenance agility might all be significantly improved if the organization adopted a safety-stock-based approach. Thus, a maintenance strategy should be considered along with the total system cost of adopting AM or adopting conventional manufacturing with an inventory.

2.2 Quantitative Models for Additive Manufacturing

Many approaches, analysis techniques, and quantitative methods are applied in order to adopt AM in the spare parts supply chain. Most of the existing studies rely on qualitative, analytical, and optimization analyses (Li et al., 2019). Research is focusing on case studies, empirical studies, and scenario analysis in order to examine the integration of additive manufacturing technologies in spare parts logistics. However, quantitative modeling is the methodology that is used the most. Quantitative modeling techniques and computer-based tools are used in business decision-making, and their applicability to AM-based supply chain choices is widely spreading (Tayur et al., 2012).

Based on the content of these methods, optimization and simulation modeling techniques are the two primary categories for quantitative models that are mostly used independently to address uncertainties in logistics and supply chains (Tordecilla et al., 2021).

Optimization models can be used for many purposes, including making span minimization in scheduling problems, supporting decisions for resource allocation, and studying the effect of resupply time on inventory performance. Mixed-integer linear programming (MILP) and Markov decision process (MDP) are other used approaches in optimization modeling. MILP is widely used due to its robustness (Brito et al., 2021).

Table 2.1 lists the simulation modeling in terms of the approaches and performance metrics. The models were developed for either single or multiple time periods. In general, only one period is considered as the planning horizon for optimization models. Discrete event simulation is broadly used in the analysis of the AM environment to simulate operational and tactical decisions. These models adopt variability and uncertainty; thus, they may represent the dynamics of the spare parts business (Caldas et al., 2019). System dynamics (SD)-based simulations are also used in the spare parts SC. They are useful for analyzing the outcomes of different scenarios by analyzing variations in parameters (Beltagui et al., 2020). System dynamics are widely applicable in situations where different ranges of materials, information flows, and complex dynamic problems intersect (Li et al., 2017). The review shows that SD-based simulation models were only used in the scenario analysis. Optimization and simulation modeling, cost models, business models, and theoretical models are adopted for many purposes. The purposes of these models include lifecycle costing analysis, the feasibility of 3D printer installation, and tackling the production of AM spares in remote locations. Cost models include cost objectives in their analysis. The stages and parameters of the economic cost models are illustrated in Table 2.2.

Table 2.1 Simulation models

Author	Approach	Performance Metrics
Khajavi et al. (2014), (2018)	Monte Carlo Simulation	Occurrence for expected spare parts demand
Li et al. (2017)	Systems Dynamics	Transportation, Manufacturing, Administrative, and Inventory costs Carbon Emission Sources
Chekurov et al. (2017)	Monte Carlo Simulation	Turnaround time
Ghadge et al. (2018)	Systems Dynamics	Inventory level and cost, the time horizon for the simulation
Zhang et al. (2019)	Discrete Event Simulation	Material, energy, operator, penalty, maintenance, AM, and parts costs Interarrival time
Caldas et al. (2019)	Discrete Event Simulation	Service Level, Lead Time, Fixed Production, and supplying Inventory Stockouts costs
Li et al. (2019)	Discrete Event Simulation	Sojourn time (queue, manufacturing time, and logistics time) penalty, machine, and logistics costs
Togwe et al. (2019)	Monte Carlo Simulation	System average lead time
Xu et al. (2021)	Discrete Event Simulation + Agent-based Simulation	Order fulfilling lead time Order fulfilling cost Proportion of cannibalization

Table 2.2 Economic models

Author	Stage	Parameters	
		Cost	**Other**
Westerweel et al. (2018)	Single stage	Production, inventory holding, downtime, repair, investment	Performance benefit, probability loss

Author	Stage	Parameters	
		Cost	**Other**
Ott et al. (2019)	Multi-stage	Preparation, job assembly, setup, part building, removing the part from the machine, separating the part from the substrate plate, and post-processing.	-
Salmi et al. (2020)	Single stage	3D printer, printer’s maintenance, raw material, labor, overhead, and sterilization.	-
Cardeal et al. (2021)	Single stage	Labour, Software, 3D scanner, Machine, Building, Energy, Raw material, Consumable, Warehouse unitary	Machine setup time, Machine clean-up time, Inspection time

2.3 Optimization Modeling of Additive Manufacturing and Conventional Manufacturing

Optimization quantitative methods are widely spread for modeling AM technology in supply chains. Optimization problem types can be linear or non-linear, deterministic, or stochastic, and discrete or continuous.

Mathematical techniques and tools which are used to solve operations research optimization problems include (Calafiore & El Ghaoui, 2014): Linear programming, Non-linear programming, Dynamic programming, Integer programming, Markov process, Game theory, Decision theory, Queuing theory, Inventory models, and Network scheduling.

Linear programming is a constrained optimization technique (Calafiore & El Ghaoui, 2014) that is mainly concerned with the maximization or the minimization of an objective function subject to linear equality and inequality constraints. Pure integer programming is when all the model variables are restricted to be an integer. The mathematical problem is called Mixed Integer Linear Programming (MILP) when only some of the variables have integer values, while other variables are allowed to be non-integer (Veli, 2010).

Mixed integer linear programming is used widely in business and engineering research because of its flexibility in modeling (Brito et al., 2021). Table 2.3 provides an overview of the optimization model structure in terms of the approaches and tools utilized in the optimization process, the model objective, parameters, the number of stages, and the nature of the planning horizon. It is shown that all models deal with time and cost minimization. Westerweel et al. (2020) investigate an infinite time horizon to explore on-site additive manufacturing for the Royal Netherlands Army. The analysis demonstrated that AM spare parts provided the best solution to prevent stock-outs between the two replenishment periods. However, whenever the conventionally made parts were delivered at the end of an order cycle, the AM part was immediately replaced and discarded since AM parts are assumed to have less reliability as they are less resistant to cyclic loading.

Table 2.3 Optimization of quantitative models

Author	Approach	Stage	Objective	Parameters	Period
Knofius et al. (2019)	Stochastic Dynamic Programming	Single stage	Cost minimization	Holding, discarding for parts and tools, Purchasing, Setup, and Backorder	Multiple
Cestana et al. (2019)	Markov Decision Process	Bi stage	Cost minimization	Holding, backorder	Single

Author	Approach	Stage	Objective	Parameters	Period
Knofius et al. (2020)	Markov Decision Process	Single stage	Cost minimization	Purchasing, maintenance, holding, and backorder	Single
Westerweel et al. (2020)	Markov Decision Process	Single stage	Cost minimization	Unit Ordering, Unit Printing, Inventory Holding, Backorder	Multiple
Yılmaz (2020)	Heuristics	Bi stage	Make span time minimization	Jobs completion time	Single
Brito et al. (2021)	MILP	Bi stage	Cost minimization	Internal facility, Holding 3D printers, Part Production, Delivery costs	Single
He et al. (2021)	MILP	Single stage	Delivery time minimization	Transportation, Route	Single

2.4 Research gaps

Based on the conducted literature review, the obtained research gaps are the following:

- Quantitative models are developed in order to investigate the adoption of AM in supply chains; however, these models lack in complexity and lack in the consideration of the effect of lead time and its uncertainty. Most of the studies recommend having dual sourcing or mixed sourcing rather than single sourcing. However, decision-makers are still uncertain about the shift to AM and whether AM-based spare parts can guarantee similar performance to conventional ones.
- Most of the AM research focuses on the aerospace industry whereas other industry sectors such as petroleum industries require heavy investment in spare parts acquisition where high-reliability levels need to be achieved. The adoption of AM in oil and gas industry is still under exploration and AM is only used for rapid

prototyping applications. Future research may focus on specific spares, technology capability, demand uncertainty, and the development of optimal SC configurations for the oil and gas industry.

2.5 Summary

This chapter has addressed RQ1 which deals with the design of supply chains to address AM requirements and RQ2 which deals with the supply chain differences between AM and CNC-based manufacturing. These questions have been addressed through conducting a systematic review of AM and conventional manufacturing methods in the spare parts supply chain. The literature review shows that research is increasing significantly in AM in the past five years. It shows that multiple aspects of opportunities were considered by researchers such as materials, processes, technology, and SC configurations. Based on the identified research gaps, the next chapter will propose a quantitative model which will consider the lead time aspect of different spare parts analyzing the trade-off between AM and CNC manufacturing methods.

CHAPTER 3 RESEARCH METHODOLOGY

This chapter describes the proposed framework and methodology adopted in this thesis which will fulfill objective 2. This objective will be addressed taking into consideration RQ3 and RQ4. Chapter 3 is divided into three subsections. Section 3.2 discusses the adopted methodology and framework for the research. Section 3.3 illustrates the modeling methodology to formulate the scenario problem. Section 3.4 includes the mathematic model formulation and data collection assumptions.

3.1 Research Framework

Figure 3.1 illustrates the research methodology adopted in this thesis. First, a systematic literature review is conducted that lead to the development of the research framework. After developing the framework, the deterministic model is formulated: where modeling assumptions are made, and variables and parameters of the problem are collected. When the problem is formulated and translated into a mathematical model, data is collected in order to test the model and to perform numerical experiments. Scenario analysis is conducted to show the robustness of the model and to indicate the model setup when some parameters are changed. Finally, the findings are discussed, and the research study concludes with future work.

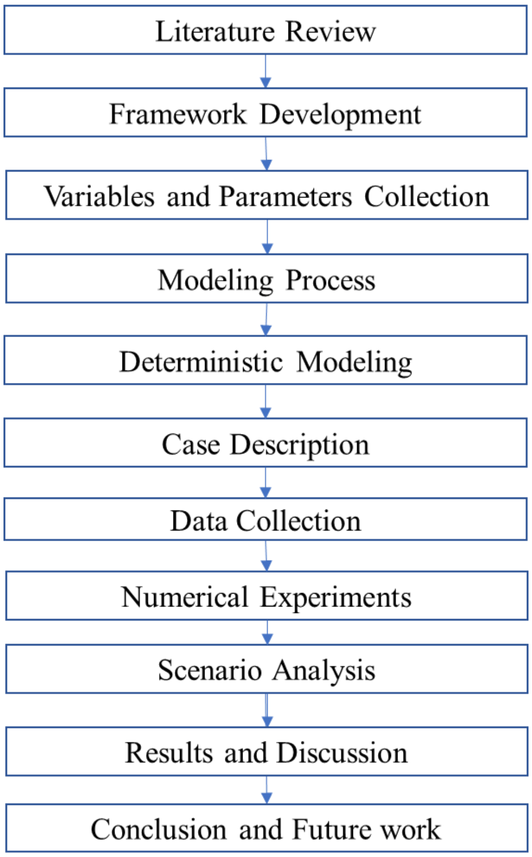

Figure 3.1 Research methodology flowchart

The proposed framework of this thesis includes different aspects of the adoption of AM technology in the supply chain of spare parts. The framework is based on the BLOC-ICE approach proposed by (Pokharel, 2022). The BLOC-ICE is introduced and explained previously in Section 2.1 (Figure 2.1).

Based on the scope of the proposed mathematical problem, the optimization model considers the following aspects in:

Inputs

- *Material availability:* raw material is available, and it can be pre-ordered, and delivered to the facility to be used in printing spare parts.
- *Demand:* demand of spare parts is fulfilled by CNC- based sourced spare parts, or

on-site additively manufactured parts, or a combination of both.

- *Uncertainties:* uncertainty exists in parameters such as demand, lead time of spare parts from the supplier, and capacity of suppliers.
- *Supply potential:* supply potential is related to the supplier capacity. The supplier of CNC-based spare parts and the supplier of AM raw materials have a certain capacity limit of parts or raw materials that can be ordered and sourced to the customer.

Constraints

- *Rules and regulations:* orders of quantities of CNC-based spare parts and AM raw materials are made on a periodic basis.
- *Sourcing:* the sourcing of the spare parts can be from the CNC-based supplier or AM on-site production or both for each spare part type.
- *Configuration:* the configuration and design of the supply chain are critical since it impacts decision-making. The adopted supply chain design in this model is composed of two suppliers, the main facility which consists of an AM facility, and warehouse, and the system where demand is generated, and spare parts are delivered.
- *AM Technology:* based on the extracted data from (Shehadeh, 2019), the adopted technology of additive manufacturing in this model is direct metal laser sintering which is based on powder bed fusion process.
- *Manpower capability:* the aspect of the capability of the workforce is included in the process of AM. A skilled labor in AM is considered in the stages of setup, and post-processing of AM -based spare parts.

Process

Development and distribution processes:

- *Manufacturing:* two manufacturing methods are considered in this model which are AM and CNC-based manufacturing.
- *Inventory control:* warehouse storage capacity and holding costs of inventory are considered.
- *Logistics:* Transportation-related costs of CNC-based spare parts and raw materials of AM are included in the model.

Analysis methods

- *Manufacturing Strategy:* the main aspect of decision-making in the proposed model is the decision on the optimal manufacturing strategy of each particular spare part in terms of lead time and cost minimization.

Output

The output of the process is the spare part that is delivered to the system in order to meet the demand.

3.2 Optimization Methodology

The proposed optimization problem in this thesis models the trade-off between CNC and AM technologies with the objective to minimize the overall costs associated with both manufacturing alternatives. The model represents the situation of combining two manufacturing methods to meet the demand of spare parts. It provides a solution for the optimal manufacturing method of each spare part type in each period of the planning horizon. There are nine different types of spare parts considered in this thesis; each having a different purchase cost from the CNC supplier and production cost with AM, different lead time delivery from the CNC supplier, and AM printing time based on their characteristics related to geometry complexity level and spare part size.

The trade-off between AM and CNC manufacturing methods is formulated as a mixed integer linear programming (MILP) problem. The mathematical problem formulation of the model is illustrated in the following subsection. The formulated problem is generic and can be applied to any spare parts system which contains spare parts that are manufacturable with AM and CNC methods. The main objective of the model is to minimize the operational costs of both manufacturing methods including purchase, ordering, and transportation costs of CNC-manufactured spare parts, purchase and transportation of AM raw material, production costs of AM-produced parts, and penalty costs of lead time and backordered demand. Figure 3.2 represents specific inputs and outputs of the analysis process. There are many software packages which are available to solve optimization problems namely, LINGO/LINDO, Microsoft Excel, MATLAB, and CPLEX. CPLEX will be utilized to implement and solve the proposed optimization formulation. IBM ILOG Optimization Studio enables rapid development of decision optimization models through the use of mathematical constraint programming (*ILOG CPLEX Optimization Studio | IBM*, 2022). The problem is coded and solved using IBM ILOG CPLEX optimization studio: 22.1.0.0. The coding is done on Windows 11 operating system with 16 GB RAM and Intel core i7 CPU. The optimization programming language (OPL) was used for programming. OPL is an optimization modeling tool that is included in the CPLEX studio package, and it uses algebraic primitives and facilitates direct mapping of decision variables, constraints, and parameters (Al-Dossari, 2021).

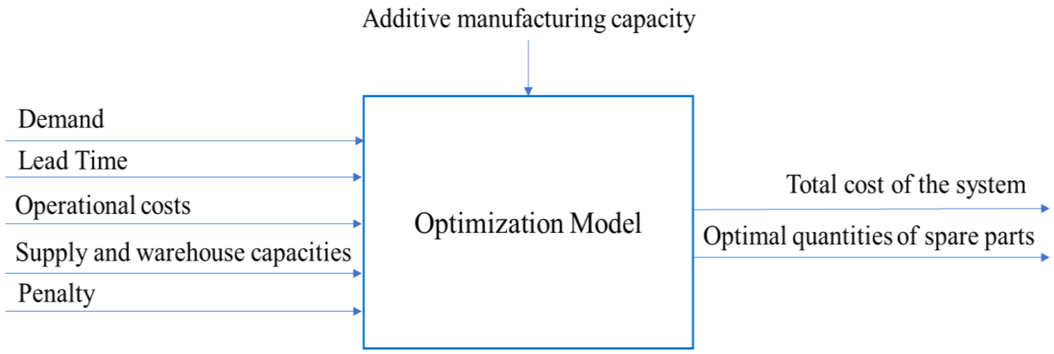

Figure 3.2 Research framework

3.3 Modelling Formulation of solution approach

The MILP used in this thesis is a generalized model. The model is mathematical programming-based where the main objective is to minimize the sum of several cost items related to purchase, ordering, transportation, inventory holding, lead-time, and backorder penalty costs. The outcome of the model will be the decision on the optimal quantity of spare parts to be sourced from the CNC supplier and the quantity of spare parts to be on-site produced through AM.

Figure 3.3 shows a graphical representation of the supply chain flow of the proposed optimization problem. The square on the right-hand side indicates the main facility, which is composed of a warehouse of raw materials and spare parts, the AM facility where the parts are printed, and the system where demand for multiple and different spare parts is generated. CNC parts are ordered from the CNC supplier and transported to the main facility. Similarly, the raw material of metal additive manufacturing which is metal powder is ordered from the supplier and delivered to the facility. The warehouse is common for both CNC parts and AM metal powder where they can be stored. In the AM facility, the AM parts are fabricated through a metal 3D printer where a skilled operator is available for the setup of the printer and post-processing activities.

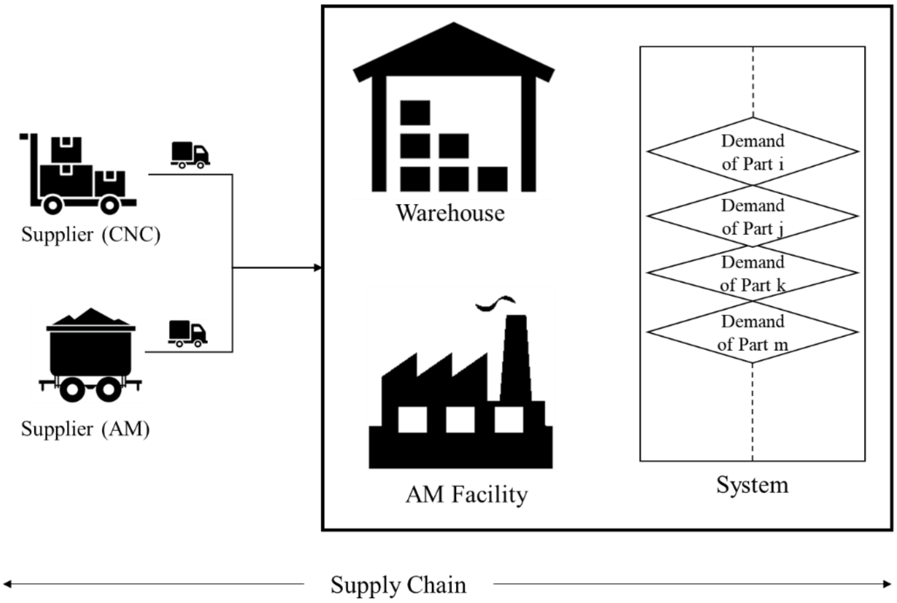

Figure 3.3 Supply chain flow of the proposed model.

3.3.1 Modeling assumptions

The following are the assumptions made for the formulation of the optimization model.

- The planning horizon of the study is set as one year based on the procurement cycle in the supply chain.
- At the beginning of each period, the demand of different nine spare parts is generated, where each demand can be fulfilled through AM, CNC, or both manufacturing methods.
- Spare parts which are produced through AM (after post-processing) and CNC-based spare parts have equivalent quality and reliability.
- CNC-based spare parts are delivered through an external supplier and AM-based spare parts are fabricated on-demand in the facility where the CNC spare parts and AM raw materials are delivered to the facility at the beginning of each period.
- All spare parts are manufacturable with both methods CNC and AM.

- All spare parts are single components that are made up of the same material (do not require assembly in the case of AM).
- The warehouse capacity is combined for both CNC-based parts and raw materials of AM. It can be allocated by spare parts, raw materials, or both.

3.3.2 Data collection and data assumptions

Nine types of spare parts are considered in this case analysis. The spare parts are categorized according to three geometries, each having three complexity levels and three sizes according to (Shehadeh, 2019). The complexity is defined as the complexity of the geometry design of the part. Table 3.1 lists the spare parts related characteristics and data. The following are the assumptions made regarding the model parameters:

- The demand of spare parts is considered deterministic and discrete in this study. Demand values follow Poisson distribution over the given planning horizon. Authors including (Cantini et al., 2022), (Sgarbossa et al., 2021), and (Knofius et al., 2019) have assumed Poisson distribution for spare parts demand arrival. λ is the mean number of events occurring over a given interval of time. In this study, λ was selected to be 40 units based on randomization. Values of demand are assumed to fluctuate in ± 10% range.
- The transportation costs for AM raw materials are shipment-based. However, transportation costs for CNC-based spare parts are quantity-dependent.
- The lead time of CNC-based spare parts is shipment-based and not quantity dependent and assumed to be constant for each particular spare part because the contract between the supplier and customer is valid for a given lead time so operations can continue.
- The lead time to print AM-based spare parts is deterministic and adopted from

(Shehadeh, 2019). The lead time of AM-based spare parts includes the setup time of production, printing time, and post-processing time of spare parts.

- The production price of CNC-based spare parts are adopted from (Shehadeh, 2019) and 10% was added as a market price to obtain the purchase price of spare parts.
- The production costs of AM-based spare parts are adopted from (Shehadeh, 2019) and include the energy costs, inert assistant gas cost (argon), and post-processing costs.
- The lead time penalty is assumed as a percent fraction of the spare part's purchase/production cost as per (Emelogu et al., 2016) where they assumed a range of 10% to 270% of the monetary value per unit of lead time. In this study, the monetary value of lead time is assumed to be 250% since the focus of this model is to prioritize the minimization of lead time
- The supply capacity of AM metal powder is assumed to be constant over the planning horizon. The supplier capacity of CNC-based spare parts is different for each spare part type and is assumed to be in the range of ± 10% of the lambda demand value ($\lambda = 40$).
- The warehouse capacity for storage is assumed to be 2 cubic meters. According to (Cantini et al., 2022), warehouses in spare parts supply chains are assumed to have unlimited capacities.
- The depreciation cost of AM machine is 20% of the capital machine investment in the first year of usage. Given the capital investment of AM machine, 1,369,863 USD, the depreciation expense in the first year is about 273,973 USD as Since the planning horizon of the study is one-year, monthly depreciation expenses are assumed to decrease gradually throughout the year.

Table 3.1 Spare parts data

Spare part type	**Complexity**	**Size**	**Volume ($\mathbf{m^3}$)**	**Mass (Kg)**	**The purchase cost of CNC-based spare parts (USD)**	**The production cost of AM-based spare parts (USD)**
1	Low	Large	0.00075	6	1111	2723
2	Medium		0.00075	6	1567	2528
3	Complex		0.00075	6	1980	1157
4	Low	Medium	0.0004	3.2	715	1081
5	Medium		0.0004	3.2	836	997
6	Complex		0.0004	2.4	1562	463
7	Low	Small	0.0003	2.4	467	338
8	Medium		0.0003	2.4	583	316
9	Complex		0.0002	1.6	1034	142

3.3.3 Notation

All notations which are used in the formulas are summarized in Table 3.2. The decision variables of the proposed MILP are the following:

- Quantity of CNC-based spares to be sourced from the CNC supplier.
- Volume of AM raw material to be sourced from the AM supplier.
- Quantity of AM-based spares to be on-site produced.
- Inventory level of CNC-based spares and AM raw material volume.
- Backorder level of spare parts.

Through the implementation of the model, optimal values of the abovementioned decision variables will be determined.

Table 3.2 Notation overview

Notation	Definition
	Sets
T	Time periods, t = 0…T
J	Parts index, j = 1...J
I	Method, $I = \{1,2\}$ where $i = 1$ refers to CNC, $i = 2$ refers to AM
	Parameters
$\boldsymbol{O_i}$	Ordering cost per shipment for method i
$\boldsymbol{Cn^t_{ij}}$	Purchase price for part j in period t for CNC method where $i = 1$
$\boldsymbol{Ca^t_{ij}}$	Production cost for part j in period t for AM method where $i = 2$
$\boldsymbol{T^t_{ij}}$	Transportation cost in period t for method i
$\boldsymbol{H^t_{ij}}$	Holding cost of inventory value in period t for method i
$\boldsymbol{L_{ij}}$	Lead time in days for part j for method i
$\boldsymbol{P}$	Purchase cost of AM raw material per meter cube
$\boldsymbol{B}$	Penalty cost per unit of backordered demand
$\boldsymbol{OP}$	Daily operator cost for AM method
$\boldsymbol{ST}$	Setup time for AM method
$\boldsymbol{PP}$	Post-processing time for AM method
$\boldsymbol{SC_j}$	Supplier capacity for part j
$\boldsymbol{Sc}$	Supplier capacity in meter cube for AM method i = 2
$\boldsymbol{W}$	Warehouse volume capacity allocated for storage
$\boldsymbol{D^t_j}$	Demand of part j in period t
$\boldsymbol{v_j}$	Volume of part j
$\boldsymbol{Lr}$	Lead time of raw material delivery for AM method i = 2
$\boldsymbol{MV_{ij}}$	Monetary value per unit of lead-time for part j of method i
$\boldsymbol{DE^t}$	Depreciation expense of AM machine in period t
$\boldsymbol{M^t}$	Maintenance expense of AM machine in period t
$\boldsymbol{S_j}$	Selling cost of remaining inventory of parts j at the end of the planning horizon
$\boldsymbol{Sa}$	Selling cost of remaining raw material of AM method at the end of the planning horizon
	Decision variables
$\boldsymbol{Q^t_{ij}}$	Quantity of part j to be ordered in period t with CNC method $i = 1$ Quantity of part j to be produced in period t with AM method i = 2
$\boldsymbol{I^t_{ij}}$	Inventory volume of part j in period t for method i
$\boldsymbol{Iu^t_{ij}}$	Inventory level (in units) of part j in period t for CNC method $i = 1$
$\boldsymbol{B^t_j}$	Backordered demand of part j in period t
$\boldsymbol{RM^t_{ij}}$	Volume of raw material in meter cube to be ordered for part j in period t for AM method i = 2

3.3.4 Model Formulation

The mathematical problem formulation of the optimization is presented in this section including the cost minimization objective function that is subject to multiple constraints.

- **Objective function**

$$minimize\ \sum_{t=1}^{12} Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + Z_6 + Z_7 + Z_8 + Z_9 + Z_{10} + Z_{11} - Z_{12}$$

(1)

$$Z_1 = \sum_{j=1}^{J} (Q_{ij}^{t} \times Cn_{ij}^{t}) \ , \qquad i = 1$$

(2)

$$Z_2 = \sum_{\mathrm{j}=1}^{\mathrm{J}} (Q_{ij}^{t} \times C\mathrm{a}_{ij}^{t}) \ , \quad i = 2$$

(3)

$$Z_3 = \sum_{\mathrm{j}=1}^{\mathrm{J}} (Q_{ij}^{t} \times T_{ij}^{t}) + O_i \ , \quad i = 1$$

(4)

$$Z_4 = \sum_{j=1}^{J} OP \times Q_{ij}^{t} \times (ST + PP)\ , \qquad i = 2$$

(5)

$$Z_5 = \sum_{j=1}^{J} \left(RM_{ij}^{t} \times P\right), \qquad i = 2$$

(6)

$$Z_6 = O_i + T_{ij}^{t}\ , \qquad i = 2$$

(7)

$$Z_7 = \sum_{j=1}^{J} \sum_{i=1}^{I} (H_{ij}^{t} \times I_{ij}^{t})$$

(8)

$$Z_8 = \sum_{j=1}^{J} Q_{ij}^{t} \times \left(MV_{ij} \times L_{ij}\right), \qquad i = 1$$

(9)

$$Z_9 = \sum_{j=1}^{J} MV_{ij} \times [(L_r + ST) + Q_{ij}^{t} \times (L_{ij} + PP)]$$

(10)

$$Z_{10} = \sum_{j=1}^{J} \left(B \times B_j^t\right)$$

(11)

$$Z_{11} = (DE^t + M^t)$$

(12)

$$Z_{12} = \sum_{j=1}^{J} \sum_{i=1}^{I} \left(Sa \times Iu_{ij}^{t}\right) + (S_j \times I_{ij}^{t})$$

(13)

The objective function for cost minimization is given in equation (1) with the purchase price of CNC-based spare parts (Z_1), production cost of AM-based spare parts (Z_2), transportation and ordering cost of CNC-based spare parts (Z_3), operational costs of AM-based spare parts (Z_4), purchase cost of AM raw material (Z_5), ordering, and transportation cost of AM raw materials (Z_6), inventory holding cost for AM raw material and CNC-based spare parts (Z_7), penalty cost of lead time of CNC-based spare parts (Z_8), penalty cost of lead time of AM-based spare parts (Z_9), penalty of backordered demand (Z_{10}), monthly depreciation and maintenance expenses of AM machine (Z_{11}), and selling cost of remaining raw material and CNC-based parts at the end of the planning horizon (Z_{12}).

- **Constraints**

AM raw material volume conversion equation

$$Q_{ij}^{t} \times v_j = RM_{ij}^{t}, i = 2, \forall j \in \mathrm{J} \tag{14}$$

Inventory of CNC-based parts conversion equation

$$Iu_{ij}^{t} \times v_j = I_{ij}^{t}, i = 2, \forall j \in \mathrm{J} \tag{15}$$

Ensuring that no inventory is left at the end of the planning horizon

$$I_{ij}^{t} = 0, \quad t = T \quad \forall j \in \mathrm{J}, \forall i \in \{1,2\} \tag{16}$$

Initial Inventory at the warehouse

$$I_{ij}^{t} = 0, \quad t = 0 \quad \forall j \in \mathrm{J}, \forall i \in \{1,2\} \tag{17}$$

Ensuring that no backordered demand is left at the end of the planning horizon

$$B_{j}^{t} = 0, \quad t = T \quad \forall j \in \mathrm{J} \tag{18}$$

Initial backordered demand level

$$B_{j}^{t} = 0, \quad t = 0 \quad \forall j \in \mathrm{J} \tag{19}$$

Warehouse capacity constraint

$$\sum_{j=1}^{J}\sum_{i=1}^{I} I_{ij}^{t} \le W, \forall t \in \mathrm{T} \tag{20}$$

Supply capacity constraint for CNC-based spare parts

$$Q_{ij}^{t} \le SC_j, \ i = 1, \ \forall t \in \mathrm{T}, \forall j \in \mathrm{J} \tag{21}$$

Supply capacity constraint for AM raw material

$$RM_{ij}^{t} \leq Sc\,, i = 2\,,\ \ \forall t \in \mathrm{T} \tag{22}$$

Inventory balance constraint

$$I_{1j}^{t-1} + I_{2j}^{t-1} + Q_{1j}^{t} + Q_{2j}^{t}\ - D_{j}^{t} + B_{j}^{t} - B_{j}^{t-1} = I_{1j}^{t} + I_{2j}^{t}\,, \forall\ t \in \mathrm{T} \tag{23}$$

Non-negativity constraint

$$Q_{ij}^{t}\,, Iu_{ij}^{t}, B_{j}^{t}, RM_{ij}^{t}, I_{ij}^{t} \geq 0,$$

$$Q_{ij}^{t}\,, Iu_{ij}^{t}, B_{j}^{t}\ \text{ integer variables } \forall t \in \mathrm{T}, \forall j \in \mathrm{J}, \forall\ i \in \{1{,}2\} \tag{24}$$

Constraint (14) converts the raw material volume of the particular spare part to spare parts quantity in units. Constraint (15) converts the inventory of CNC-based spare parts from cubic meter volume to quantity in units. Constraint (16) ensures that no inventory of AM raw material or CNC-based spare parts will be left at the end of the planning horizon. Constraint (17) sets the initial inventory of both AM raw material and CNC-based spare parts at the warehouse equal to zero. Constraint (18) ensures that no backordered demand for spare parts is left at the end of the planning horizon. Constraint (19) sets the initial backordered demand level equal to zero. Constraint (20) ensures that the inventory level has to be less than or equal to the storage capacity of the warehouse. Constraints (21) and (22) represent the supplier capacity constraints. Constraint (21) ensures that the ordered quantity of CNC-based spare parts does not exceed the supplier capacity of CNC-based spare parts. Constraint (22) ensures that the volume of ordered raw material of AM does not exceed the supplier capacity of AM metal powder. Constraint (23) represents the inventory balance constraint where the inventory level equals to the summation of the produced quantity of AM-based spare parts, the sourced quantity of CNC-based spare parts, the backordered demand level, and the previous period’s inventory which are subtracted from the demand level and the previous period’s backordered demand. Constraint (24) is the non-negativity constraint. It is to note that the variables Q_{ij}^{t} , Iu_{ij}^{t}, B_{j}^{t} are integers, while the rest are float numbers.

3.4 Summary

This chapter has addressed RQ3 and RQ4 which consider the framework and modeling process that analyzes and assesses the differences between AM and CNC manufacturing methods.

In this chapter, general modeling and data collection assumptions were listed. The model handles different cost components associated with CNC and AM manufacturing methods. The research framework has been developed based on the BLOC-ICE diagram. The application of the proposed model will be demonstrated in the next chapter.

CHAPTER 4 RESULTS AND DISCUSSION

This chapter is divided into three sections. Section 4.1 provides the results of the numerical analysis and experiments. Section 4.2 presents the scenario analysis which is conducted to test the performance of the model. Section 4.3 discusses the main findings of the study along with the managerial implications and insights of the model.

4.1 Numerical Experiments

Numerical experiments are performed for the proposed optimization formulation according to the presented data based in the literature in Table 4.1.

Table 4.1 Data used in parameter values

Parameter	Value	Unit	Reference
$\boldsymbol{D_j^t}$	40 [2]	Units	(Cantini et al., 2022)
$\boldsymbol{L_{1j}}$	57,65,70,53,49,51,42,38,45	days	(Cantini et al., 2022)
$\boldsymbol{L_{2j}}$	1.5, 1.5, 1.5, 0.8, 0.8, 0.6, 0.6, 0.6,0.4	days	(Shehadeh, 2019)
$\boldsymbol{T_j^t}$	N~ (104,30)	\$/unit	(Cantini et al., 2022).
$\boldsymbol{Ta^t}$	N~ (73,30)	\$/shipment	Assumption by thesis writer
$\boldsymbol{O_1}$	2212	\$/shipment	(Pour et al., 2019)
$\boldsymbol{O_2}$	442	\$/shipment	(Pour et al., 2019)
$\boldsymbol{H_{1j}^t}$	30% per year	Of inventory value or revenue	(Sgarbossa et al., 2021)
$\boldsymbol{H_{2j}^t}$	20% per year	Of inventory value or revenue	(Emelogu et al., 2016)
$\boldsymbol{P}$	147	\$/kg	(Atzeni & Salmi, 2012)
$\boldsymbol{OP}$	14	\$/hour	(Baumers et al., 2012)
$\boldsymbol{ST}$	0.5	hour/unit	Assumption by thesis writer

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[2] Demand of each spare part for all periods is attached in Appendix A online

Parameter	Value	Unit	Reference
$\boldsymbol{PP}$	1	hour/unit	Assumption by thesis writer
$\boldsymbol{S_j}$	333,470,594,215,251,469,140,175,310	\$/unit	Assumption by thesis writer
$\boldsymbol{Sa}$	44	\$/kg	Assumption by thesis writer
$\boldsymbol{MV_{1j}}$	2778,3918,4950,1788,2090,3905,1168,1458,2585	\$/unit of lead time	(Emelogu et al., 2016)
$\boldsymbol{MV_{2j}}$	6809,6319,2893,2703,2492,1157,846,790,356	\$/unit of lead time	(Emelogu et al., 2016)
$\boldsymbol{L_r}$	7	Days	(Emelogu et al., 2016)
$\boldsymbol{W}$	2	m^3	Assumption by thesis writer
$\boldsymbol{SC_j}$	40,39,40,40,40,41,39,40,40	units	Assumption by thesis writer
$\boldsymbol{Sc}$	0.05	m^3	Assumption by thesis writer
$\boldsymbol{M^t}$	1840	\$/month	(Ruffo et al., 2006)
$\boldsymbol{B}$	4000	\$/unit	(Cantini et al., 2022)
$\boldsymbol{DE^t}$	41096,34247,34247,27397,27397,27397,21918,19178,13699,10959,10959,5479	\$/month	Assumption by thesis writer

4.1.1 Model Implementation and Solution

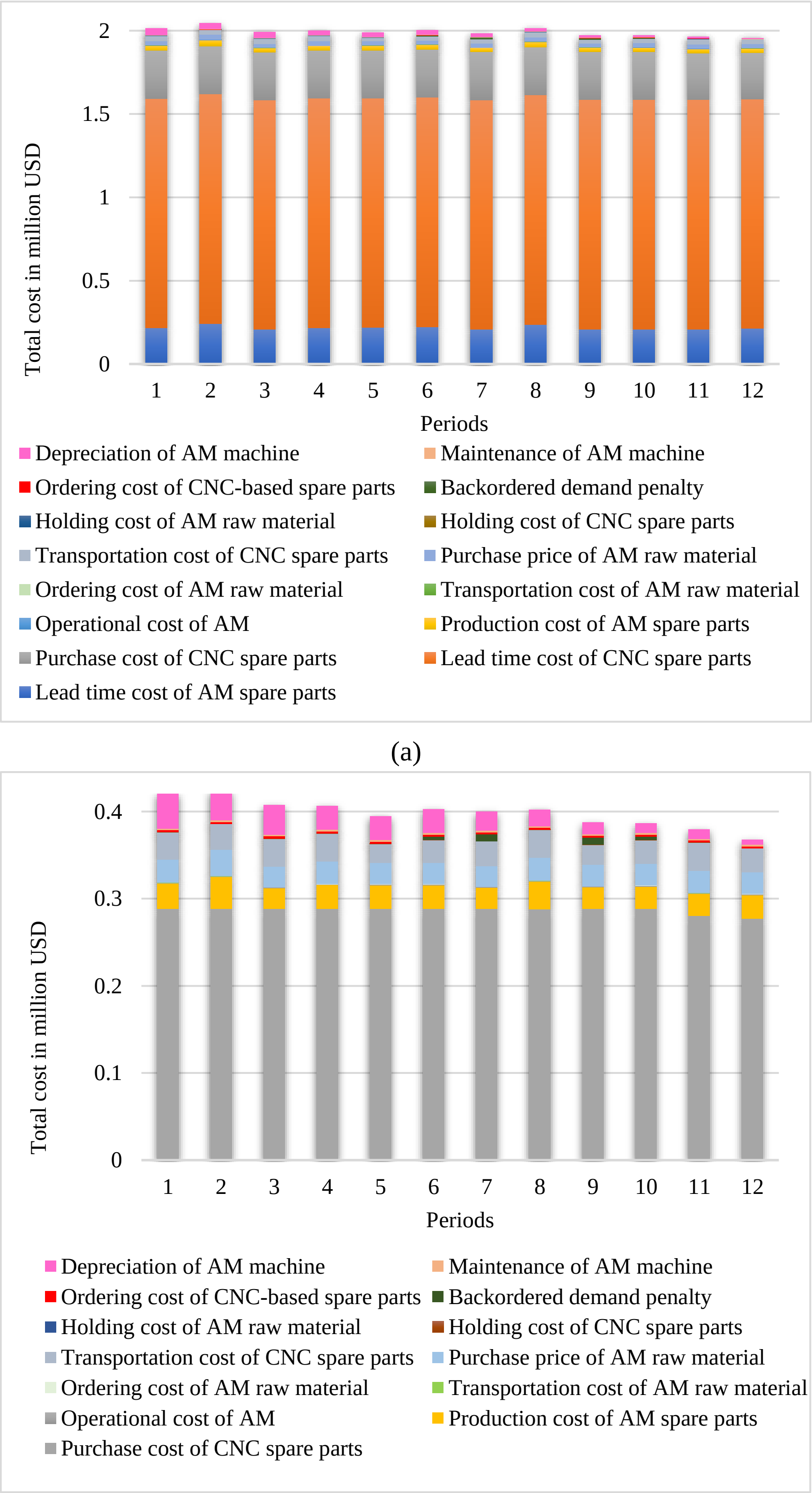
The proposed MILP model in this study was implemented and solved optimally in CPLEX OPL. We considered a small-scale system consisting of nine spare parts, twelve periods, and two manufacturing methods. The solver platform took 0.03 seconds to solve the MILP problem with 24 iterations, 1026 variables, and 1476 constraints. The global optimal solution was found to be $\text{Total Cost}_{\text{min}} = 23{,}910{,}352$ USD. It is to mention that CPLEX solver handles problems with a minimum size of 1000 variables and 1000 constraints. The analysis of the model results and decision variables outcome will be conducted from the period perspective and from the spare part type perspective. It is to note that the decision-maker knows the lead times and demand values of all spare parts for all periods priorly. Accordingly, orders will be made at the scheduled time.

4.1.1.1 Analysis of model performance by period

The optimization model was implemented for a planning horizon which consists of 12 periods. Table 4.2 illustrates the total cost associated with all nine spare parts on a period basis. The second period has the largest cost among all periods because of the high cost associated with the purchase cost of AM raw material powder and the production cost of AM-based spare parts. Furthermore, the second period has the largest accumulated demand of all nine spare parts compared to other periods; therefore, AM-based spare parts were produced more in order to meet the demand which explains the high cost of AM raw material purchase. Figure 4.1 represents the total periodic cost breakdown per cost component. It is observed that the average cost in each period fluctuates below and above 2,000,000 USD.

Table 4.2 Total cost of each period

Period	**Total cost ($)**
1	2,014,797
2	2,044,120
3	1,991,181
4	2,000,847
5	1,989,553
6	2,002,647
7	1,984,319
8	2,015,668
9	1,972,903
10	1,972,164
11	1,965,524
12	1,956,640



(a)

(b)

Figure 4.1 Cost breakdown for total cost per period a) including costs of CNC and AM lead time b) excluding CNC and AM lead times

According to Figure 4.1, the dominant cost among all periods is the purchase price of CNC-based spare parts which can be explained as most of the spare parts are sourced through CNC supplier. Meanwhile, AM was only used when demand cannot be satisfied with CNC-based spare parts. The second dominant cost is the depreciation expenses of AM machine. The depreciation expenses of equipment and machines in the first year of usage are about 20% of the capital investment. The cost of purchasing AM raw materials, the transportation cost of CNC-based spare parts, and the production cost of AM-based parts are considered significant compared to other costs which are relatively low. Figure 4.2 shows the quantity, inventory, demand, and backordered demand of each spare part taking the example of period 6.

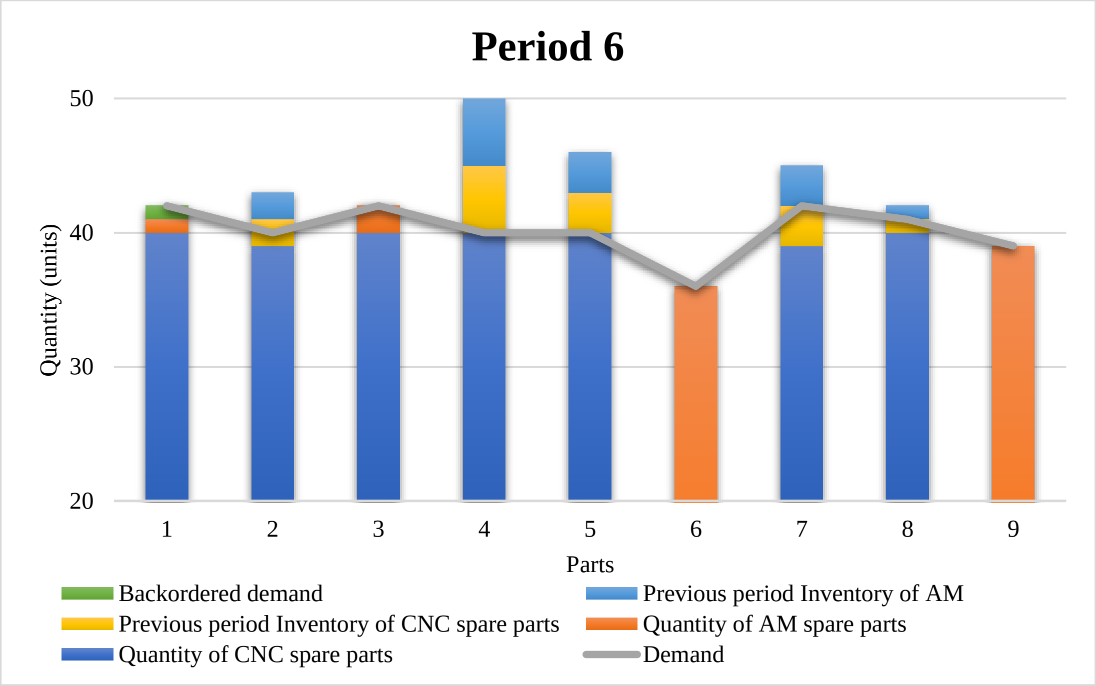


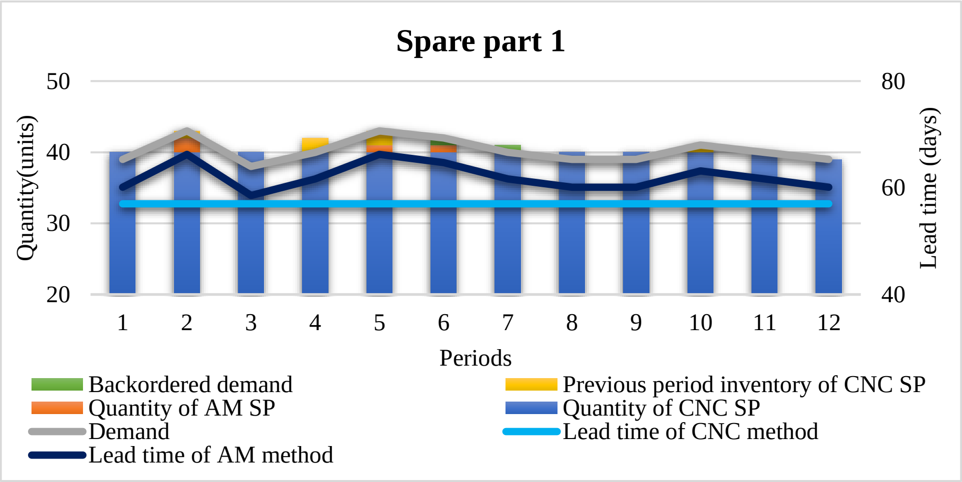
Figure 4.2 Quantity, inventory, backorder, and demand of spare parts in period 6.

Spare part 1 was sourced mainly from the CNC supplier; however, one demand unit was backordered, and one unit was produced with AM. The supplier capacity for sourcing spare part 1 is 40 units, and the demand for spare part 1 in period 6 is 42 units, that is why the model chose to produce one spare part via AM and backorder the second part. Spare parts 6 and 9 have less production costs with AM compared to their purchase price with CNC, and their demand is 36 and 39 units respectively, so printing them with AM yields in less lead time rather than sourcing them with CNC. That is why the model decided to produce them through AM. Regarding spare parts 1, 2, and 3, they are mainly sourced with CNC. However, for spare parts of types 4, 5, 7, and 8, although sourcing them with CNC takes longer than AM, the associated cost of purchasing raw material and printing AM-based spare parts is very high so it is more cost-effective to order them from the CNC supplier.

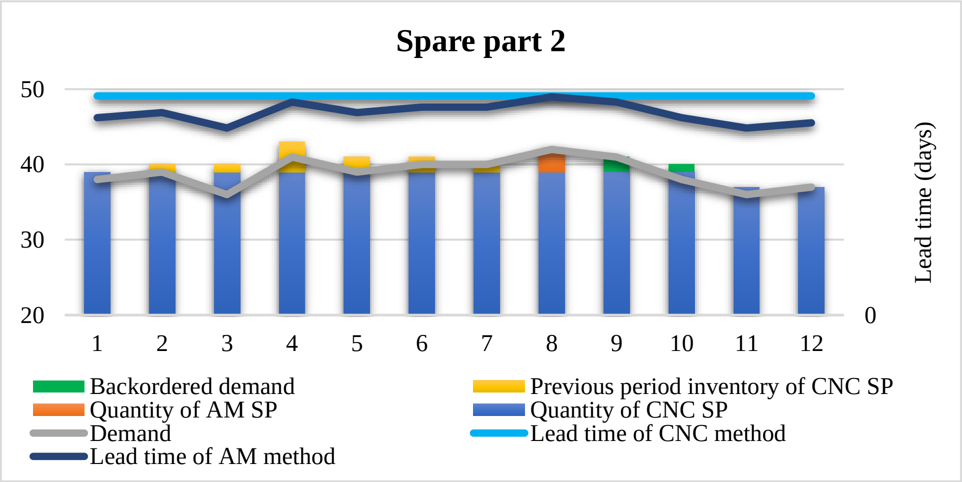
Because of the variation of the supplier capacity from spare part type to another, and in some cases the demand for the spare part exceeds the supplier capacity, hence the model orders extra spare part units in order to store and use them in the next period (such as spare parts 4 and 5).

4.1.1.2 Analysis of model performance by spare part types

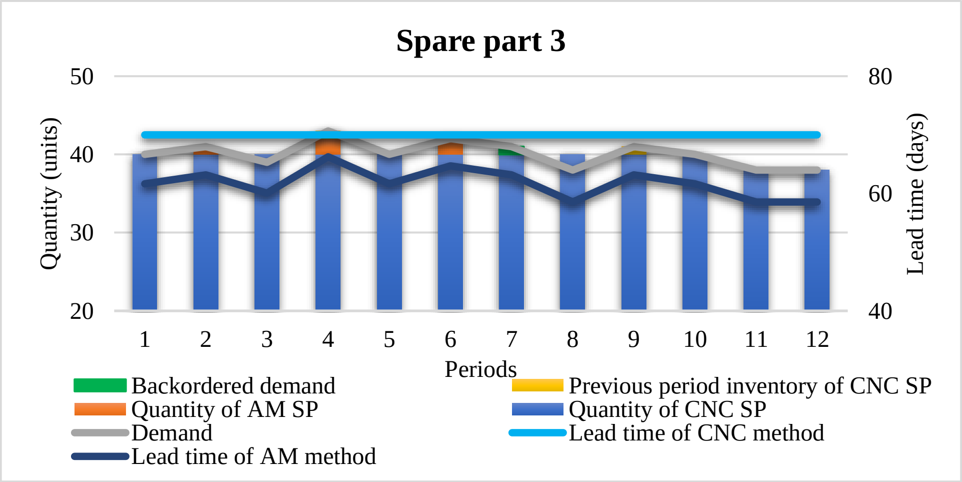
This section will present and discuss the decision variable outcomes from the spare part type perspective throughout the twelve periods. Figure 4.3 show the quantity, inventory, and demand of the nine spare part types in all periods. It is observed that CNC-based manufacturing was the most used method to source the spare parts and to satisfy the demand for 7 of the parts while AM was mainly used for 2 spare part types only. However, AM-based spare parts were produced in some cases to satisfy the demand in cases where demand could not be fulfilled through CNC.



(a)



(b)



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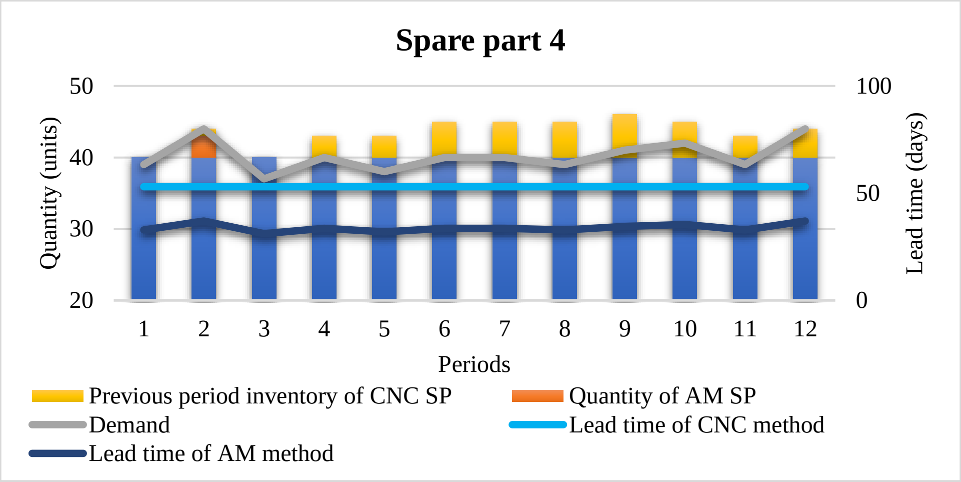
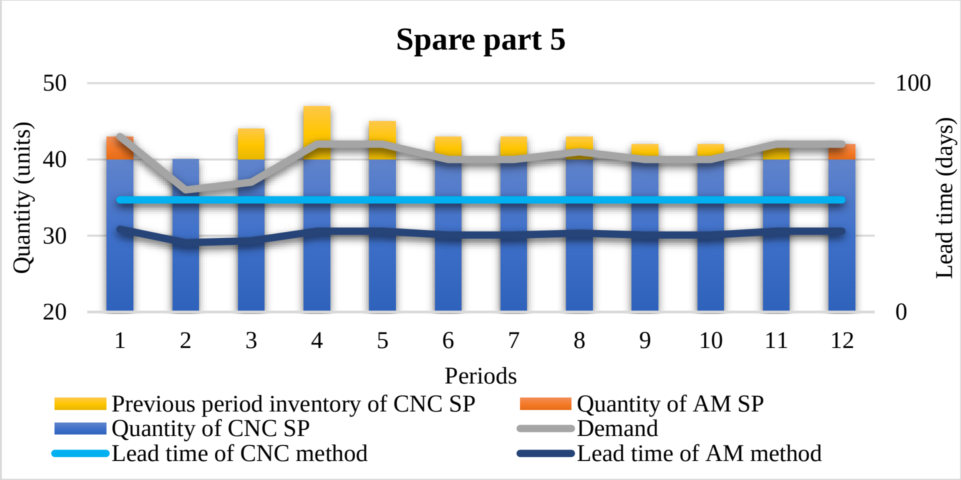
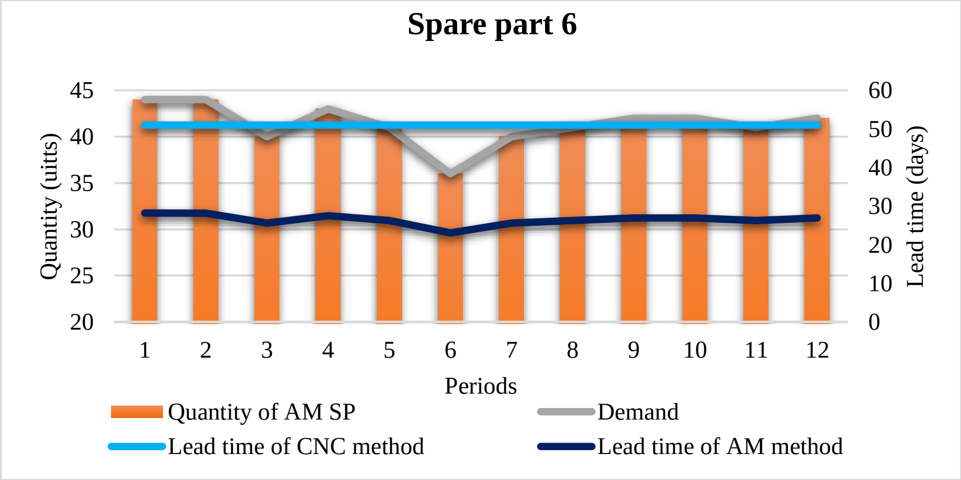

Spare part 4
Quantity (units)
50
40
30
20
100
50
0
Lead time (days)
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC SP
Quantity of AM SP
Demand
Lead time of CNC method
Lead time of AM method

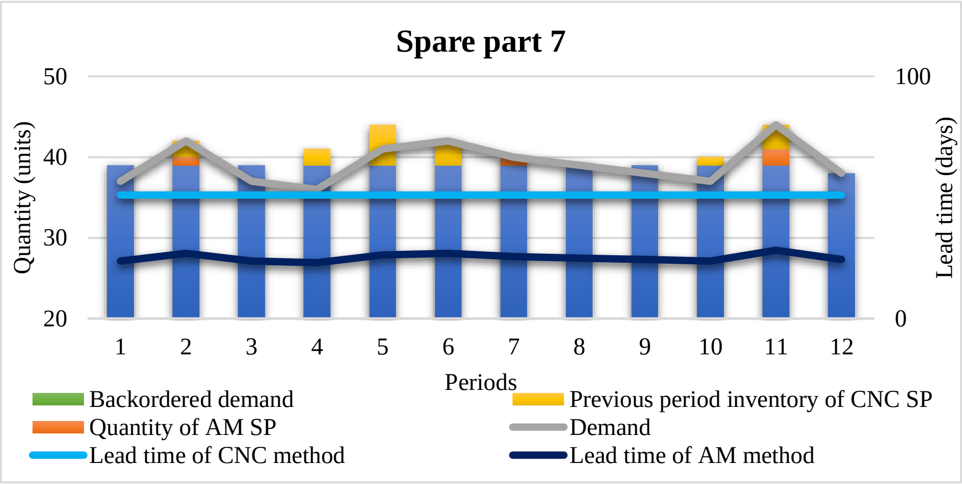
(d)


Spare part 5
Quantity (units)
50
40
30
20
100
0
Lead time (days)
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC SP
Quantity of AM SP
Quantity of CNC SP
Demand
Lead time of CNC method
Lead time of AM method

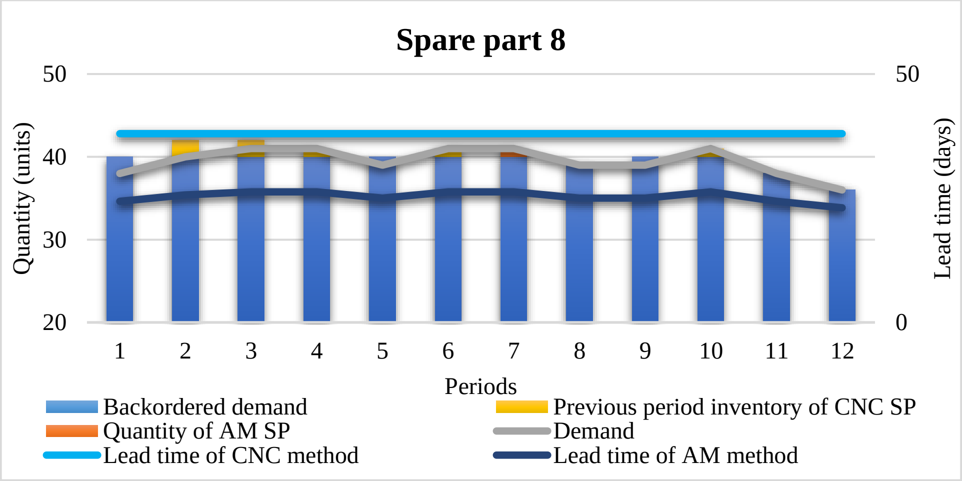
(e)


Spare part 6
Quantity (uitts)
45
40
35
30
25
20
60
50
40
30
20
10
0
Lead time (days)
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Quantity of AM SP
Demand
Lead time of CNC method
Lead time of AM method

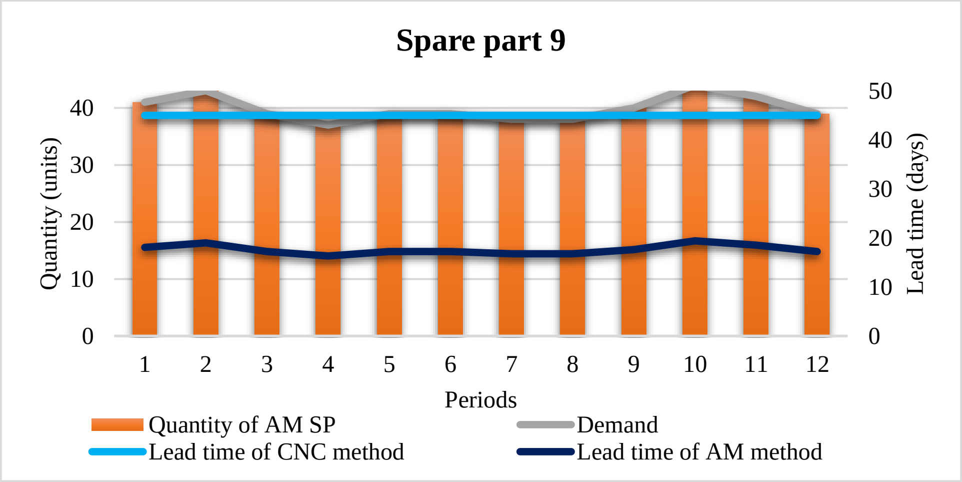
(f)



(g)



(h)



(i)

Figure 4.3 Decision variable outcome of all spare part types

- **Results of spare parts 1, 2 and 3**

For the spare part of type 1 according to Figure 4.3 a) it can be observed that the lead time to source it by CNC is always shorter than the lead time of AM method. The maximum supplier capacity to supply spare part 1 is 40 units.

In the first period, when demand was 39 units, 40 units were ordered, and the extra unit was stored in the warehouse.

In the second period, the demand was quite higher than in period 1 where it was 43 units so 40 units were sourced from the CNC supplier, 1 unit was already stored in the warehouse from the previous period and the last unit was printed with AM, so the demand was satisfied.

In the third period, the demand has decreased to 38 units. The ordered quantity from the CNC supplier was 40 units hence 2 units were stored in the warehouse.

In the fourth period, the demand was 40 units so 40 units exactly were ordered from the CNC supplier therefore the demand was satisfied.

In the fifth period, demand has increased to 43 units, so 40 units were ordered from the CNC supplier, 2 units were already stored in the warehouse from the third period, and the last unit was printed with AM in order to satisfy the demand.

In the sixth period, the demand went down to 42 units, however, it was not satisfied and there was a backordered demand of 1 unit in that period. The model has chosen to backorder this unit since the backorder cost 4,000 USD/backordered unit, while the lead time penalty of this part is 6,809 USD/unit of lead time. Besides that, the cost of purchasing AM raw materials is already high with a rate of 147 USD/kg of metal powder. Consequently, it is more economical to backorder that part and satisfies its demand in the coming periods.

In the seventh period, the demand for spare part 1 was 40 units which is exactly equivalent to the ordered quantity.

In the eighth and ninth periods, the ordered quantity of spare part 1 was 40 units while the demand in both periods was 39 units. The extra ordered unit in period 8 was used to satisfy the backordered demand in period 6. However, the stored unit in period 9 was used in period 10 to satisfy the 41 units' demand. For periods 11 and 12, the ordered quantities were exactly equivalent to the demand in order to have zero inventory at the end of the planning horizon as per the set constraint in the model formulation.

For spare parts type 2 and type, we can observe that the demand of spare parts 2 and 3 are satisfied with CNC in mainly. The behavior of spare parts 2 and 3 in terms of quantities, backorder, and inventory are similar to spare part type 1.

- **Results of spare parts 4, 5 and 6**

For spare part 4, it is shorter to print the demanded quantities in every period instead of waiting for the CNC shipment which will take 53 days. However, the production cost of spare part 4 with AM costs 1,081 USD while purchasing it with CNC is much cheaper with a price of 715 USD/ part. Also, the purchase price of raw materials is already high. Therefore, since the main objective of the model is to minimize the total costs, the main selected manufacturing method for spare part 4 is CNC.

The maximum units of spare parts 4 that the CNC supplier can source is 40 units. The demand for spare part 4 fluctuates to reach values of 42 and 43 units. That is why we can observe from periods 4 to 11 that the system is storing CNC parts in order to satisfy the demand for the whole planning horizon. The exceptional period is the second period where 1 unit of AM was produced and delivered to the system to satisfy the demand.

We can conclude that it is much costly to produce spare part 4 with AM, this is why the model is storing CNC parts in the warehouse and uses them in coming periods to meet the demand.

For spare part 5, the lead time required to source it from the CNC supplier is 49 days while producing the demanded units with AM will always be shorter than CNC. The production cost of spare part 5 with AM costs 997 USD meanwhile purchasing it from the CNC supplier costs 836 USD. We can conclude that the high cost associated with producing AM spare parts, and raw material purchase cost lets the model decides to order CNC-based spare parts which cost less than AM ones although they take longer lead times.

The proposed manufacturing method of spare part 6 is AM during all periods of the planning horizon. First of all, the production cost of spare part 6 with AM (463 USD) is much less than ordering it from the CNC supplier (1,562 USD). This is because spare part 6 has a high geometry complexity level thus its production cost with CNC is high. Secondly, the lead time of AM-based spare parts is much shorter than CNC-based spare part shipment arrival. Therefore, it is more cost and more time-saving to manufacture spare part 6 with AM rather than sourcing it from the CNC supplier.

- **Results of spare parts 7, 8 and 9**

For spare part 7, the lead time to print the demand in each period is always less than the CNC supplier lead time. Also, the cost to print spare part 7 with AM is less than its purchase price with the CNC method. Despite that AM method seems to offer the least lead time and least production cost, the model still decides to source spare part 7 through the CNC supplier.

The behavior of spare part 8 is similar to the behavior of spare part 7. The lead time and costs of AM are less compared to CNC ones, but the selected manufacturing method is CNC.

The cost of CNC purchase price of spare part 9 is extremely higher than its production with AM with values of 1,034 USD and 142 USD respectively. Furthermore, the lead time to print spare part 9 with AM is considered short compared to other parts. For these reasons, the selected manufacturing method for spare part 9 is AM for all periods throughout the planning horizon.

In summary, AM is more feasible to produce spare parts with high geometry complexity and small to medium spare part sizes offering shorter lead time. Whereas CNC-based manufacturing is cost-effective for large-sized spare parts having low and medium geometry complexity.

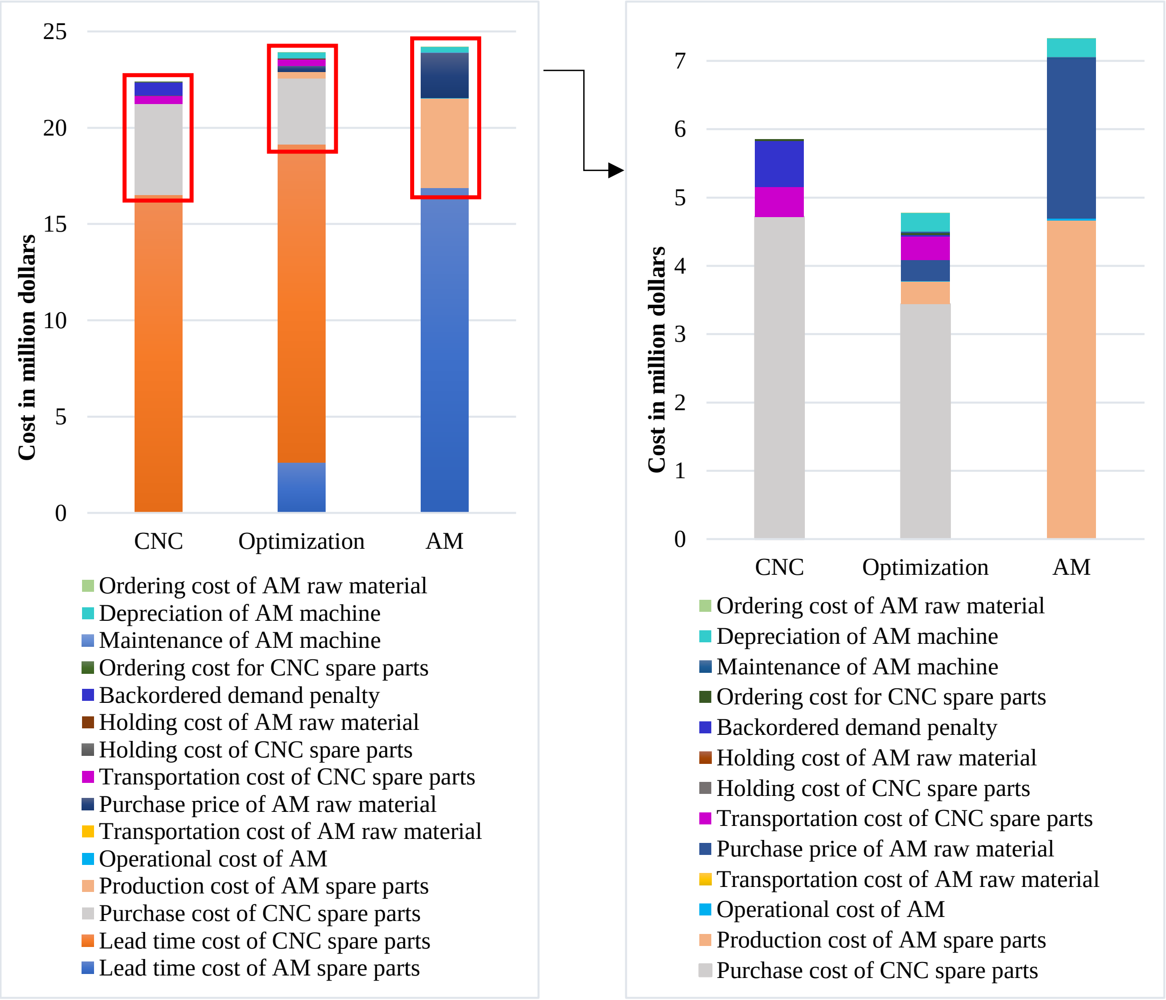
4.1.2 Model performance evaluation

In order to test the performance of the model, a similar model formulation was implemented with the same dataset used in the base case model for two case scenarios: satisfying all the demand by one manufacturing method, AM only, and CNC only. Table 4.3 shows the number of variables, constraints, iterations, and solving time of the mixed integer linear programming model. The CNC-only case scenario has the least cost since CNC-based spare parts are cheaper than AM ones and have moderately long lead times. In contrast, AM has the highest total system cost because of the high costs associated with raw material purchasing, and the production cost of AM-based spare parts.

Table 4.3 Characteristics of different case scenarios

Case Scenario	Variables no.	Constraints no.	Iterations	CPU time (s)	Total cost ($)
Optimization	1026	1476	24	0.03	23,910,362
AM only	675	936	31	0.05	24,200,239
CNC only	576	1134	18	0.05	22,375,443

Figure 4.4 a) and b) show the cost breakdown for the three case scenarios when including and excluding the costs of lead time penalty, respectively. For the CNC-based scenario, there is an associated cost of the backordered demand, as when the system is not able to satisfy the demand with the available supplier capacity, it backorders the unsatisfied demand. Regarding the AM-based case, the significant cost of purchasing AM raw materials and printing the spare parts is observed. There are also some costs associated with the depreciation of AM machines. In the proposed optimization case, the large cost items which are presented in CNC and AM scenarios, are rather minimized and compromised denoting that the proposed model finds a trade-off between the long lead time and cheap CNC method and the shorter lead time and expensive AM technology.



(a) (b)

Figure 4.4 Total cost comparison a) including costs of lead time b) excluding the cost of lead time

4.2 Scenario Analysis

Scenario analysis is conducted for a set of model parameters in order to test the performance and robustness of the base case model. These parameters include spare parts demand, lead time of CNC-based spare parts delivery from the supplier, and lead time of AM raw material delivery where they will be variated from their nominal value by a specified range. Scenario analysis will illustrate how the change of parameters affects the outcome of model decision variables and how AM and CNC spare parts quantities react to this variation.

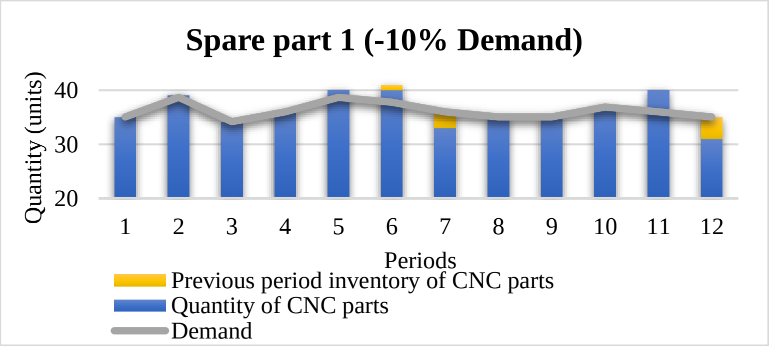
4.2.1 Demand scenario analysis

Scenario analysis is performed for the demand parameter where it is changed by ±10% while keeping the rest of the parameters at their original values. In a factory working environment, demand usually fluctuates within the proposed range of ± 10%.

- **Decision variables analysis**

The quantity analysis of spare part 1 and spare part 6 are demonstrated in the main text. The rest of the spare part types have been placed in Appendix B[3].

Figure 4.5 and Figure 4.6 show the quantity of AM-produced spare parts and CNC-based sourced spare parts used to satisfy the demand when it is variated by ± 10% for spare part 1 and spare part 6 respectively.



(a)

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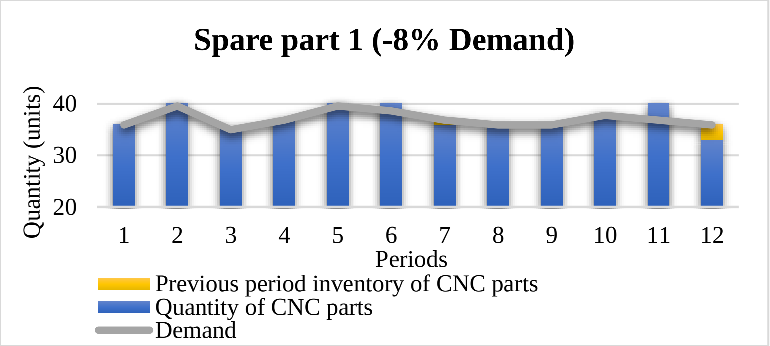
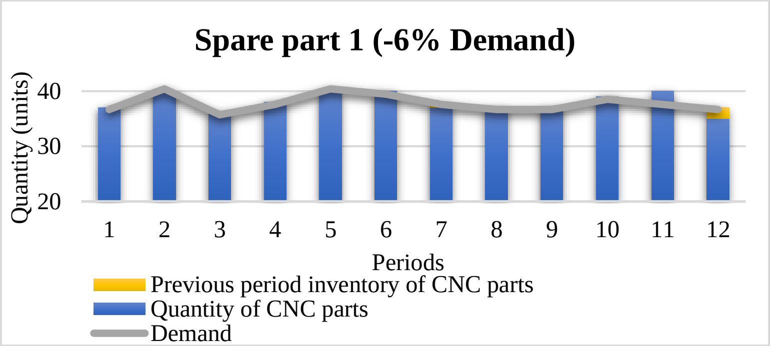
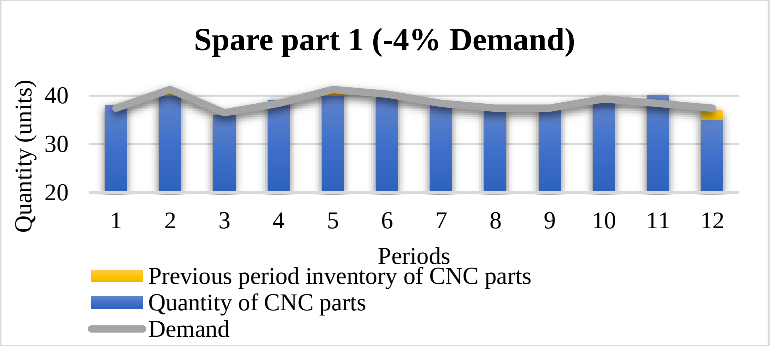
[3] Appendix B is available online


Spare part 1 (-8% Demand)
Quantity (units)
40
30
20
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC parts
Quantity of CNC parts
Demand

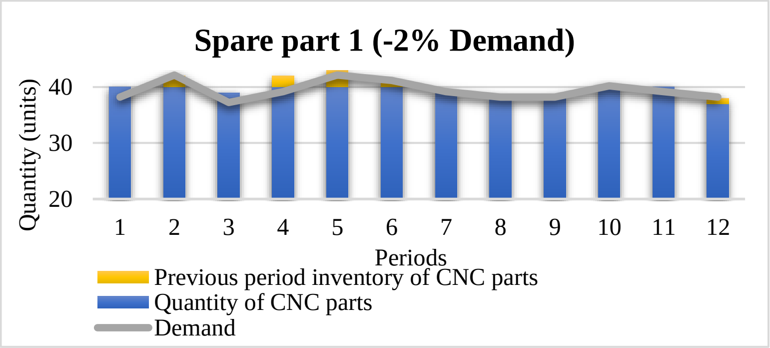
(b)


Spare part 1 (-6% Demand)
Quantity (units)
40
30
20
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC parts
Quantity of CNC parts
Demand

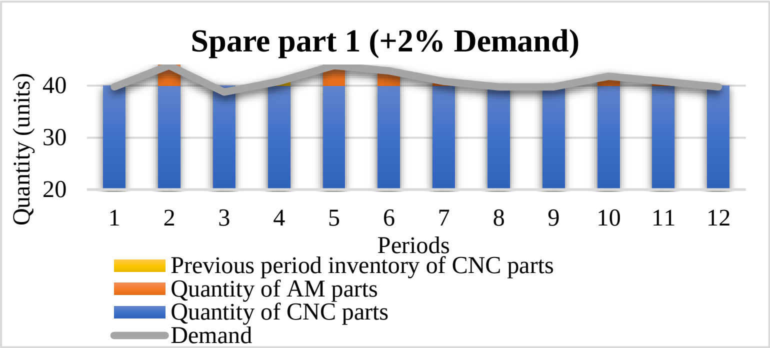
(c)


Spare part 1 (-4% Demand)
Quantity (units)
40
30
20
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC parts
Quantity of CNC parts
Demand

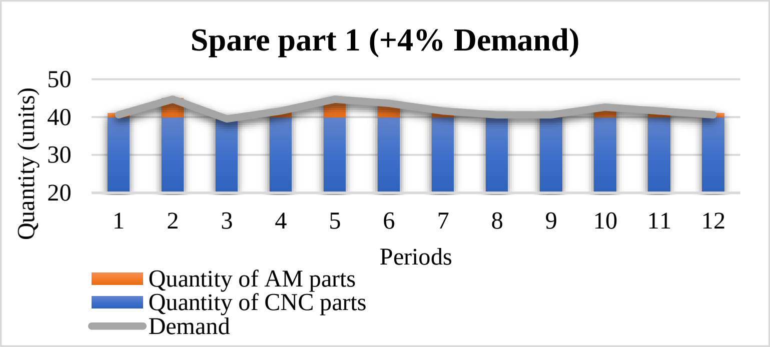
(d)


Spare part 1 (-2% Demand)
Quantity (units)
40
30
20
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC parts
Quantity of CNC parts
Demand

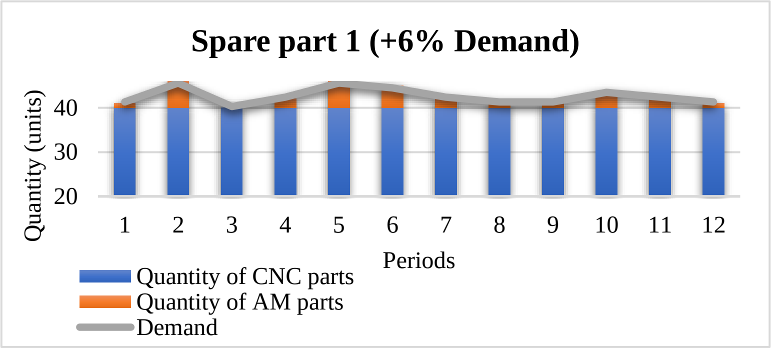
(e)


Spare part 1 (+2% Demand)
Quantity (units)
40
30
20
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC parts
Quantity of AM parts
Quantity of CNC parts
Demand

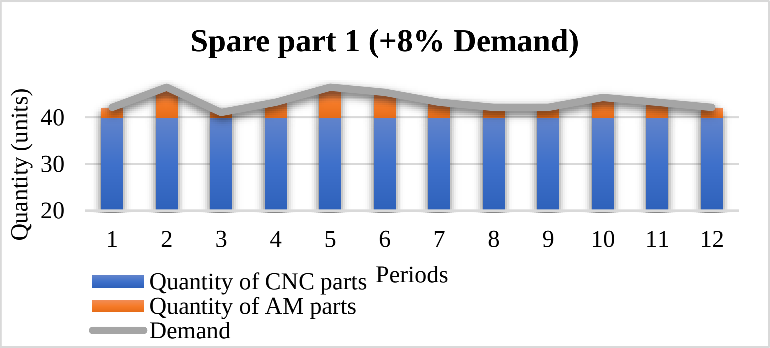
(f)


Spare part 1 (+4% Demand)
Quantity (units)
50
40
30
20
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Quantity of AM parts
Quantity of CNC parts
Demand

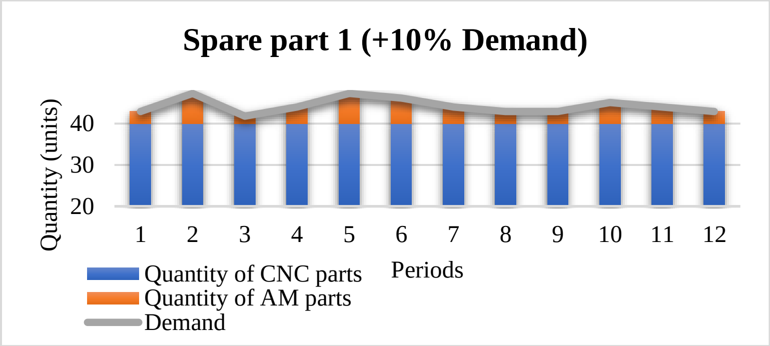
(g)


Spare part 1 (+6% Demand)
Quantity (units)
40
30
20
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Quantity of CNC parts
Quantity of AM parts
Demand

(h)

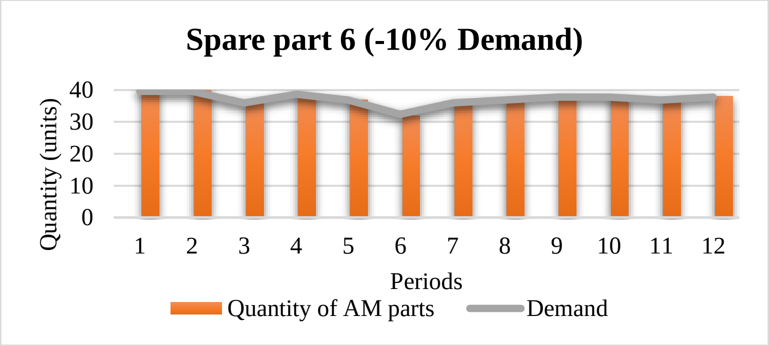

Spare part 1 (+8% Demand)
Quantity (units)
40
30
20
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Quantity of CNC parts
Quantity of AM parts
Demand

(i)

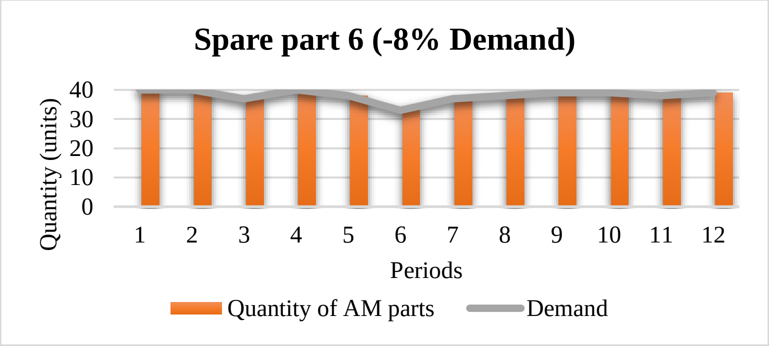


(j)

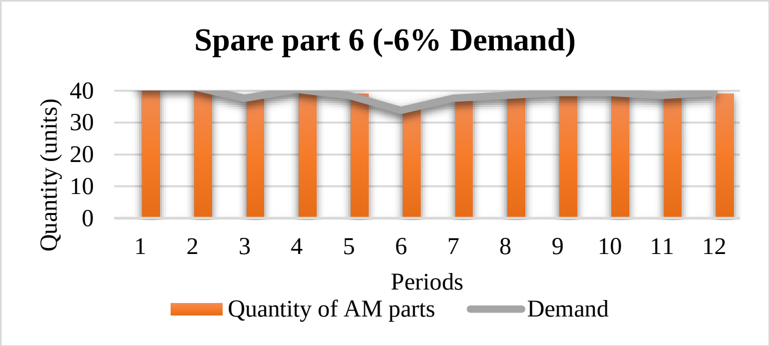
Figure 4.5 Quantity of spare part 1 when variating the demand by ± 2%, ±4%, ±6%, ±8%, ±10%.



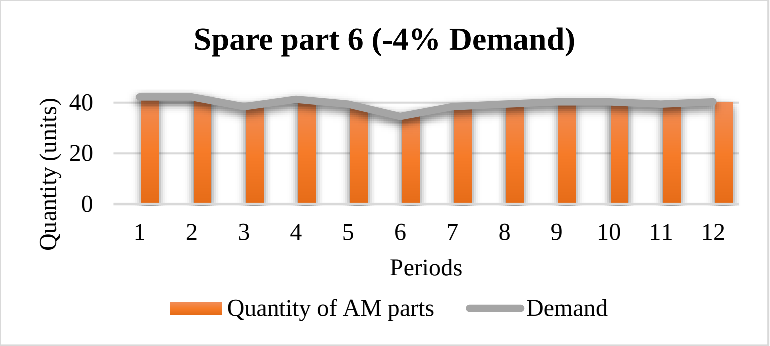
(a)



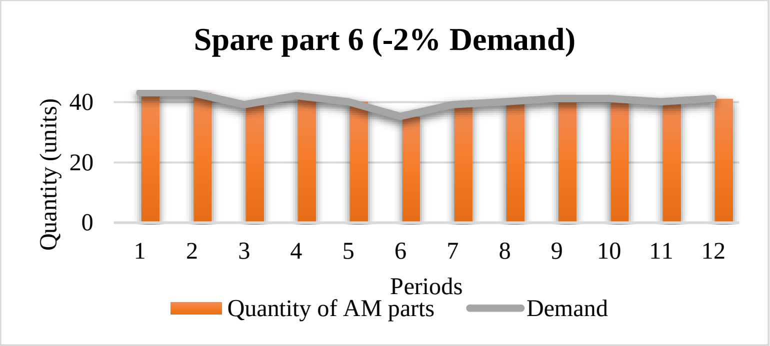
(b)


Spare part 6 (-6% Demand)
Quantity (units)
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Quantity of AM parts
Demand

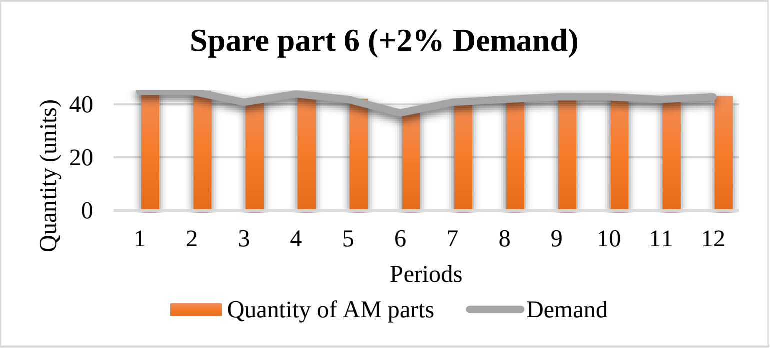
(c)


Spare part 6 (-4% Demand)
Quantity (units)
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Quantity of AM parts
Demand

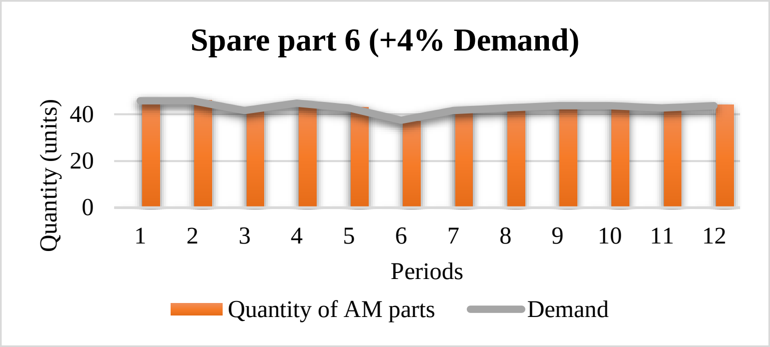
(d)


Spare part 6 (-2% Demand)
Quantity (units)
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Quantity of AM parts
Demand

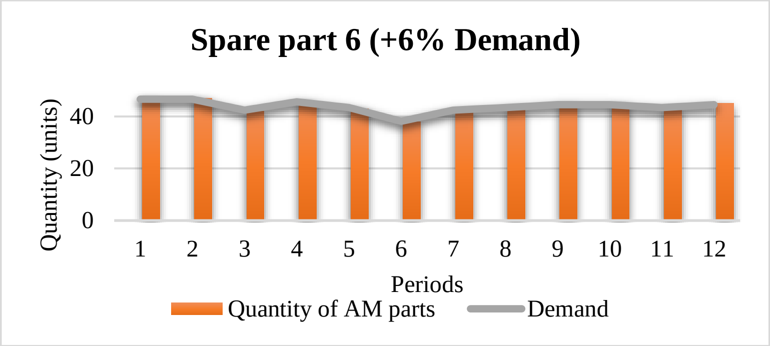
(e)


Spare part 6 (+2% Demand)
Quantity (units)
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Quantity of AM parts
Demand

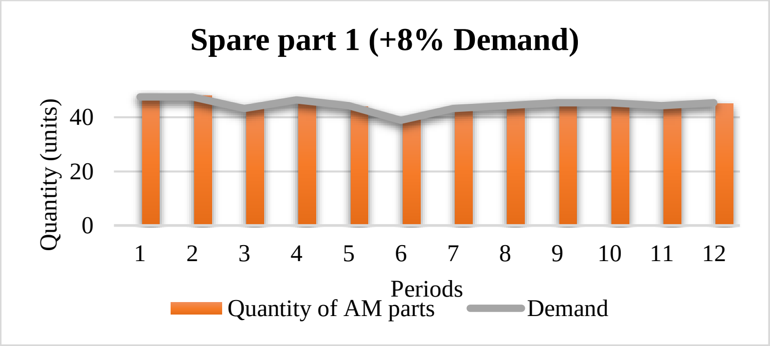
(f)



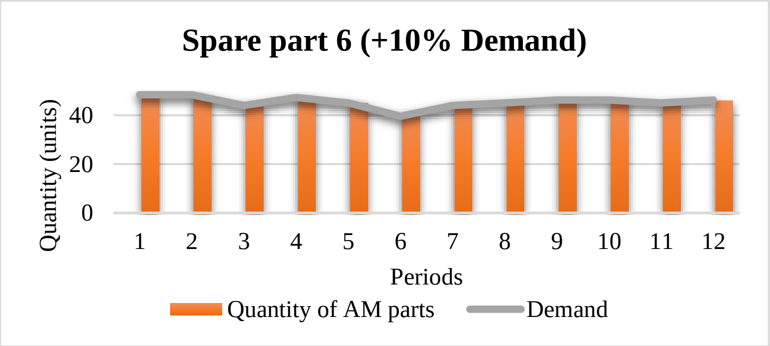
(g)



(h)



(i)



(j)

Figure 4.6. Quantity of spare part 6 when varying the demand by ± 2%, ±4%, ±6%, ±8%, ±10%.

For spare part 1, as observed previously in (demand is at its nominal value), when demand could not be satisfied with CNC-based spare parts, the model uses AM-printed spare parts to satisfy the demand. In the case when demand is decreased, the model is able to source all spare parts through a CNC supplier. In contrast, when the demand is increased, we can notice that the model decides to print more AM-based spare parts along with the ordered CNC-based spare parts in order to meet the demand. The maximum supplier capacity to source spare part 1 is 40 units, so the model decides to order the 40 units from the CNC supplier and produces the rest of the spare parts with AM. Therefore, spare part 1 is sensitive to demand changes.

The behavior of spare part 6 remains unchanged in all cases whether demand is decreased or increased. All the demand of spare part 6 is met through AM throughout the twelve periods. Since the lead time to print the demand of 48 units will require 29 days which is shorter than waiting for the CNC spare parts shipment (51 days), and the cost to produce spare part 6 with AM is less than purchasing it through CNC, it is cost-effective to produce spare part 6 with AM. Thus, spare part 6 is insensitive to any changes in demand. Spare part 9 exhibits similar behavior to spare part 6, and spare parts 2,3,4,5,7, and 8 have similar behavior to spare part 1 and they are attached in appendix 1.

- **Cost analysis**

The total cost of the base case model changes with the change in demand. Table 4.4 illustrates the change in the total cost of the base case, CNC, and AM scenarios subject to demand change. The decrease in demand affects the total cost by 3%, meanwhile, the increase in demand increases the total cost by 10%. This increase is explained by the increase in the production cost of AM-based spare parts and the high purchase cost of raw materials since we are depending on AM to fulfill the demand. When the demand is decreased by 10%, the total cost of AM case is decreased by 9% whereas in the proposed optimization case the total cost decreased by 3%. This concludes that AM is more cost-effective for low-demand volumes. The change in the total cost in the AM case is linearly proportional to the change in the demand. In the CNC case, the decrease of the demand is linear with the change in cost but when demand is increased, the cost of the system increases exponentially. This drastic is due to the increase in the penalty of backordered demand as the system has ordered the maximum limit of spare parts of CNC supplier capacity so when demand increases, the system starts to backorder the demand which it cannot satisfy. Figure 4.7 show the change in the total CNC costs and total AM costs of the base case model subject to demand change where the grey area represents the total system cost. Although the range of the demand variation is assumed to be ±10% in our study, in order to examine and emphasize the difference between CNC and AM costs, the range of demand change was assumed to be wider (-60% to +60%) where a similar demand change range between 50% to 150% has been presented in the literature (Emelogu et al., 2016). In Figure 4.7, we can observe that when the demand increases, the CNC costs increase till they become constant while the AM-related costs always increase with the increase in demand. This is because when the demand gets higher, the system sources a maximum capacity of CNC-based spare parts and depends on AM to be able to satisfy the demand. The break-even point where the costs of AM and CNC are equivalent is when the demand change is approximately 1.4 (increased by +40%). At this particular point, the CNC costs reach a steady state, and AM costs continue on increasing.

Figure 4.8 shows the behavior of the three case scenarios along the demand change. The CNC-based shows a drastic increase when demand increases. This is because the CNC supplier spare parts limit capacity is reached, so the system starts to backorder the demand units which cannot be satisfied. For the proposed optimized system, the total cost did not change significantly when demand increased, however, the total cost of the proposed optimization is still less than the AM-based scenario when demand is high. As observed when demand decreases, the AM option has the least cost demonstrating that AM technology is cost-effective for low-demand volumes.

Table 4.4 Change scenarios subject to demand change

Demand change	Base case total cost ($)	Change in the total cost	CNC case total cost ($)	Change in the total cost	AM case total cost ($)	Change in the total cost
-10%	23,263,117	-3%	21,199,244	-5%	22,007,085	-9%
-8%	23,378,803	-2%	21,322,593	-5%	22,542,802	-7%
-6%	23,476,936	-2%	21,427,406	-4%	22,991,116	-5%
-4%	23,522,268	-2%	21,489,302	-4%	23,162,342	-4%
-2%	23,638,211	-1%	21,662,846	-3%	23,651,950	-2%
0	23,910,362	0%	22,375,443	0%	24,200,239	0%
2%	24,389,457	2%	24,884,783	11%	24,748,527	2%
4%	24,865,933	4%	27,300,708	22%	25,238,135	4%
6%	25,006,426	5%	28,104,696	26%	25,398,724	5%
8%	25,460,437	6%	30,644,696	37%	25,857,675	7%
10%	25,995,585	9%	33,292,696	49%	26,393,392	9%

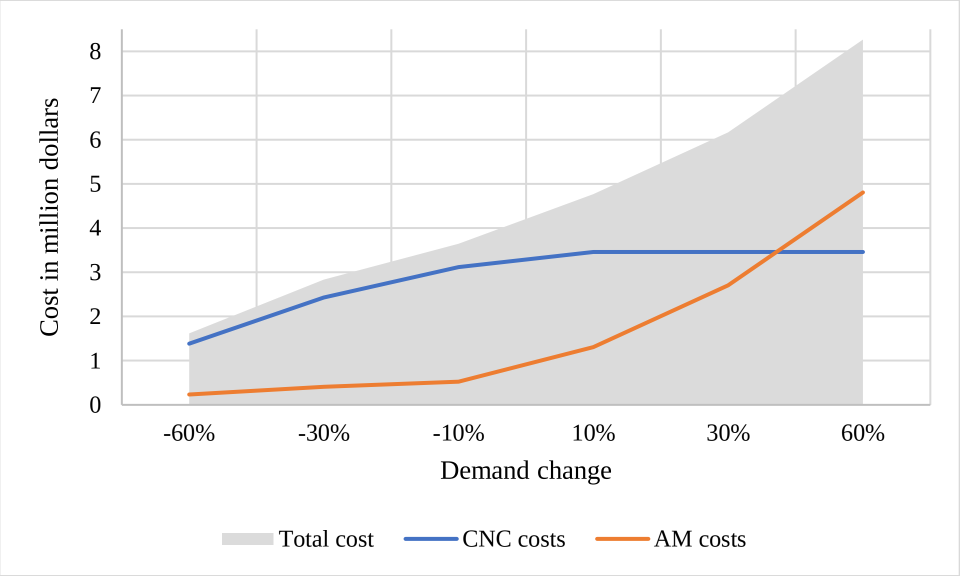


Figure 4.7 CNC costs and AM costs subject to demand change of base case scenario including all parts

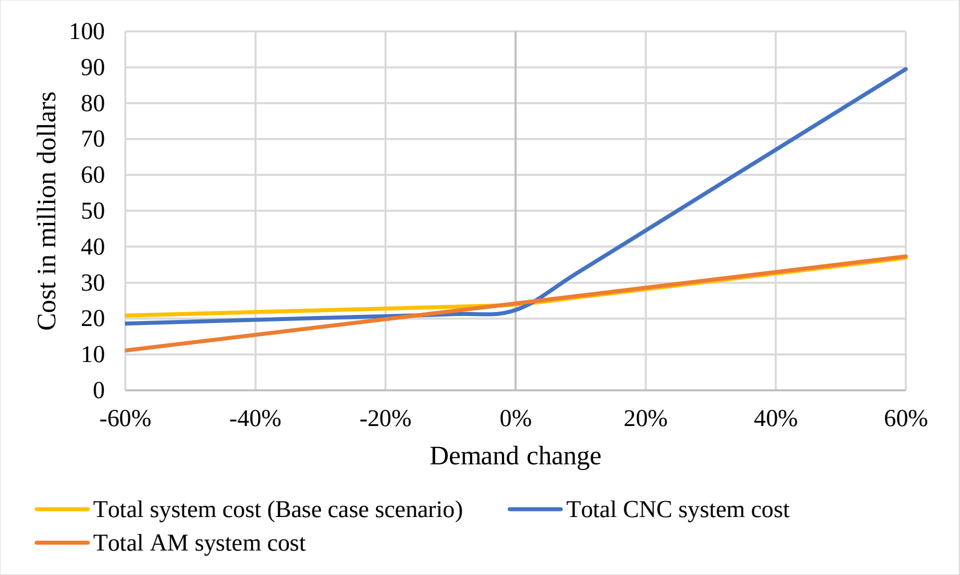


Figure 4.8 Total costs of three scenarios subject to demand change

4.2.2 Lead time scenario analysis

Scenario analysis is conducted for the lead time parameter for a range from -20% to +20% based on a factory working environment.

4.2.2.1 Lead time of CNC

Each spare part has a guaranteed lead time to be delivered from the supplier. The scenario analysis will be done for all lead times of the nine parts.

- **Decision variables analysis**

Figure 4.9 show the decision variable outcomes of spare part 1 when the CNC lead time of the CNC supplier is changed from -20% to +20%. It is observed that when the CNC lead time is decreased, the lead time of AM exceeds the CNC lead time, however, when the CNC lead time is increased, it starts reaching AM lead time till it exceeds in the +20% case. In all these changes, the quantities of spare part 1 in terms of AM, CNC quantities, and backorder remained unchanged. Although the lead time is an important factor to decide on the manufacturing method, there are some other associated costs with AM such as the purchase price of raw materials and the AM machine depreciation expense which affects the decision-making process.

The decision variable outcomes for spare part 6 are shown in Figure 4.10. When the lead time of the CNC supplier changes between -20% to +20%, the AM lead time is always less than the CNC one. Thus, we can conclude that spare part 6 is insensitive to any changes in the CNC supplier lead time for the [-20%, +20%] range. The rest of the spare parts decision variables outcomes are listed in Appendix C[4].

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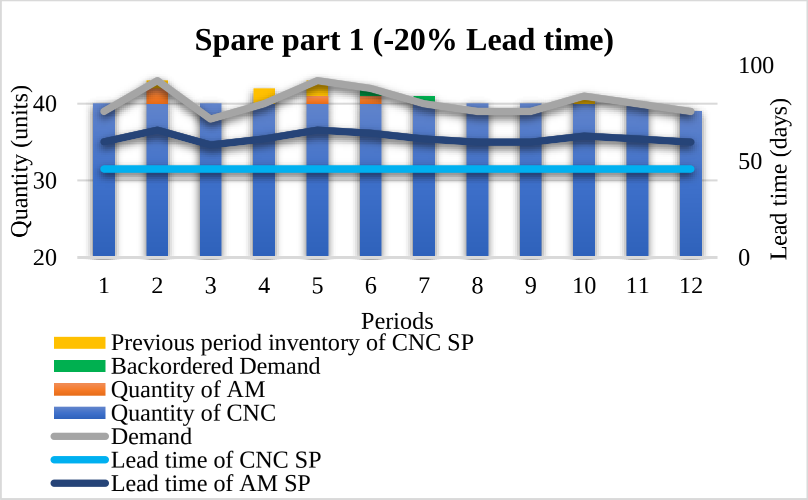
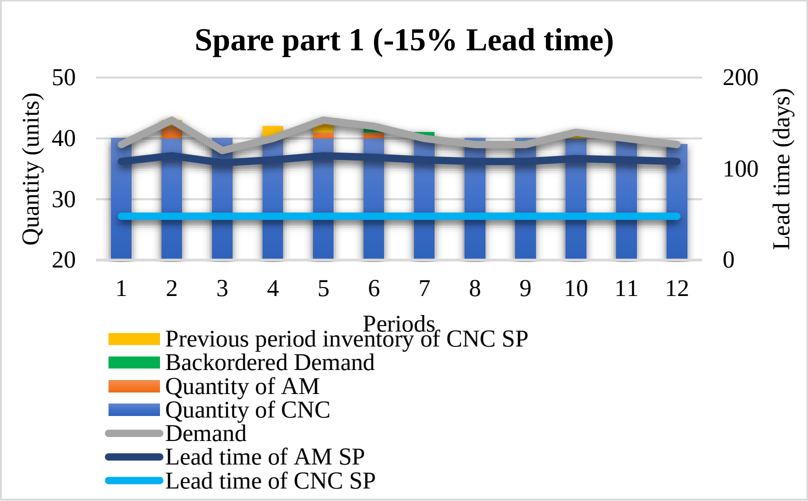
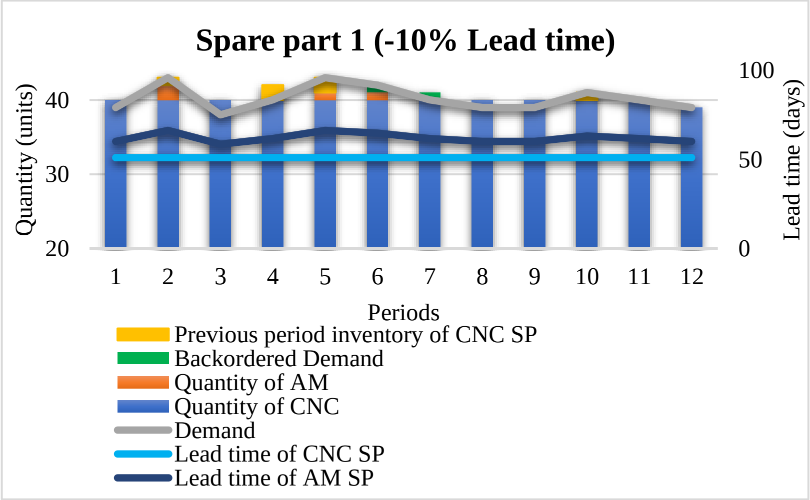
[4] Appendix C is available online


Spare part 1 (-20% Lead time)
Quantity (units)
Lead time (days)
20
30
40
0
50
100
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC SP
Backordered Demand
Quantity of AM
Quantity of CNC
Demand
Lead time of CNC SP
Lead time of AM SP

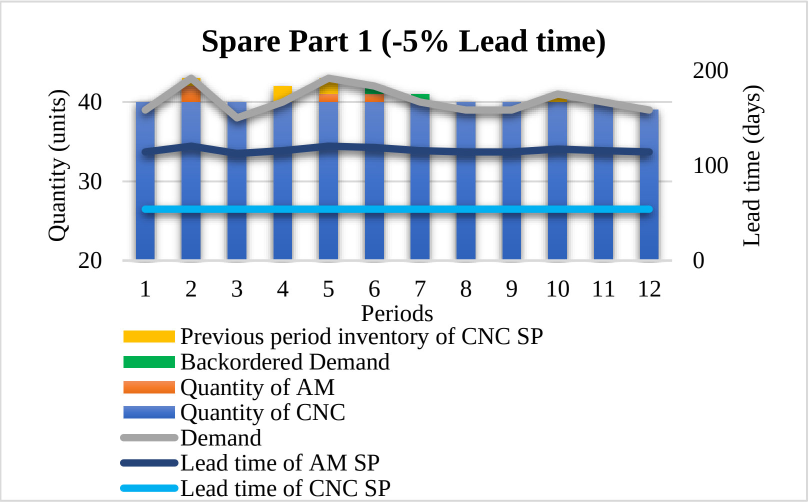
(a)


Spare part 1 (-15% Lead time)
Quantity (units)
Lead time (days)
20
30
40
50
0
100
200
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC SP
Backordered Demand
Quantity of AM
Quantity of CNC
Demand
Lead time of AM SP
Lead time of CNC SP

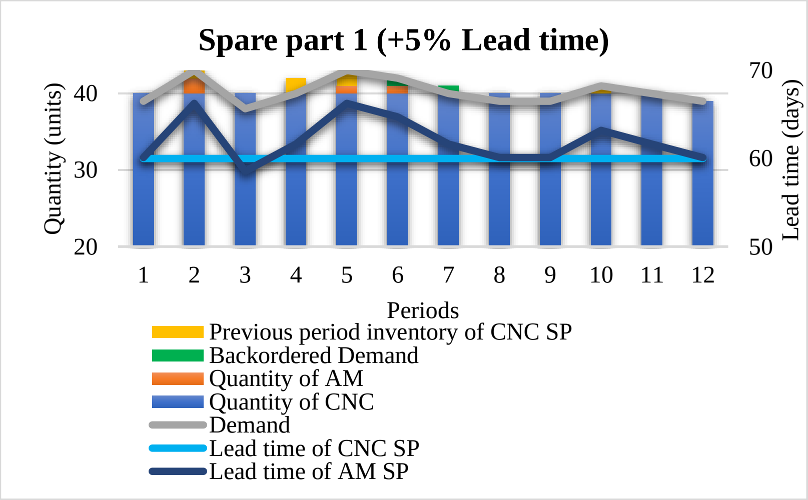
(b)


Spare part 1 (-10% Lead time)
Quantity (units)
Lead time (days)
20
30
40
0
50
100
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC SP
Backordered Demand
Quantity of AM
Quantity of CNC
Demand
Lead time of CNC SP
Lead time of AM SP

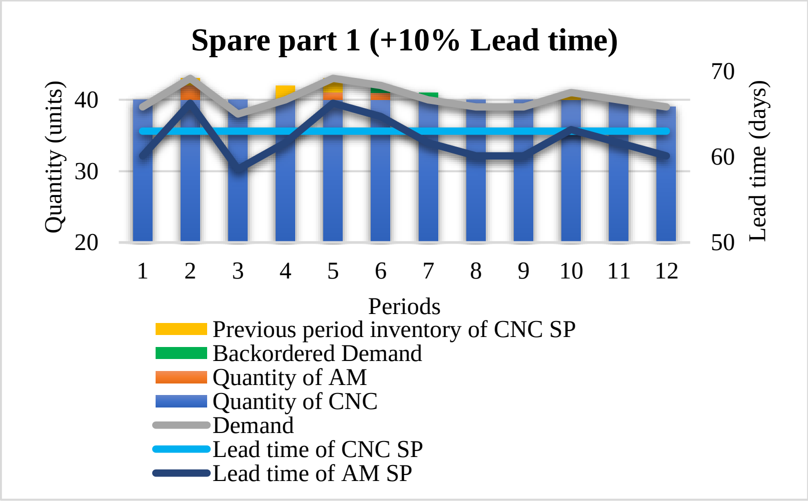
(c)


Spare Part 1 (-5% Lead time)
Quantity (units)
40
30
20
200
100
0
Lead time (days)
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC SP
Backordered Demand
Quantity of AM
Quantity of CNC
Demand
Lead time of AM SP
Lead time of CNC SP

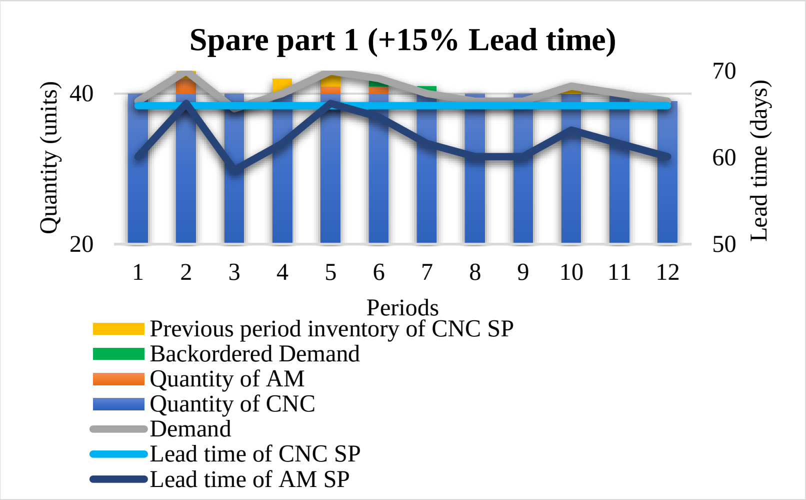
(d)


Spare part 1 (+5% Lead time)
Quantity (units)
40
30
20
70
60
50
Lead time (days)
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC SP
Backordered Demand
Quantity of AM
Quantity of CNC
Demand
Lead time of CNC SP
Lead time of AM SP

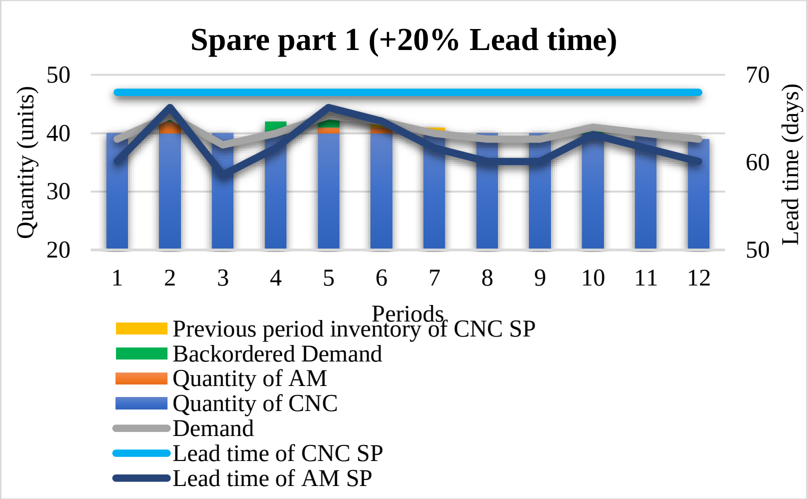
(e)


Spare part 1 (+10% Lead time)
Quantity (units)
40
30
20
70
60
50
Lead time (days)
1
2
3
4
5
6
7
8
9
10
11
12
Periods
Previous period inventory of CNC SP
Backordered Demand
Quantity of AM
Quantity of CNC
Demand
Lead time of CNC SP
Lead time of AM SP

(f)

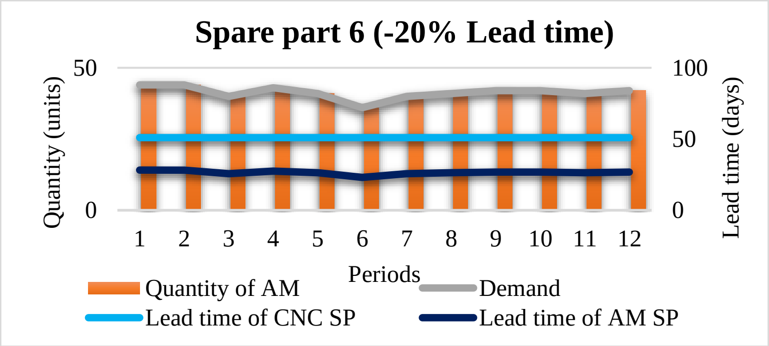


(g)

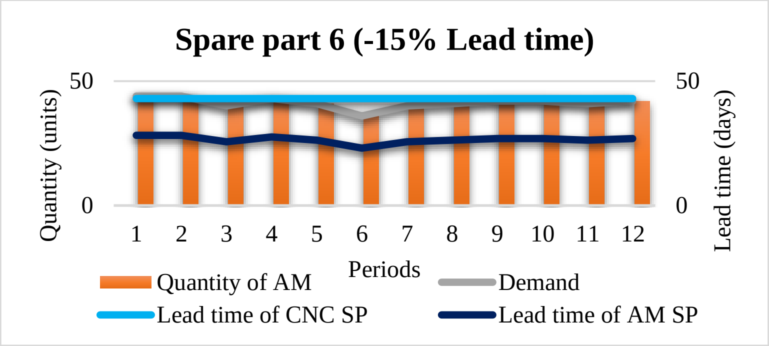


(h)

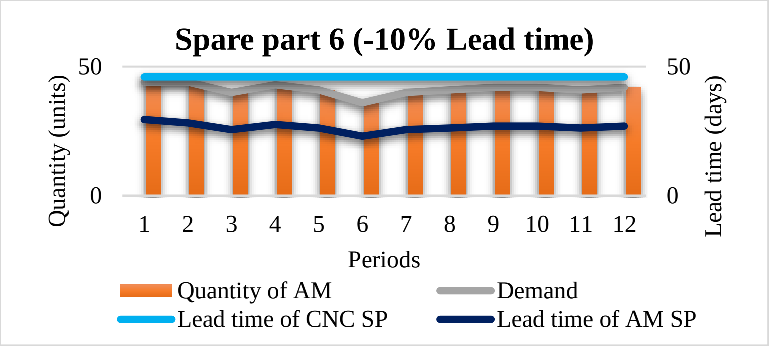
Figure 4.9 Quantity of spare part 1 when varying the lead time by ± 20%.



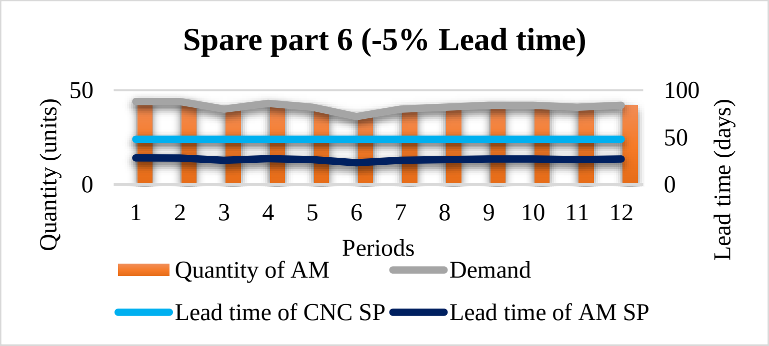
(a)


Spare part 6 (-15% Lead time)
Quantity (units)
50
0
Lead time (days)
50
0
1 2 3 4 5 6 7 8 9 10 11 12
Periods
Quantity of AM
Demand
Lead time of CNC SP
Lead time of AM SP

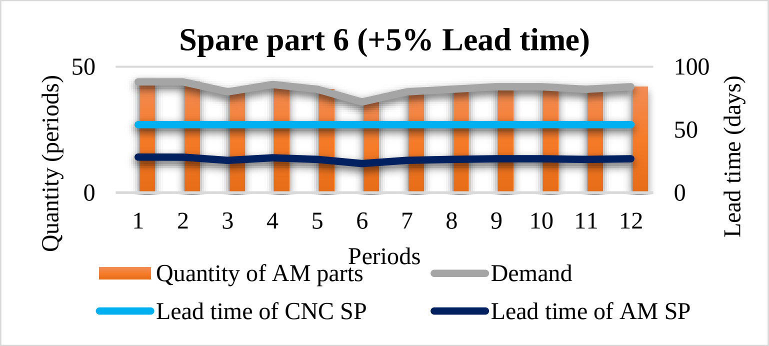
(b)


Spare part 6 (-10% Lead time)
Quantity (units)
50
0
Lead time (days)
50
0
1 2 3 4 5 6 7 8 9 10 11 12
Periods
Quantity of AM
Demand
Lead time of CNC SP
Lead time of AM SP

(c)


Spare part 6 (-5% Lead time)
Quantity (units)
50
0
Lead time (days)
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12
Periods
Quantity of AM
Demand
Lead time of CNC SP
Lead time of AM SP

(d)


Spare part 6 (+5% Lead time)
Quantity (periods)
50
0
Lead time (days)
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12
Periods
Quantity of AM parts
Demand
Lead time of CNC SP
Lead time of AM SP

(e)

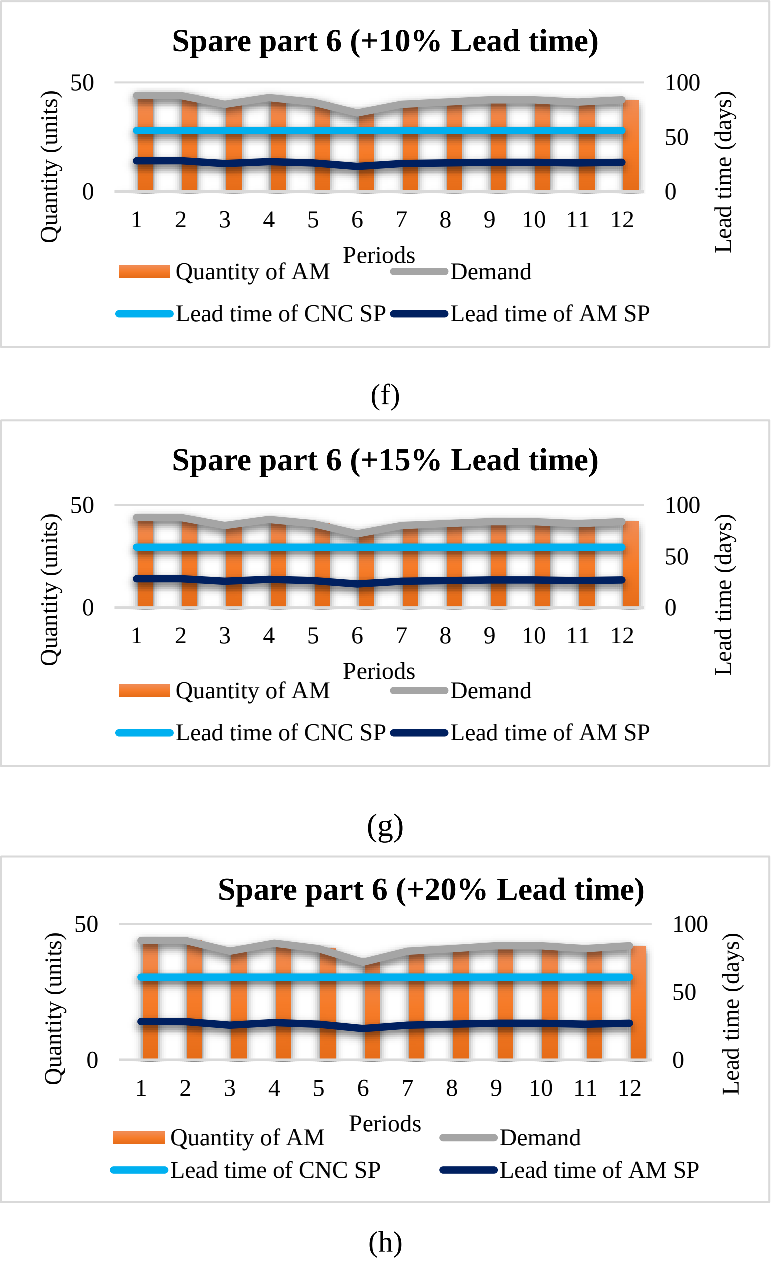


Figure 4.10 Quantity of part 6 when varying the lead time by ± 20%.

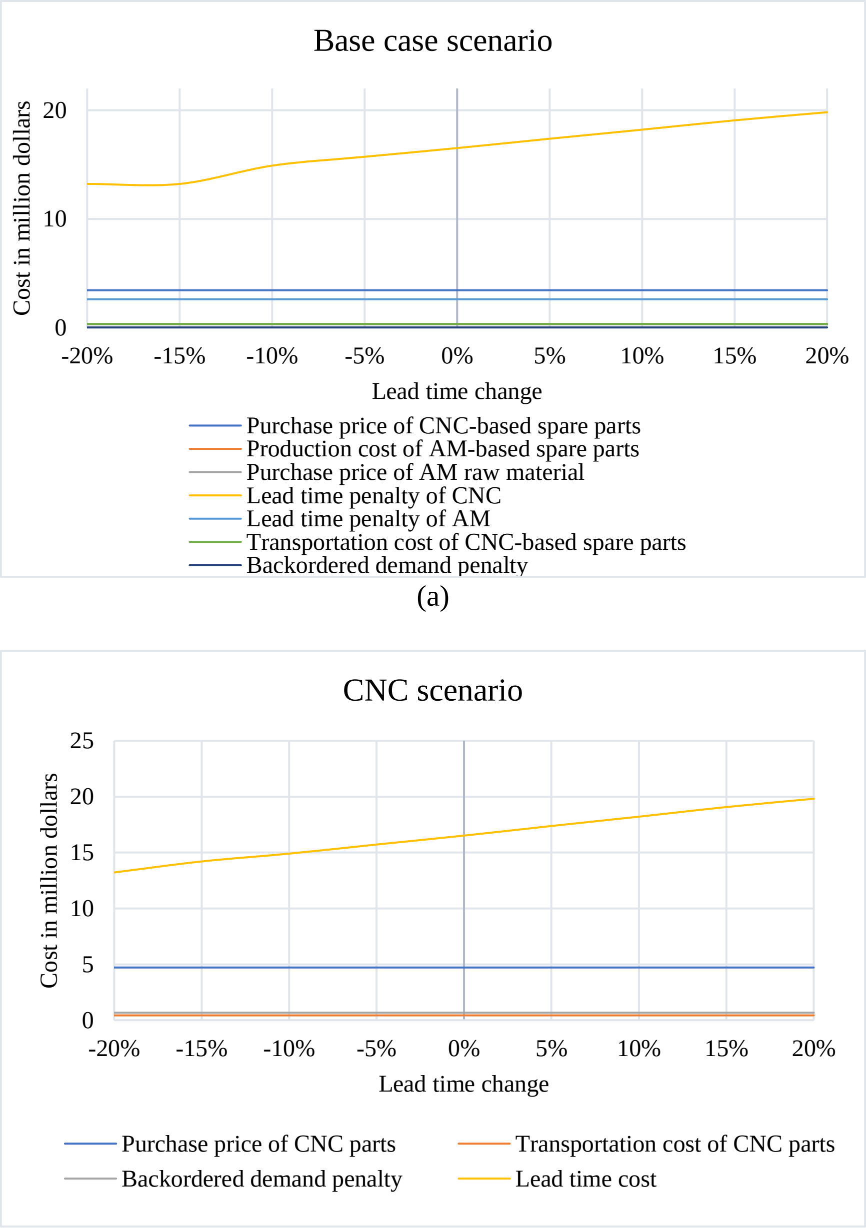
- **Cost analysis**

The change in the total cost of the base scenario and CNC-based scenario are very similar. The changes in total costs of both scenarios are presented in Table 4.5.

Figure 4.11 show the individual cost components of base case and CNC scenarios. We can observe that the penalty cost of lead time is increasing while the other cost components remain unchanged. This is expected since no change has happened in the outcome of the decision variables of spare parts 1 and 6. That is why the increase in total costs is reflected only in the cost of the lead time of the CNC supplier. The increase in the CNC costs for both spare parts is explained by the increase in the lead time cost due to the lead time increase. Thus, we can conclude that spare part 1 and spare part 6 are insensitive to CNC lead time change in the ±20% range.

Table 4.5 Change scenarios subject to CNC lead time change

Lead time change	**Base case total cost ($)**	**Change in the total cost**	**Total CNC system cost ($)**	**Change in the total cost**
-20%	20,614,166	-14%	19,079,247	-14%
-15%	21,417,878	-10%	19,882,959	-10%
-10%	22,295,342	-7%	20,760,423	-7%
-5%	23,110,934	-3%	21,576,015	-3%
0%	23,910,362	0%	22,375,443	0%
5%	24,769,190	4%	23,234,271	4%
10%	25,603,418	7%	24,068,499	7%
15%	26,462,246	11%	24,927,327	11%
20%	27,206,558	14%	25,671,639	14%



(a)

(b)

Figure 4.11 Cost items subject to the lead time change of a) Base case scenario b) CNC only scenario

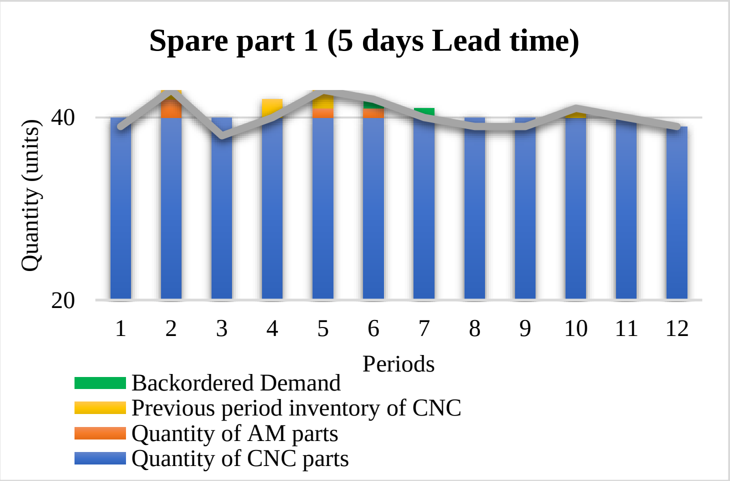
4.2.2.2 Lead time of AM

Scenario analysis is conducted for the raw material delivery lead time of AM. The nominal value of AM lead time in the base case model is 7 days. The outcome of model decision variables will be analyzed when the lead time fluctuates between 5 days and 9 days.

- **Decision variable analysis**

Figure 4.12 shows the decision variable outcomes of spare part 1 when the lead time of AM raw material varies from 5 days to 9 days. Spare parts 1 and 6 are presented in the main text, while the rest of the parts are attached in Appendix D[5]. The behavior of spare part 1 remains unchanged when the lead time of AM raw material delivery changes. This is expected because spare part 1 is sourced mainly from the CNC supplier and it is produced with AM only when demand cannot be satisfied through CNC.

Figure 4.13 illustrates the decision variables outcome of spare part 6 when AM raw material lead time is changing. In fact, the behavior of spare part 6 remains the same when the lead time is changed. Therefore, spare parts 1 and 6 are insensitive to changes in AM lead time raw material for the [-20%, +20%] range.



(a)

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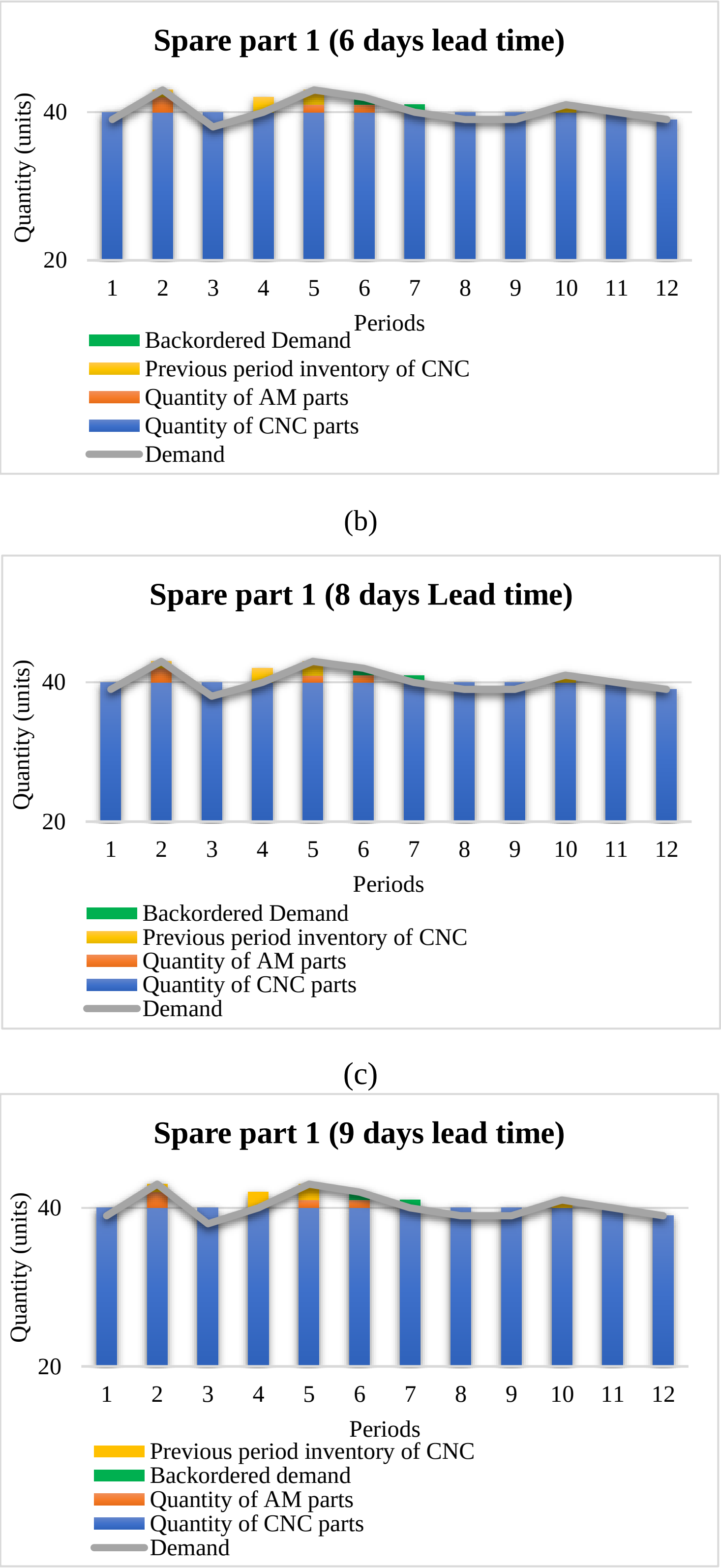
[5] Appendix D is available online

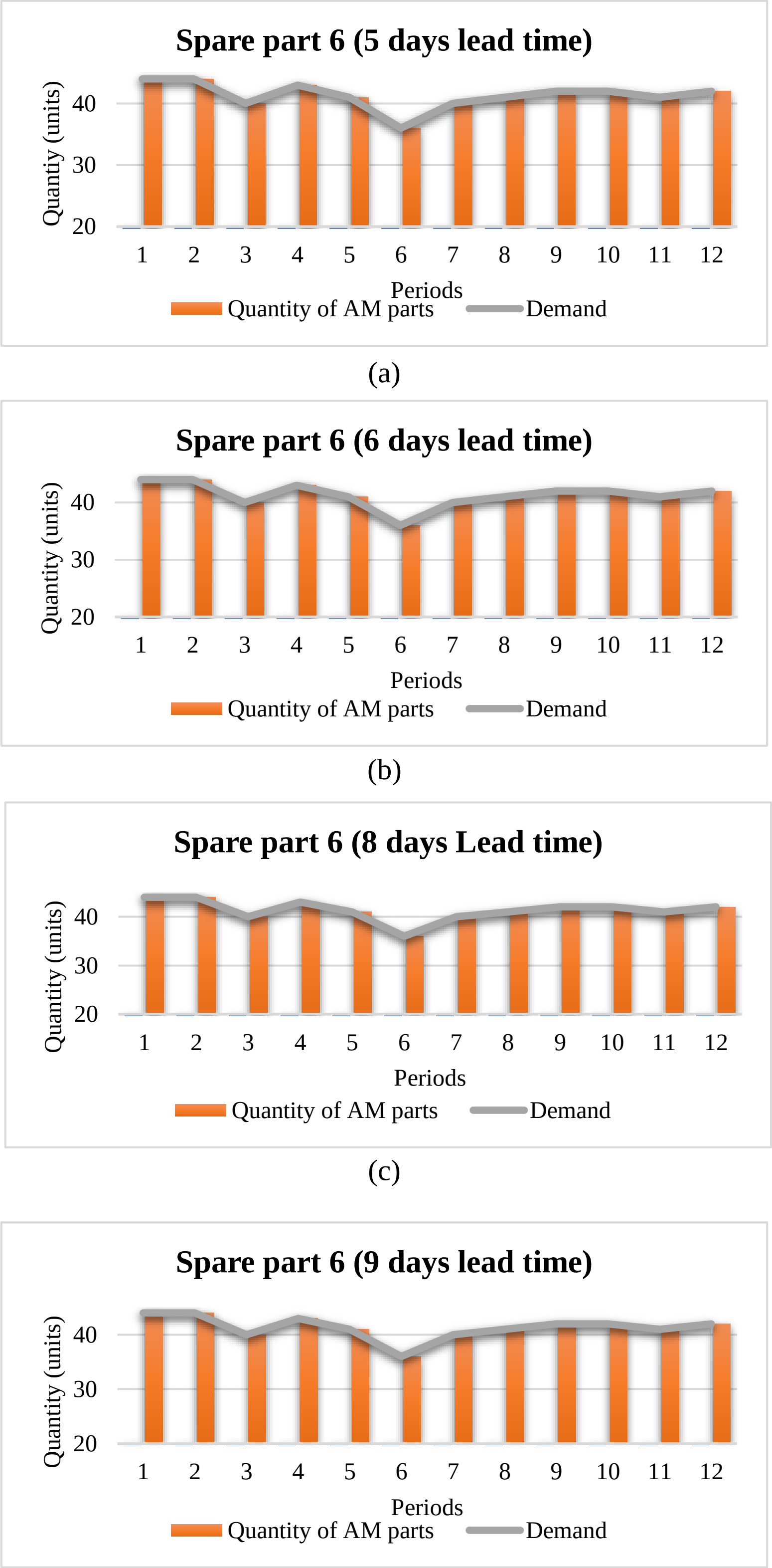


(b)

(c)

(d)

Figure 4.12 Quantity of part 1 when demand varies between 5 and 9 days



(a)

(b)

(c)

(d)

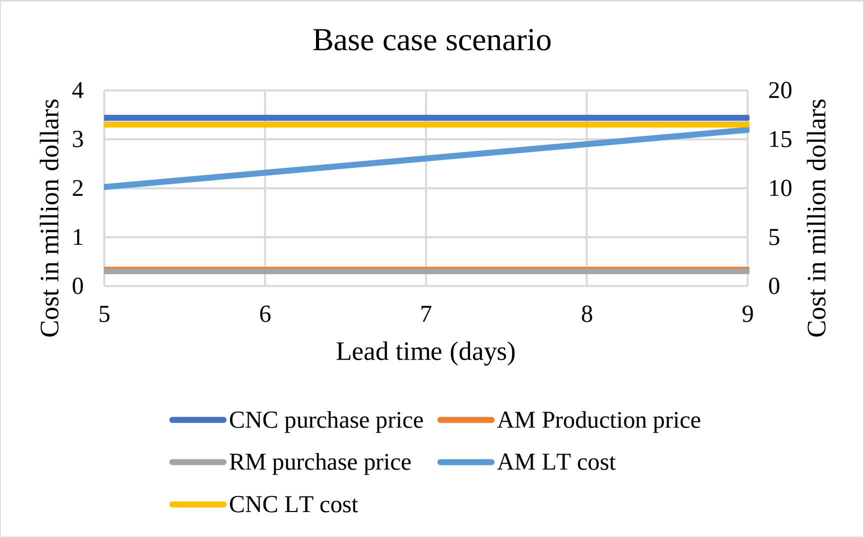
Figure 4.13 Quantity of part 6 when demand varies between 5 and 9 days

- **Cost analysis**

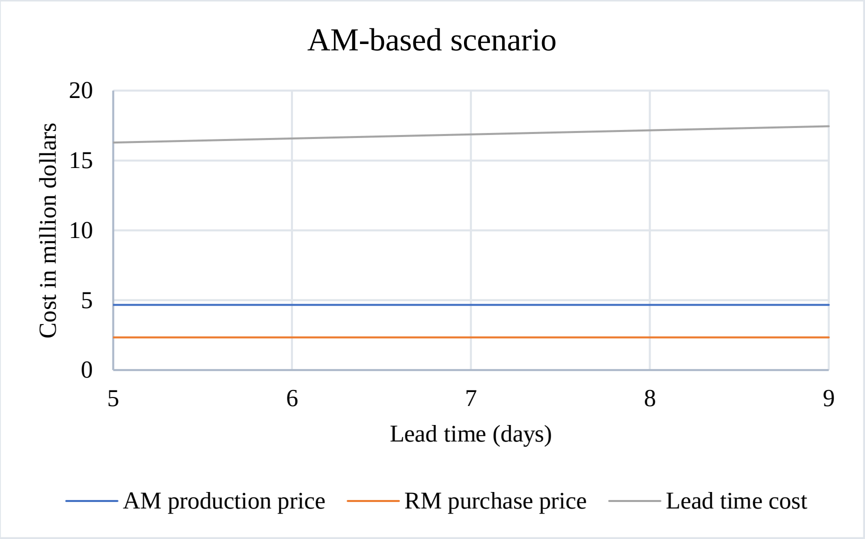
The change in total cost behavior of the base case scenario and AM scenario is similar as shown in Table 4.6. In Figure 4.14, it is shown that all cost items remain constant with the change of lead time, except for the lead time cost that increases in both cases of base case and AM scenarios. There is an increase in the AM costs which is due to the increase in the raw material lead time cost. Therefore, the model is insensitive to any change in the lead time of AM raw material for ± 20% range.

Table 4.6 Change scenarios to AM lead time change

Lead time (days)	Base case total cost ($)	Change in the total cost	AM total cost ($)	Change in the total cost
5	23,325,602	-2%	23,615,479	-2%
6	23,617,982	-1%	23,907,859	-1%
7	23,910,362	0%	24,200,239	0%
8	24,202,742	1%	24,492,619	1%
9	24,495,122	2%	24,784,999	2%



(a)



(b)

Figure 4.14 Cost items subject to the lead time change of a) Base case scenario b) AM scenario

4.3 Discussion

A generic framework has been proposed in this thesis for the analysis of AM in the spare parts supply chain. The framework is supported by an optimization model to analyze the trade-off between AM and CNC methods which can be applied to any practical case.

The numerical experiments show that each spare part exhibits a different behavior than the other. The different behavior of spare parts is resulted from demand fluctuations, lead time changes, and the characteristics of each particular spare part. Overall, the model outcome shows that most of the spare parts are to be sourced via the CNC supplier and AM technology is to be utilized as an integrative method that complements the CNC method. Spare parts of types 1, 2,3,4,5,7, and 8 are to be sourced mainly from the CNC supplier, however, due to the supply potential constraint, when the maximum spare parts quantity is sourced from the CNC supplier, hence, AM-based spare parts are produced in order to meet the demand. For spare parts of types 6, and 9, they are on-site produced with AM throughout the planning horizon. This can be explained by the characteristics of these spare parts as spare parts 6 and spare part 9 have high complexity in terms of geometry design. Therefore, the cost to produce the high geometry complex spare parts is less costly than sourcing them from the CNC supplier. Also, the lead time to print spare parts 6 and 9 is shorter compared to sourcing them from the CNC supplier.

The total system cost fluctuates slightly below and above 2,000,000 USD every period. The accumulated demand for all spare parts in the second period is the highest, this is why period 2 has the largest cost. As mentioned previously, most of the spare parts are to be sourced via a CNC supplier throughout the planning horizon, hence the largest periodic cost component is the purchase cost of CNC-based spare parts followed by the depreciation cost of AM machine, and purchase cost of AM raw material.

The proposed optimization was compared with CNC-based and AM-based scenarios where the highest cost was reported for the AM scenario and the least cost was reported for the CNC option. This is because, in the AM option, the lead times are considered relatively short, but the costs associated with AM raw material and spare parts production are high. However, for the CNC scenario, lead times tend to be longer, but the costs to purchase the CNC-based spare parts and backordered demand penalty are high. In the proposed optimization, the highest cost components of CNC and AM scenarios are compromised solving the trade-off between the lead time and cost.

Figure 4.15 shows the accumulated total cost of each spare part over the planning horizon. Spare part type 3 has the largest cost; this spare part has the highest price of purchase from the CNC supplier and the highest cost of production through AM. This is because of the characteristics of this part which were mentioned earlier in Chapter 3 (Table 3.1); the spare part of type 3 is large-sized and has a high geometry complexity, which is what explains the high cost associated with it. AM has proved its feasibility in producing complex stainless parts in less time and less cost compared to CNC machining. As the complexity of the geometry of part increases, its manufacturing cost with CNC increases, however, the cost to produce it with AM may not change (Quinlan et al., 2017) because the printing cost and energy of a complex part do not depend on the shape complexity. Although it is more cost-effective to print a complex geometry spare part rather than producing it with CNC, in the proposed model, spare part type 3 is recommended for sourcing by CNC. This spare part is large in size, and we can notice that all large-sized spare parts (types 1,2, and 3) are to be sourced through CNC. This finding is aligned with the finding in the literature of (Zhang et al., 2019) where the author mentioned that the spare part size impacts the AM operation making

AM in some cases not able to compete financially with conventional methods. It is more economic to manufacture large spare parts with CNC rather than AM as printing them when AM requires more material, printing time, and energy, thus, increasing costs.

Overall, in terms of cost-effectiveness, spare parts with high complexity in geometry are to be manufactured with AM. Spare parts with large sizes are to be manufactured through CNC. However, based on the study's findings, it is not always the case because many other costs are involved in the decision-making of the manufacturing process. Although AM method offers shorter lead times and enables design customization, it can be costly because of the high purchase price of AM raw material, printing energy costs, and depreciation cost of AM machine.

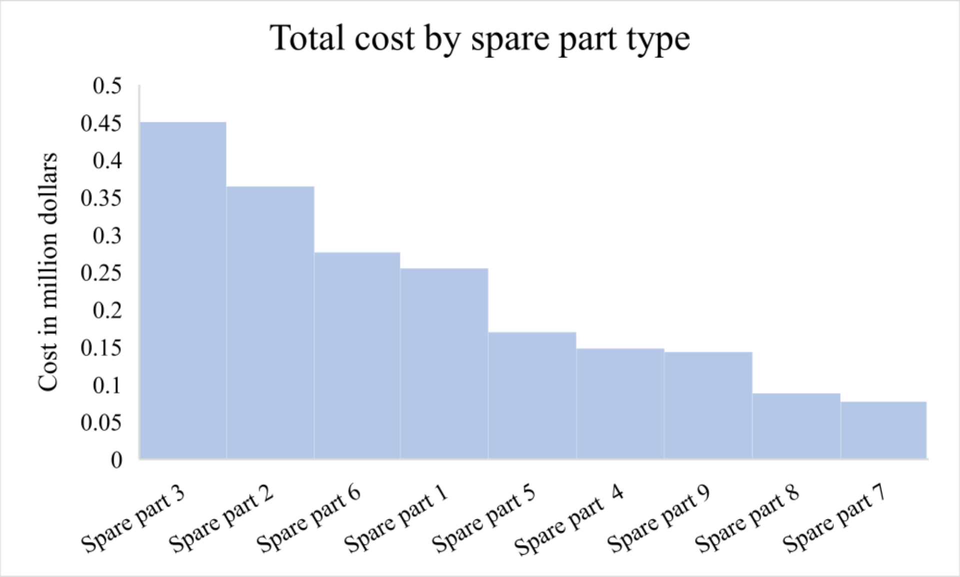


Figure 4.15 The total cost of each spare part over the twelve periods

The developed model is applicable in the generic scenario, and we can use it in order to do multiple scenario analysis for demand change, and lead time changes. Based on the performed scenario analysis, we can see that the total cost is always sensitive to changes in the demand and lead time parameters. When the demand changes from -60% to 60%, a change in the mix of AM and CNC is observed highlighting that AM can complement the CNC method so it can be used for urgent or offshore spare parts applications.

The decision variable outcomes in terms of AM and CNC quantities are sensitive in the case of the demand change for some spare parts only. For most of the spare parts, the mix between AM and CNC is sensitive to the demand variation. However, a few spare parts such as spare part type 6 and spare part type 9 are insensitive to any demand change. For the lead time scenario analysis, all spare parts are insensitive to any changes in the lead time of both methods. Table 4.7 lists the adopted parameters for scenario analysis along with ranges of changes and sensitivity on the total cost of the base case scenario. In Table 4.8, the sensitivity of the decision variables outcome of each spare part type to each parameter change is listed. All spare part types in terms of AM and CNC decision variables are insensitive to any change in the lead time whether it is the lead time of CNC or AM for a variation range between -20% to +20%. However, all spare part types are sensitive to changes in the demand for a varied range of ±10% except spare part 6 and spare part 9 which are insensitive.

Table 4.7 Effect of parameter variation on the total cost

Parameter	Range of change	Sensitivity on the total cost
Demand	[-10%,10%]	Sensitive
Lead time of CNC-based spare parts	[-20%,20%]	Sensitive
Lead time of AM raw material	[-20%,20%]	Sensitive

Table 4.8 Effect of parameter variation on decision variable outcome by spare parts type

	Parameter		
Spare parts type	**Demand**	**Lead time of CNC spare parts**	**Lead time of AM raw material**
1	Sensitive	Insensitive	Insensitive
2	Sensitive	Insensitive	Insensitive
3	Sensitive	Insensitive	Insensitive
4	Sensitive	Insensitive	Insensitive
5	Sensitive	Insensitive	Insensitive
6	Insensitive	Insensitive	Insensitive
7	Sensitive	Insensitive	Insensitive
8	Sensitive	Insensitive	Insensitive
9	Insensitive	Insensitive	Insensitive

AM technology has recently changed the structure of supply chains allowing on-demand and on site-production. In cases of supply chain disruptions such as in global pandemics or blockades, longer lead times and transportation delays may be faced when relying only on conventional manufacturing methods. However, with the adoption of AM, raw materials are stored in fewer volumes having the ability to produce a wide variety of customized and functional parts. This would be useful, especially in aerospace and defense industries where customized spare parts are needed on an immediate basis. The digital storage of spare parts through CAD models contributes to eliminating the physical stock of spares and therefore reducing overall inventory level, holding costs, and material movement (Huang et al., 2013).

AM has significantly improved supply chain resilience through various aspects including unpredictable customer demand, flexibility, production reallocation, and logistics multi-sourcing (Naghshineh & Carvalho, 2021).

Overall, the adoption of AM technologies significantly and positively influences supply chain integration through prerequisites such as integrated inventory management systems, inter-functional data sharing, and integrated logistics support systems (Naghshineh & Carvalho, 2020).

4.3.1 Insights and managerial implications of the model

The optimization model analysis was used to assess a few of the questions as mentioned below.

- How much to order from CNC spare parts supplier?
- How much to order raw materials from AM supplier?
- When to produce on-demand AM spare parts?
- How much to store and for how long?

The answers to the above-mentioned questions are addressed in the outcome of decision variables of the optimization model. The answer to "how much to order from CNC spare parts supplier" is addressed in the quantity of CNC-based spare parts to be ordered. The question of "how much to order raw material from AM supplier?" is answered through the raw material volume to be ordered and to be used for producing AM-based spare parts. The outcome of the inventory units stored in the warehouse in each period addresses the question "How much to store and for how long"? These questions are answered through the MILP optimization model which guides the decision of the optimal quantities and when to implement them in order to minimize the total costs.

The model offers an economic inventory production schedule considering the trade-off between CNC manufacturing and AM for decision-makers. In real-life decision-making, this kind of model implementation offers insight for decision-makers to give them the opportunity to take the right decisions and negotiate with supply chain partners based on information that cannot be previously quantifiable. The proposed model is generic therefore it can be implemented in any spare part business for spare parts that are manufacturable by AM and CNC machining. A feature of this model allows dual sourcing in the manufacturing method for each spare part. As well as it considers the lead time factor which increases the downtime cost, especially in heavy industries such as oil and gas where the cost of downtime is very high. Another distinctive feature of the model lies in the consideration of multiple spare parts having different characteristics such as spare part size, geometry complexity, and lead time which enables the model to be a reliable decision-making tool. The decision-making process on the manufacturing method of each spare part varies according to the spare part's characteristics such as geometry complexity, size, volume, production cost, and lead time.

The presented scenario analysis of various model parameters allows the decision maker to explore and investigate which influential parameters affect the system significantly and how they affect it. These types of scenarios give insight to stakeholders who are involved in planning which parameters to estimate roughly and which to estimate precisely. The adequate and proper planning of logistics, optimal and economic order quantities, inventory control, and resource allocation contribute to increased process efficiency, lower costs, and improved supplier experience and customer satisfaction.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

In large and heavy industries like petroleum, aerospace, and military sectors, the unavailability of critical spare parts may increase the downtime cost significantly and cease production activities. This is why continuous sourcing of spare parts is required to maintain the continuity of operations.

In this thesis, an integrated framework is proposed by highlighting the inputs, processes, constraints, and output of additive manufacturing technology in the spare parts supply chain. The trade-off between CNC-based spare parts and AM-based spare parts is analyzed through a multi-period multiple spare parts mixed integer linear programming which optimizes the quantity of CNC-based spare parts to be ordered and AM-based spare parts to be produced at the minimal total cost. The formulated problem includes nine different spare parts having different geometry complexities, sizes, lead times, and costs with each manufacturing alternative.

This study highlights the effect of lead time, spare part geometry complexity, and size factors on the economic feasibility of CNC-based and AM-based spare parts supply chains. Results have shown that AM is economically feasible for small and medium-sized spare parts which have a complex geometry. The advantage of AM technology lies in the ability to produce complex geometry spare parts which may not be possible to produce through conventional methods, or they take long production times (Emelogu et al., 2016). The fabrication time of AM-based spare parts is insensitive to the complexity of the geometry of the part. Spare parts which are large in size and have low to medium geometry complexity, are CNC-based, and AM was used as a complementary method to satisfy the demand. This finding supports the finding of the literature of (Thomas & Gilbert, 2014) where they mentioned that two manufacturing technologies can be complementary and adopted alongside each other in order to gain greater benefits rather than adopting each technology separately. The continuous increase of AM adoption may lead to a reduction in the AM raw material costs through economies of scale which will result in more integration of AM in the supply chains of systems and organizations. The cost of some plastic-based AM machines has decreased by 51% in the past two decades. Metal-based AM machines will likely follow the similar exhibited trend for plastic-based ones which will increase the economic feasibility of AM. AM technology in fact may offer many advantages over traditional manufacturing methods including lightweight parts, extended useful life, and more sustainable and recyclable products.

5.1 Limitations

Limitations of this work are the following:

- The proposed model looks only at the considered spare part types with the three proposed geometry complexities and sizes. The model did not take into consideration other spare part types with different characteristics.
- The data used for the model implementation is based on the data given in the literature. The availability of real data and practical examples from real industry cases would reflect the whole situation in a holistic manner.

5.2 Future Research

- The current study has considered a deterministic model which has captured rational values such as spare parts demand change, lead times, supply situation, and costs changes. However, in real-case scenarios, these parameters are not always deterministic where they fluctuate from one period to another. Therefore, in order to capture the uncertainty of these parameters, extending the model to a stochastic-based optimization model would better represent real-life decision-making and enhance the model's performance.
- The proposed optimization is a single objective optimization for cost minimization. Extending this work to multi-objective optimization where the environmental aspect may be included in order to investigate the ability of AM technology to reduce emissions and carbon cap would highlight the advantage of AM technology from the environmental perspective.
- Another future direction of this analysis can be in involving further supply chain parties such as the consideration of multiple suppliers, multiple facilities and warehouses, and multiple AM hubs which would enable the analysis of different supply chain configurations in order to comprehensively examine the trade-off between AM and CNC manufacturing methods.

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