On the Integration of Additive Manufacturing for Aircraft Spare Parts Inventory Control

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On the Integration of Additive Manufacturing for Aircraft Spare Parts Inventory Control

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Abstract

Spare parts inventory management represents a challenge for aircraft companies. Determining the optimal allocation and consumption of spare parts is problematic due to the intermittent demand. Original equipment manufacturer (OEM) uses different models to evaluate inventory stock level to avoid the non-availability of the desired spare parts when required. With the recent implementation of additive manufacturing (AM) in many sectors, the implications of AM for spare parts inventory management and control models need more attention. This paper aims to evaluate the advantage of AM integration for spare parts optimization in a multi-echelon inventory system. It compares three scenarios for non-moving, slow-moving, and fast-moving spare parts. A scenario-based modeling approach is followed to draw out insights for managers. The first scenario considers the conventional case where there is no integration of AM. The second scenario considers AM integration only in the central maintenance center (CMC). The third scenario assumes AM integration in CMC and regional maintenance centers (RMC). This analysis showed that when AM repair time is inferior to conventional process (CP) repair time, the best scenario for AM manufacturing integration is a decentralized AM location. And when AM repair time equals CP repair time, and AM repair probability is superior to 70%, the decentralized scenario still the optimal integration solution. However, when the AM repair time equals CP repair time, and the AM repair probability is inferior to 70%, the centralized scenario is the optimal integration solution. Moreover, non-moving and slow-moving spare parts are the most suitable categories for optimal AM allocation. Finally, the paper offers guidelines on adopting AM in the aircraft supply chain and the impact on spare part inventory management.

Keywords: Spare parts, inventory model, aircraft, additive manufacturing, multi-echelon, supply chain.

1. Introduction

An aircraft consists of many expensive complex systems and components encompassing different subassemblies containing multiple parts that may need repair or replacement (Lau and Song, 2008). Providing the right spare part at the right time and place represents a challenge in inventory management for aerospace companies. The total spare parts inventory value for supporting the operations of all airlines in the global aviation market reaches US$50 billion, accounting for 75% of airline inventory funds and 25% of working capital (Wang et *al.*, 2021). The need to have the right spare parts at the right place and time inevitably call for optimization of maintenance logistics, resources, and spare parts (Wang & Djurdjanovic, 2018). The prediction of spare parts consumption is a complex process mainly due to the intermittent demand (Antosz & Ratnayake, 2019). The demand for spare parts arises whenever a component fails or requires replacement, and its patterns are often intermittent, variable in size, and interspersed by periods (Syntetos et al., 2012).

During the last few years, AM technology has gained the interest of both academia and industry. AM permits reducing production costs due to a lower setup and tooling costs for low-volume parts (Gibson et al., 2010). The AM industry has become a mature technology adopted by many industries for their manufacturing applications for commercial end-use components production, and the new cost-efficient production machines are emerging in more significant quantities (Wohlers Report, 2019). The Aerospace industry, an early adopter of AM, is already designing small to large AM parts saving time, material and costs. AM also offers the biggest advantage critical to the aerospace manufacturers weight reduction. It also accelerates the supply chain by manufacturing non-critical parts on demand to maintain JIT (Just-in-time) inventory. The adoption of AM in aerospace might lead to a drastic change in the supply chain configuration and operations since the parts can be manufactured on-demand, near the service locations, and within a short period of time (Reeves, 2008; Khajavi et al., 2014). Using AM to produce spare parts could be considered a solution to improve efficiency and increase customer value (Mashhadi et al., 2015). According to Khajavi et al. (2018), AM is a feasible production process for spare parts manufacturing that offers products and services that address consumers' requirements regarding time and cost-effective delivery (Tziantopoulos et al., 2016).

Several studies have discussed ways to configure a spare parts supply chain when adopting AM (Walter et al. 2004; Holmström et al. 2010; Khajavi, Partanen, and Holmström 2014; Liu et al. 2014; Li et al. 2017). These research involve comparing different supply chain configurations (traditional, centralized, and decentralized) regarding inventory, life-cycle costs, and environmental effects. The first stream uses qualitative analysis to study the advantageous of the centralized and decentralized location (Holmström et al. (2010); Khajavi, Partanen, and Holmström (2014); Liu et al. (2014); Li et al. (2017); Li et al., (2019); Montero et al. (2020); Cantini et al. (2022)). The second stream uses quantitative study (Ashour Pour et al. (2017). Thus a few quantitative papers addressed the integration of additive manufacturing in the supply chain. As reported by Ghadge et al. (2018), the literature lacks methods to quantitatively capture the differences between CP and AM supply chains, providing more robust evidence on when the adoption of AM supply chain could ensure higher performance compared to CP. Moreover, most of these studies assumed that demand is homogenous. Liu et al. (2014) is the only study considering heterogeneous demand when addressing the adoption of AM in the spare parts supply chain. To fill these gaps, the objective of this paper is to compare different configurations of spare parts supply chains when adopting AM using quantitative method. Other factors such as demand variation, repair time, repair probability, and cost are carefully analysed to understand the best configuration of spare parts supply chains.

Motivated by the evaluation of the impact of potential integration of AM for aircraft spare parts management in multi-echelon inventory models, this paper is concerned with a two-echelon repairable item inventory system under stationary Poisson demands and limited repair capacity (Sherbrooke 1968). In other words, based on the multi-echelon technique for the recoverable item control (METRIC) system, this study aims to compare different configurations (e.g., conventional, centralized, and decentralized) of spare parts supply chains in terms of their performance: demand, repair time and cost. Then, the objective is to evaluate the best configuration of AM-based spare parts supply chains through an effective allocation of machines within supply chains. The specific aim is also to answer the following research question (RQ):

RQ: What are the main factors affecting the decision on a multi-echelon configuration system for additive manufacturing for aircraft spare parts?

The remainder of the article is structured as follows. Section 2 reviews the state-of-the-art literature, and section 3 presents the research methodology. The mathematical model development is introduced in section 4, where the details of mathematical model formulation are explained. The experimentation and the main results are presented in section 5, followed by the impact of the demand profile in section 6. Section 7 shows a sensitivity analysis. Section 8 presents the discussion, and finally, section 9 summarizes the main finding as a conclusion of this study.

2 Literature review

In this section, we discuss three streams of literature. First, we consider theories for the multi-echelon of spare parts inventories to set the ground for the methodology applied in this paper. Second, we review the literature on AM technologies integration in supply chains. Third, we analyze the recent literature that studies the impact of AM integration in the supply chain, specifically on the supply chain configuration.

2.1. Spare Parts and Multi-Echelon literature in aerospace

The study of multi-echelon inventory systems originated from the work of Clark and Scarf (1960). The authors show that an echelon-based stock policy is optimal for a serial inventory system. As a result, the fixed order cost is charged only at the highest echelon. Feeney and Sherbrooke (1966) extend Scarf's results for multi-echelon systems by applying Palm's theorem and demonstrating that if demand follows the Poisson process, then the outstanding distribution follows the Poisson process. This result leads to the Research and Development Corporation (RAND) to develop the Multi-Echelon Technique for Recoverable Item Control (METRIC) model for the U.S. Air Force (Sherbrooke, 1968). Multi-echelon inventory management focuses on inventory optimization across the network to minimize the costs of the stocks (echelons), subject to customer service constraints. Two or more warehouses characterize a multi-echelon inventory system, e.g., in a two-echelon system; the lower echelon may contain regional maintenance centers (RMC) that service the customer; The upper–echelon, or central maintenance center (CMC), resupplies the lower echelon and makes the significant reparation that does not exist in the regional warehouse. The multi-echelon structure corresponds to the application of the spare parts flow for the Maintenance, Repair & Overhaul (MRO) business of an aerospace company. The multi-echelon system may reduce total inventory costs by 50% (Muckstadt and Thomas, 1980).

Most inventory multi-echelon models characterize the spare parts inventory problem by focusing on different perspectives: backorders and stock allocation; and inventory planning and control. From a backorder and stock allocation perspectives, Costantino et al. (2013) performed a marginal analysis to reduce backorders and spare parts allocation. Karsten and Basten (2014) proposed a new structure of the cost function in the inventory model with back-ordering to reduce inventory cost by pooling common spare parts between multiple companies. Rezaei Somarin et al. (2017) proposed a heuristic technique for the stock allocation problem based on relative value function and average backorder cost at a single base to minimize the expected backorder cost. Lee et al. (2008) developed a simulation that integrates the multi-objective evolutionary algorithm (MOEA) with the multi-objective computing budget allocation (MOCBA). The authors apply it to a multi-objective aircraft spare parts allocation problem to find a set of non-dominated solutions.

From an inventory planning and controlling perspective, Simao and Powell (2009) use approximate dynamic programming to present a model and a solution approach to determining the inventory levels at each warehouse. Sun and Zuo (2013) proposed a marginal analysis to determine the stock level in the multi-echelon system. Zanjani and Nourelfath (2014) proposed a mathematical programming model to find the optimal spare part order quantity and interval to maximize system availability or minimize system downtime. Gu et al. (2015) developed a non-linear programming model to reduce the total cost by finding the optimal order time and quantity. Patriarca, Costantino, and Di Gravio (2016a) defined a systemic approach for determining the stock levels of repairable items in a complex network by a genetic algorithm optimization process. Ghaddar et al. (2016) propose a genetic programming-based symbolic regression methodology that integrates spare parts stocking problems (SPS) with the level of repair analysis (LORA) optimization model. Patriarca, Costantino, Di Gravio, et al. (2016b) proposed a performance-based contract (PBC) named PBC-METRIC model to minimize the spare parts supply cost in compliance with the airline availability requirements.

Table 1 summarizes the reviewed papers and positions our work.

Table 1. Literature review on spare parts Multi-echelon in Aerospace.

Studies	**Inventory planning and control**	**Stock allocation**	**Poisson process**	**Policies (S-1, S)**	**Stochastic demand**	**AM**	**Multi-item**
(Clark and Scarf, 1960)	x				x		
(Feeney and Sherbrooke, 1966)	x		x	x	x		x
(Sherbrooke, 1968)	x		x	x	x		x

(Muckstadt and Thomas, 1980)	x		x	x	x		x
(Lee et al., 2008)	x		x	x	x		
(Simao and Powell, 2009)	x				x		x
(Holmström et al., 2010)		x	x			x	x
(Costantino et al., 2013)	x		x	x	x		x
(Sun and Zuo, 2013)	x						x
(Liu et al., 2014)		x				x	
(Kaebernick, 2014)		x				x	
(Khajavi et al., 2014)		x				x	
(Zanjani and Nourelfath (2014)	x		x		x		x
(Karsten and Basten, 2014)	x		x	x			
(Simkin and Wang, 2014)		x				x	
(Gu et al., 2015)	x				x		
(Mashhadi et al., 2015)		x				x	
(Van Jaarsveld et al., 2015)			x				
(Knofius et al., 2016)		x				x	
(Lindemann and Koch, 2016)		x				x	
(Patriarca et al., 2016a)	x		x	x			
(Patriarca et al., 2016b)	x		x	x			
(Ghaddar et al., 2016)	x		x	x	x		x
(Rezaei Somarin et al., 2017)	x		x	x	x		
This study	x	x	x	x	x	x	x

2.2 Additive Manufacturing and Spare Parts Supply chain

AM is "*the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining*" (Standard, 2012). AM is commonly known as three-dimensional printing (3DP), a method of producing an object directly from a three-dimensional computer-aided design file (Frazier, 2014). AM processes emerged in the 1980s as prototyping tools, and these processes were called rapid prototyping (Gibson et al., 2010). AM has several promising characteristics for improving manufacturing and aftersales supply chains (Holmström et al., 2010; Markillie, 2012; Pérès and Noyes, 2006). This technique has many significant advantages, including the possibility of producing highly complex geometries (Holmström et al., 2010; Holmström et al., 2016). This production technique has captured the attention of the aerospace industry because of its invaluable features. It allows part components consolidation, reliability improvement, weight reduction, and waste alleviation throughout life (Mellor et al., 2014; Rao, 2016).

AM technology has also created other opportunities to improve supply chain performance by reducing lead time, waste raw materials, manufacturing parts near the customers, and reducing inventory (Liu et al., 2014). Using AM to produce spare parts could be considered a solution to improve efficiency and increase customer value (Mashhadi et al., 2015). This leads to modifying the supply chain configuration (Khajavi et al., 2014). Several authors have analyzed the benefit of integrating AM in the supply chain. They highlight the possibility of easy on-demand manufacturing and manufacturing in remote locations while shortening the supply chain (Attaran, 2017; Liu et al., 2014; Montero et al., 2018; Oettmeier & Hofmann, 2016; Thomas, 2016). Moreover, Goldsby and Zinn (2016) stated that using AM to lower costs brings opportunities for changes in inventory policies and warehouse management.

AM became a mature technology adopted by many industries and various manufacturing applications for commercial end-use components production. New cost-efficient production machines are emerging in more significant quantities (Wohlers Report, 2019). According to Khajavi et al. (2018), AM is a feasible production process for spare parts manufacturing that offers products and services that address consumers' requirements regarding time and cost-effective delivery (Tziantopoulos et al., 2016). Usage of AM in the spare parts supply chain has been studied by several authors (Muir and Haddud 2018; Ghadge et al. 2018; Holmström et al. 2016; Khajavi, Partanen, and Holmström 2014). AM can be economically attractive, particularly for low-volume spare parts production, and it provides flexibility in producing spare parts (Frandsen et al., 2020). It supports the maintenance of after-sales service supply chains, which often span several decades (Knofius, Van Der Heijden, et al., 2016).

An abundant number of literature papers have drawn attention to the adoption of AM technology in managing the spare parts supply chain. The first literature stream focuses on the technical problems relevant to process design, such as selection, data pre-processing, part-to-AM printer planning and scheduling, and security management (Lan 2009; Ransikarbum et al. 2017; Ha et al. 2018). The second stream of the literature focuses on configuring a spare parts supply chain when adopting AM (see Table 2). Walter et al. (2004) et Holmström et al. (2010) propose two approaches to integrating AM into spare parts manufacturing in an aerospace supply chain. The first approach is the centralization of the AM to replace the maintenance stock, consolidating the demand from different regions in one place. The second approach is the decentralization of AM in each service point. This approach is beneficial when the production volume is high but requires the justification of the investment. It allows the elimination of the stock and reduces transportation costs and delivery time (Kunovjanek et al., 2020). Liu et al. (2014) evaluate the impact of AM integration in the aircraft spare parts supply chain by comparing three supply chain configurations: (a) conventional (as-is) supply chains, (b) centralized AM supply chains, and (c) distributed AM supply chains using an operation reference model. They show how using AM offers various opportunities to reduce the required safety inventory of aircraft spare parts in the supply chain. A similar comparison based on system dynamics simulation can be found in Li et al. (2017) study. It compares three supply chain configurations regarding total variable costs and carbon emissions. In more recent studies, Ashour Pour et al. (2017) compare the traditional two-level supply chain with an AM-based model of total system costs. They conclude that AM adoption adds flexibility to the whole system. In the same stream, Muir and Haddud (2018) investigate the possible impact of AM adoption on inventory performance and customer satisfaction in a spare parts supply chain. The results reveal that AM has the potential to improve a firm's inventory performance. Li et al. (2019) compare two supply chain configurations, centralized and decentralized, when adopting AM considering heterogeneous demand and make-to-demand strategy. They conclude that decentralized is more suitable, but centralized is the best choice when the demand rate is high; centralized is the best choice due to the pooling effect. They also propose principles to conduct mixed supply chain configuration. Montero et al. (2020) present a methodology for designing and manufacturing digital spare parts using AM in decentralized facilities. It shows a decentralized way to re-design and re-manufacture spare parts using AM. Cantini et al. (2022) propose a decision support system to compare the total costs of decentralized, centralized, and hybrid supply chain configurations characterized by different centralization degrees with AM and conventional manufacturing process (CP) for spare parts.

Table 2 summarizes the reviewed papers and positions our work.

Table 2. Spare parts supply chains and AM.

Literature	Method Analysis	Factors					Decision-Making Variable	Configuration comparison
		Demand	Cost	Repair time	Probability of repair	Inventory (Stock)		

Walter et al. (2004)	Qualitative	Slow-moving Fast-moving	Inventory costs				Inventory costs	Centralization Decentralization
Holmström et al. (2010)	Qualitative	Slow moving Fast-moving	Production costs Distribution costs Inventory obsolescence costs Life-cycle costs				Production costs	Centralization Decentralization
Khajavi, Partanen, and Holmström (2014)	Scenario modelling		Operating cost Downtime cost				Total operating cost	Current Cenralisation Current Decentralisation Future Centralisation Future Decentralisation
Liu et al. (2014)	Analytical - Quantitative	Heterogeneous demand		Lead time		Safty inventory reduction	Safty inventory reduction	Conventional Centralization Decentralization
Li et al. (2017)	Simulation-Quantitative	Homogeneous demand and make-to-inventory	transportation cost, manufacturing cost, administrative cost and inventory cost				Total variable cost and carbon emission.	Conventional Centralization Decentralization
Ashour Pour et al. (2017)	Analytical analysis	Homogeneous demand	Holding cost Stock-carrying cost ordering cost transportation cost				Total cost	Centralization Traditional manufacturing Centralization additive manufacturing
(Li et al., 2019)	Qualitative-Simulation	Heterogeneous demand	Capacity-building costs Material costs, Machine/Manufacturing costs Inventory costs Logistics costs overhead, labor, and post-processing costs	Sojourn time			Total cost Sojourn time	Centralization Decentralization Mixed configuration
(Montero et al., 2020)	Qualitative						Process model	Decentralization
(Cantini et al., 2022)	Quantitative		Purchasing costs Transportation costs Backorder costs				Decision tree cost-based comparison	Centralization Decentralization Hybrid
This study	Quantitative	Non-moving Slow-moving Fast-moving	Inventory cost	Repair time	Probability of repair	Stock level	Stock level Backorders costs	Conventional Centralization Decentralization

2.3. Research gaps

Several qualitative research analyzed supply chain configuration changes after AM integration in spare parts production phase (Holmström et al. 2010). These studies tried to understand when it is convenient (economic) to switch from CP to AM technologies for producing items (Sgarbossa et al., 2021) or having the optimal configuration of the supply chain considering AM as the manufacturing technology (Khajavi, Partanen, and Holmström 2014). A few quantitative papers addressed the integration of additive manufacturing in the supply chain. As reported by Ghadge et al. (2018), the extant literature lacks methods to quantitatively capture the differences between CP and AM supply chains, providing more robust evidence on when the adoption of AM supply chain could ensure higher performance compared to CP. Besides, in the literature (Table 2), most of these studies assumed that demand is homogenous. Liu et al. (2014) is the only study considering heterogeneous demand when addressing the adoption of AM in the spare parts supply chain.

To fill these gaps, the objective of this paper is to compare different configurations of spare parts supply chains when adopting AM. Other factors such as demand variation, repair time, repair probability, and cost are carefully analyzed to understand the best configuration of spare parts supply chains, given the specific demand and AM-based spare parts production conditions. Moreover, the proposed model will support managers and practitioners in deciding which spare parts supply chain (AM or CP) to adopt based on a quantitative method using a METRIC system.

3. Research methodology

This paper adopts a stepwise and quantitative scenario-based modeling approach as a research methodology to study the integration of additive manufacturing in the spare parts inventory model in the aerospace industry. This methodology follows three phases design, as shown in Figure 1.

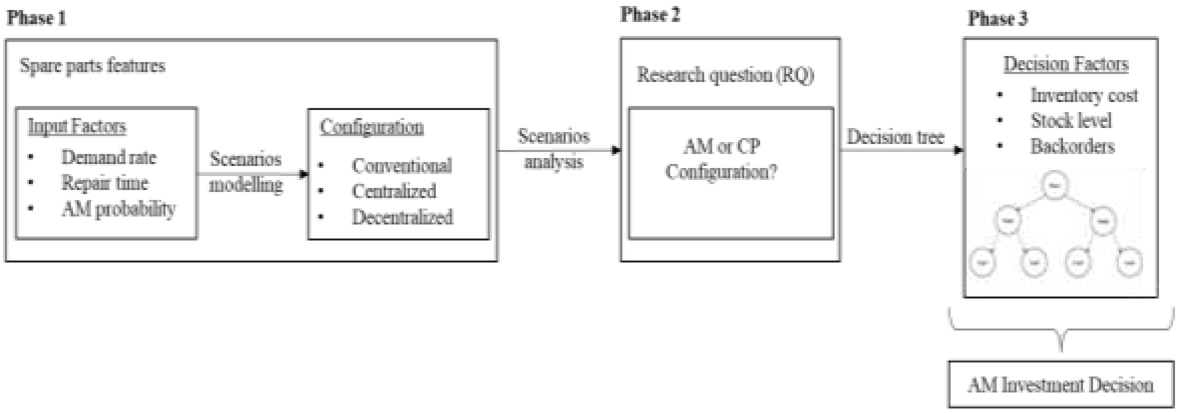

Figure 1. Research methodology

Phase 1 (Scenario modeling): First, we have to define a baseline model that does not consider AM integration. We have defined a METRIC as a baseline model based on the literature review presented in Table 1. The baseline model is characterized by the specificities required for the spare parts inventory management, such as the echelon number (Network), demand characteristics (Stochastics or deterministic), inventory policy (continuous or discrete), and the assumptions related to the model. In this study, the baseline model is the METRIC model developed by Sherbrooke (1968).

Phase 2 (AM best integration configuration): The objective of this phase is to propose an inventory model to evaluate the stock level required if we integrate AM, besides which configuration network (conventional, centralized, or decentralized) is optimal for the select spare parts. Then, we should determine suitable spare parts for the additive that bring value to the organization depending on the specificity and functionality of the parts.

Phase 3 (Investment decision): This step will allow managers to have a rational decision and methodology for AM spare parts decision based on the Expected backorders and the cost related calculated in the scenario modeling in phase 2, especially the service level that will offer to the customer. This will justify the relevance and value of the investment for integrating AM as a viable method for spare parts management in the aircraft sector.

4. Mathematical models developments

The methodology of this research is scenario modeling. The scenario model investigates the use of AM to produce functional spare parts. To evaluate a METRIC system for the integration of AM, we elaborate on three scenarios. The first model without AM integration (Baseline scenario) is presented in section 4.3. The second model with centralized AM is presented in Appendix A (model/scenario 1). The third model with decentralized AM is presented in Appendix B (model/scenario 2). The next sub-section presents the different assumptions and models' development steps.

4.1. General assumptions

The main METRIC model assumptions are:

- The decision as to whether a base repair an item does not depend on stock levels or workload;
- The estimated demand is stationary;
- The upstream echelon has high repair capacities relative to the low demand requirements for repairable parts;
- The base is resupplied from the depot, not by lateral supply from another base;
- The (s - 1, s) inventory policy is appropriate for every item at every echelon.
- If the spare part is not repairable, it could be provided by suppliers (Supply0)

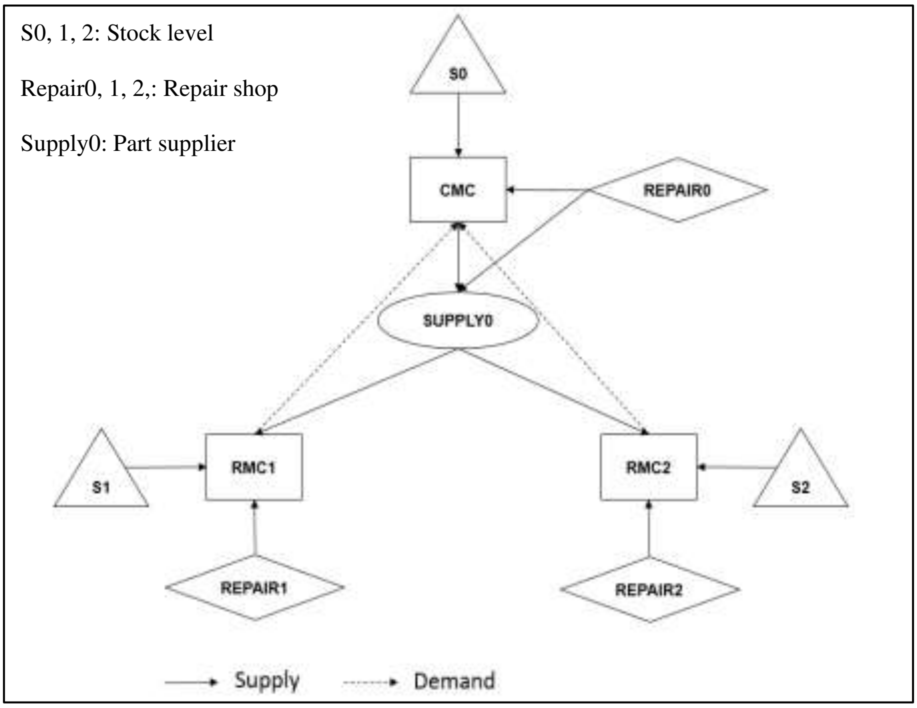

Figure 2. Spare parts inventory management system without AM integration (Baseline)

4.2. General notations

i Item number, i = 1,2

j Site number, j = 0,1,2, j = 0 represent CMC

λ Mean demand rate

υ Mean time to repair with the conventional process (CP)

ρ Repair probability (possibility of repairing the spare part)

γ Mean time to repair (manufacturing time) with AM

ϕ AM repair probability (possibility of repairing AM spare part)

τ Mean time between shipment and receipt for repair parts

α Mean time between shipment and receipt for AM parts

μ Mean number of parts under repair or under resupply

S_{ij} Stock level for parts for item *i* at site *j*.

EBO_{ij}^{AM} Expected Backorder for the AM parts for item *i* at site *j*

EBO_{ij}^{RP} Expected Backorder for the repair parts for t item *i* at site *j*

EBO_{ij} Expected Backorder for the whole system for item *i* at site *j*

4.3. Mathematical Formulation for Baseline Model

The RMC cannot make all kinds of reparation in the baseline scenario, but the CMC has more capabilities (capacity and equipment) to make all reparation coming from the field. Therefore, the spare parts reparation is done using the CP, as shown in Figure 2.

Total Expected Backorder at the Depot

First, we must calculate the average repairable demand at the CMC and the fraction of demand that is not repairable at each base. Thus, the total main demand at the CMC is as follows (Sherbrooke, 1968):

$$\lambda_{i0}^{*} = \lambda_{i0}\rho_{i0} + \sum_{j=1}^{2} \lambda_{ij}\left(1 - \rho_{ij}\right) \tag{1}$$

The number of parts under repair or resupply that is repairable at the CMC equals:

$$\mu_{i0}^{RP} = \nu_{i0}\left(\lambda_{i0}\rho_{i0} + \sum_{j=1}^{2} \lambda_{ij}\left(1 - \rho_{ij}\right)\right) \tag{2}$$

The total expected backorder (EBO) for the depot (Sherbrooke, 1968) equals:

$$\mathrm{EBO}_{\mathrm{i0}}^{\mathrm{RP}}\left(s_{i0}\right) = \mu_{\mathrm{i0}}^{\mathrm{RP}} \frac{\left(\mu_{\mathrm{i0}}^{\mathrm{RP}}\right)^{s_{i0}}}{s_{i0}\,!} e^{-\mu_{\mathrm{i0}}^{\mathrm{RP}}} + \left(\mu_{\mathrm{i0}}^{\mathrm{RP}} - s_{i0}\right)\left(1 - \sum_{l=0}^{s_{i0}} \frac{\left(\mu_{\mathrm{i0}}^{\mathrm{RP}}\right)^{l}}{l\,!} e^{-\mu_{\mathrm{i0}}^{\mathrm{RP}}}\right) \tag{3}$$

Total Expected Backorder for each base

The average total demand that is repairable at the base equals the average demand of repairable at the base plus the demand resupply from the CMC. We are assuming that the demand is following the Poisson process. Since the sum of Poisson processes is a Poisson process (Sherbrooke, 1968), the fraction demand that is repairable at each base is expressed as follow:

$$\lambda_{ij}^{*} = \lambda_{ij}\rho_{ij} + \lambda_{ij}\left(1 - \rho_{ij}\right) \tag{4}$$

Thus, the number of parts under repair or resupply that is repairable at the CMC equals:

$$\mu_{ij}^{RP} = \lambda_{ij}\left(\rho_{ij}\nu_{ij}\right) + \left(1-\rho_{ij}\right)\left(\tau_{ij} + \frac{EBO_{i0}\left(s_{i0}\middle|\mu_{i0}\right)}{\lambda_{i0}^{*}}\right) \quad (5)$$

The $EBO_{i0}\left(s_{i0}\middle|\mu_{i0}\right)$ is the expected number of resupply outstanding at the depot at a random point. The quantity $\frac{EBO_{i0}\left(s_{i0}\middle|\mu_{i0}\right)}{\lambda_{i0}^{*}}$ represents the average delay added daily to resupply requests, resulting from the fact that the depot does not always have stock on the shelf. τ_{ij} represents the order-and-ship time from the CMC to the RMC. Thus, the expected backorder at the base equals:

$$EBO_{ij}^{RP}\left(s_{ij}\right) = \mu_{ij}^{RP}\frac{\left(\mu_{ij}^{RP}\right)^{s_{ij}}}{s_{ij}!}e^{-\mu_{ij}^{RP}} + \left(\mu_{ij}^{RP} - s_{ij}\right)\left(1 - \sum_{l=0}^{s_{ij}}\frac{\left(\mu_{ij}^{RP}\right)_{ij}^{l}}{l!}e^{-\mu_{ij}^{RP}}\right) \quad (6)$$

5. Experimentation and results

5.1 . Baseline model: numerical example

In this section, we present the scenario calculation. The goal is to analyze the best supply chain configuration for spare parts management with AM integration. First, the results are compared to the baseline scenario (scenario 1), which does not include AM. For the sake of this study, we rely on the information of a conventional manufacturing process and costs presented in the study by Patriarca, Costantino, Di Gravio, et al. (2016a), which include data on activities involved in aircraft spare parts. Since the adoption of AM technology for spare parts inventory management is still in its infancy, obtaining the actual data of AM-based production is not easy compared to the conventional manufacturing process. Thus, for AM repair time, we consider three different conditions: a) CP repair time equals AM repair time (CP = AM); b) CP repair time equals two times AM repair time (CP = 2 AM), and c) AM repair time equals half CP repair time (AM = 0.5 CP). Table 3 presents a sample of spare part data used for calculation.

Table 3. Data for the numerical example (Patriarca, Costantino, Di Gravio, et al., 2016a).

Site	i	j	Item Code	m	Repair Probability (ρ ij)	Repairing time ν ij [years]	Order and ship time (τ i0) [years]	P j ($)
CMC	0	1	xxxxx162	10	1	0,065753	-	400
CMC	0	2	xxxxx163	75	1	0,076712	-	4 000
CMC	0	3	xxxxx164	150	1	0,095890	-	4 500
RMC1	1	1	xxxxx162	10	0,4	0,153425	0,054795	400
RMC1	1	2	xxxxx163	75	0,3	0,161644	0,054795	4 000
RMC1	1	3	xxxxx164	150	0,2	0,106849	0,054795	4 500
RMC2	2	1	xxxxx162	10	0,9	0,079452	0,082192	400
RMC2	2	2	xxxxx163	75	0,9	0,098630	0,082192	4 000
RMC2	2	3	xxxxx164	150	0,9	0,060274	0,082192	4 500

5.2. Models' validation

First, the objective is to confirm the validity of the developed models (baseline, models 1 and 2). Thus, we used Matlab® to perform a simulation for three different models (baseline, model 1, and model 2) by considering that CP's repair time is the same as the repair time for AM. Figure 3 shows the impact of the repair time on different spare parts demand quantity: m = 10; m = 75; m = 150. It demonstrates that if the repair time for CP equals AM, there is no change in EBO quantities and costs. This fact confirms that models are valid since the results from the three models (baseline, model 1, and model 2) should be equal, considering that we have the same repair time.

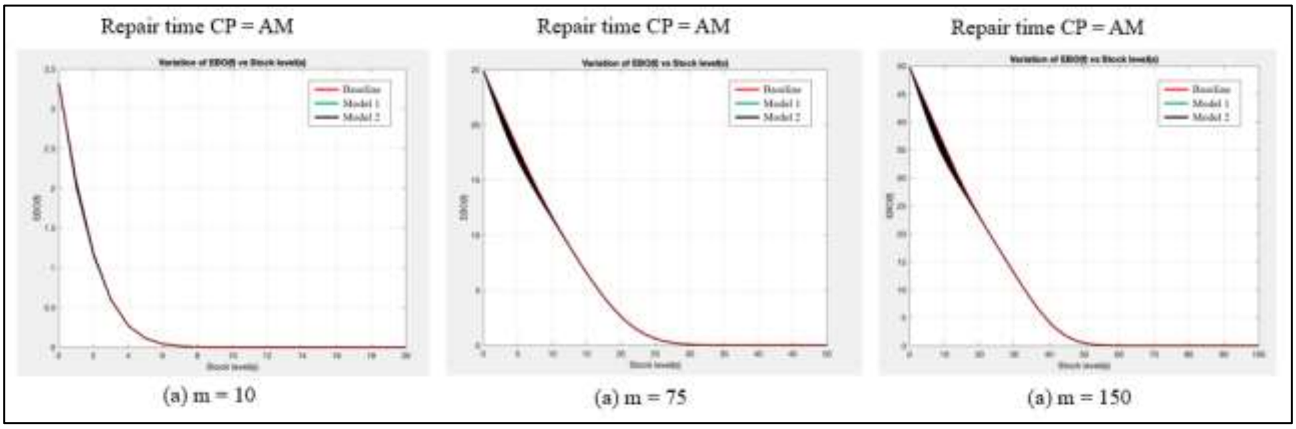

Figure 3. EBO quantity for different stock levels.

5.3. The impact of repair time of AM process

Table 4 shows the results for all parts presented in Table 3, showing the optimal configuration. The detailed calculation is presented in appendix C. It shows that depending on the AM repair time and AM probability; we have the EBO required for a specific stock level (0, 1,.., 5). The AM repair time should be inferior to CP repair time to opt for a decentralized configuration. However, the centralization configuration is more suitable if we have an equal repair time and AM repair probability is inferior to 0.8 (Appendix C). Finally, if the AM repair time is superior to CP repair time, it's evident that the baseline configuration with no AM is required. Table 5 presents the calculated cost for the EBO for a given stock level.

Table 4. Expected backorder.

Item	**Scenario**	**m**	**AM Repair time**	**AM prob**	**0**	**1**	**2**	**3**	**4**	**5**
xxxxx162	Baseline	10	0.5	0.9	3.32	2.09	1.18	0.60	0.27	0.11
xxxxx162	Centralized AM	10	0.5	0.9	2.61	1.49	0.77	0.35	0.14	0.05
xxxxx162	Decentralized AM	10	0.5	0.9	**2.42**	**1.19**	**0.53**	**0.21**	**0.07**	**0.02**
xxxxx163	Baseline	75	1	0.9	28.75	27.30	25.86	24.41	22.97	21.54
xxxxx163	Centralized AM	75	1	0.9	28.75	27.02	25.45	23.97	22.52	21.09
xxxxx163	Decentralized AM	75	1	0.9	28.75	**26.86**	**25.00**	**23.21**	**21.54**	**20.01**
xxxxx164	Baseline	150	2	0.9	**59.42**	**57.95**	**56.48**	**55.00**	**53.53**	**52.06**
xxxxx164	Centralized AM	150	2	0.9	95.67	93.75	91.92	90.20	88.59	87.05
xxxxx164	Decentralized AM	150	2	0.9	82.58	80.68	78.78	76.88	74.98	73.08

AM repair time = 0,5 (AM = 0,5 CP); AM repair time = 1 (CP = AM); AM repair time = 2 (AM = 2 CP).

Table 5. Expected backorder costs ($).

Item	**Scenario**	**m**	**Repair time**	**AM prob**	**0**	**1**	**2**	**3**	**4**	**5**
xxxxx162	Baseline	10	0,5	0,9	1 327	835	472	240	109	44
xxxxx162	Centralized AM	10	0,5	0,9	1 043	597	309	140	55	19
xxxxx162	Decentralized AM	10	0,5	0,9	**970**	**477**	**212**	**83**	**28**	**8**
xxxxx163	Baseline	75	1	0,9	114,986	109,208	103,431	97,657	91,894	86,157
xxxxx163	Centralized AM	75	1	0,9	114,986	108,062	101,793	95,869	90,083	84,378
xxxxx163	Decentralized AM	75	1	0,9	114,986	**107,451**	**100,019**	**92,856**	**86,157**	**80,059**
xxxxx164	Baseline	150	2	0,9	**267 410**	**260 778**	**254 147**	**247 515**	**240 884**	**234252**
xxxxx164	Centralized AM	150	2	0,9	430 519	421 894	413 649	405 921	398 664	391730
xxxxx164	Decentralized AM	150	2	0,9	371 600	363 050	354 500	345 950	337 402	328857

AM repair time = 0,5 (AM = 0,5 CP); AM repair time = 1 (CP = AM); AM repair time = 2 (AM = 2 CP).

AM is not viable for spare parts when the AM repair time is superior to CP repair time (appendix C). So, the remaining analysis focuses only on when the repair time is inferior to or equal to CP repair time (AM = 0,5 CP and AM = CP).

6. The impact of the demand profile

This section aims to evaluate the two scenarios (centralized AM and decentralized AM) given different cases of demand profiles of spare parts known as fast, slow, and non-moving (FSN) spare parts (Ferreira et al., 2018). This experimentation is based on the parameters and the compliance of demand distribution of FSN spare parts. Such strategy reflects the reality of spare parts inventory management, specifically in the aircraft industry, where uncertainty about the aircraft's lifetime, the components' reliability, and the failure cost are observed.

For the first group (N), we consider non-moving spare parts; usually, the annual demand is less than ten (10) units for this type of spare part (Knofius, Van Der Heijden, et al., 2016). Let's assume that the annual demand rate equals ten (10) for the three scenarios models and two different repair times, as shown in Figure 4. We have the slow-moving spare part for the second group (S), and the annual demand is estimated to be between 10 and 100 units (Knofius, Van Der Heijden, et al., 2016). In this study, we assume that the yearly demand rate is seventy-five (75) units for the three scenarios models and for two different repair times, as shown in Figure 4. In the third group (F), we consider the fast-moving spare parts, and the annual demand is estimated to be more than 100 units (Knofius, Van Der Heijden, et al., 2016). In this study, we assume that the annual demand rate is 150 units for the three scenarios models and for two different repair times, as shown in figure 4. The analysis is performed for stock level 0.

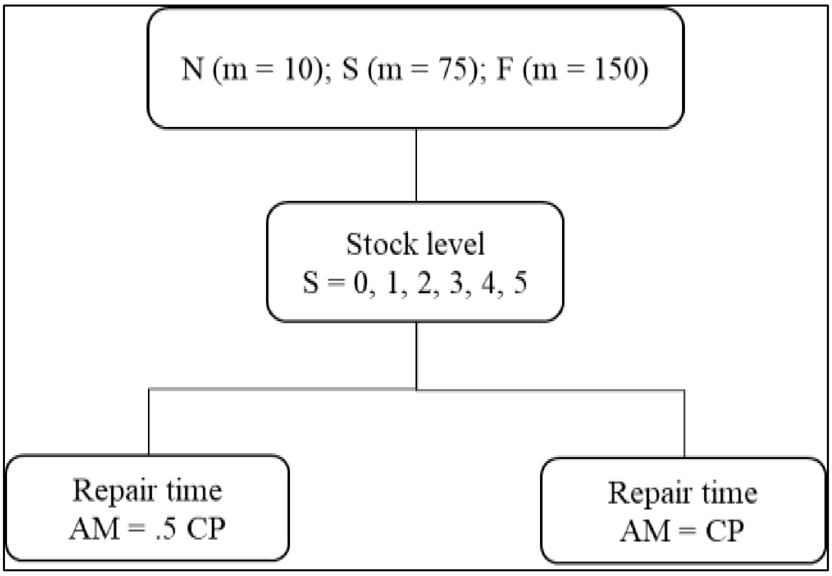

Figure 4. Repair time relation between CP and AM

The objective is to evaluate the impact of the repair time on AM integration in three scenarios depending on spare parts groups. Moreover, we want to estimate the EBO quantity and the relative cost depending on the repair time for different potential AM integration (AM probabilities). Hence, it gives which scenario is the best solution when the repair time of AM is equal to or inferior to CP. Tables 6 summarize the main result after executing the different scenarios for the spare part "xxxxx162". The results for all parts are presented in appendix C.

Based on the spare parts EBO indicator, Table 6, the decentralized scenario of AM is the optimal solution for integrating AM for the three groups (non-moving, slow-moving, and fast-moving parts). Table 6 shows that for non-moving spare parts (N), it is possible to achieve the lowest level of EBO of spare parts compared to slow (S) and fast-moving spare parts (F). But, when the AM repair time is equal to CP (AM = CP) and AM probability equal to 0.1 the centralized scenario of AM is the optimal solution for integrating AM for slow-moving and fast-moving parts. Also, at the stock level 0 and repair probability 0.1 there is no difference between the three scenarios.

Table 6. EBO, repair time and AM repair probability for different scenarios for stock level (xxxxx162).

m	Scenario	Repair time	AM prob	0	1	2	3	4	5
N	Baseline	0.5	0.1	3.32	2.09	1.18	0.60	0.27	0.11
N	Centralized AM	0.5	0.1	3.24	2.01	1.13	0.57	0.25	0.10
N	Decentralized AM	0.5	0.1	**3.22**	**1.99**	**1.10**	**0.55**	**0.24**	**0.09**
S	Baseline	0.5	0.1	24.88	23.47	22.06	20.65	19.26	17.88
S	Centralized AM	0.5	0.1	24.29	22.74	21.30	19.89	18.51	17.15
S	Decentralized AM	0.5	0.1	**24.14**	**22.70**	**21.27**	**19.83**	**18.42**	**17.03**
F	Baseline	0.5	0.1	49.77	48.36	46.94	45.53	44.12	42.71
F	Centralized AM	0.5	0.1	48.58	46.94	45.44	44.01	42.59	41.18
F	Decentralized AM	0.5	0.1	**48.28**	**46.84**	**45.40**	**43.96**	**42.53**	**41.09**
N	Baseline	0.5	0.9	3.32	2.09	1.18	0.60	0.27	0.11
N	Centralized AM	0.5	0.9	2.61	1.49	0.77	0.35	0.14	0.05
N	Decentralized AM	0.5	0.9	**2.42**	**1.19**	**0.53**	**0.21**	**0.07**	**0.02**
S	Baseline	0.5	0.9	24.88	23.47	22.06	20.65	19.26	17.88
S	Centralized AM	0.5	0.9	19.56	17.92	16.47	15.15	13.93	12.80
S	Decentralized AM	0.5	0.9	**18.18**	**16.32**	**14.53**	**12.87**	**11.38**	**10.07**
F	Baseline	0.5	0.9	49.77	48.36	46.94	45.53	44.12	42.71
F	Centralized AM	0.5	0.9	39.12	37.37	35.75	34.25	32.83	31.46
F	Decentralized AM	0.5	0.9	**36.36**	**34.48**	**32.61**	**30.75**	**28.92**	**27.13**
N	Baseline	1	0.1	3.32	2.09	1.18	0.60	0.27	0.11
N	Centralized AM	1	0.1	3.32	**2.06**	**1.17**	**0.60**	**0.27**	**0.11**
N	Decentralized AM	1	0.1	3.32	2.08	1.18	0.60	0.27	0.11
S	Baseline	1	0.1	24.88	23.47	22.06	20.65	19.26	17.88
S	Centralized AM	1	0.1	24.88	**23.24**	**21.74**	**20.32**	**18.93**	**17.57**
S	Decentralized AM	1	0.1	24.88	23.45	22.01	20.58	19.16	17.77
F	Baseline	1	0.1	49.77	48.36	46.94	45.53	44.12	42.71
F	Centralized AM	1	0.1	49.77	**48.02**	**46.40**	**44.89**	**43.45**	**42.02**
F	Decentralized AM	1	0.1	49.77	48.33	46.89	45.45	44.02	42.58
N	Baseline	1	0.9	3.32	2.09	1.18	0.60	0.27	0.11
N	Centralized AM	1	0.9	3.32	2.06	1.17	0.60	0.27	0.11
N	Decentralized AM	1	0.9	3.32	**2.01**	**1.15**	**0.59**	**0.27**	**0.11**
S	Baseline	1	0.9	24.88	23.47	22.06	20.65	19.26	17.88
S	Centralized AM	1	0.9	24.88	23.24	21.74	20.32	18.93	17.57
S	Decentralized AM	1	0.9	24.88	**23.03**	**21.23**	**19.57**	**18.09**	**16.77**
F	Baseline	1	0.9	49.77	48.36	46.94	45.53	44.12	42.71
F	Centralized AM	1	0.9	49.77	48.02	46.40	44.89	43.45	42.02
F	Decentralized AM	1	0.9	49.77	**47.89**	**46.02**	**44.16**	**42.32**	**40.54**

7. Sensitivity analysis

We conduct a sensitivity analysis to investigate the demand and repair probability impacts for the three scenarios. In doing so, we expect to further understand the strengths and weaknesses of different supply chain configurations under various conditions. Figure 5 presents the backorders vs. demand. The demand represents the non-moving, slow-moving, and fast-moving spare parts. It shows clearly that the variations of the backorders are related to the stock level variation. Moreover, the decentralization configuration of the supply chain is the optimal option for spare parts-based-AM integration. Only for the non-moving parts (m = 10), from stock level 5 and up, there is no difference between the three scenarios.

AM integration relies on the repair time, which should be inferior to or equal to CP repair time. The repair time is used as the performance value of assets to make smarter decisions for asset management. It represents a maintenance metric that measures the average time required to troubleshoot and repair failed equipment. It reflects how quickly an organization can respond to unplanned breakdowns and improve them. The time to repair is also used as a baseline for increasing efficiency and finding ways to limit unplanned downtime.

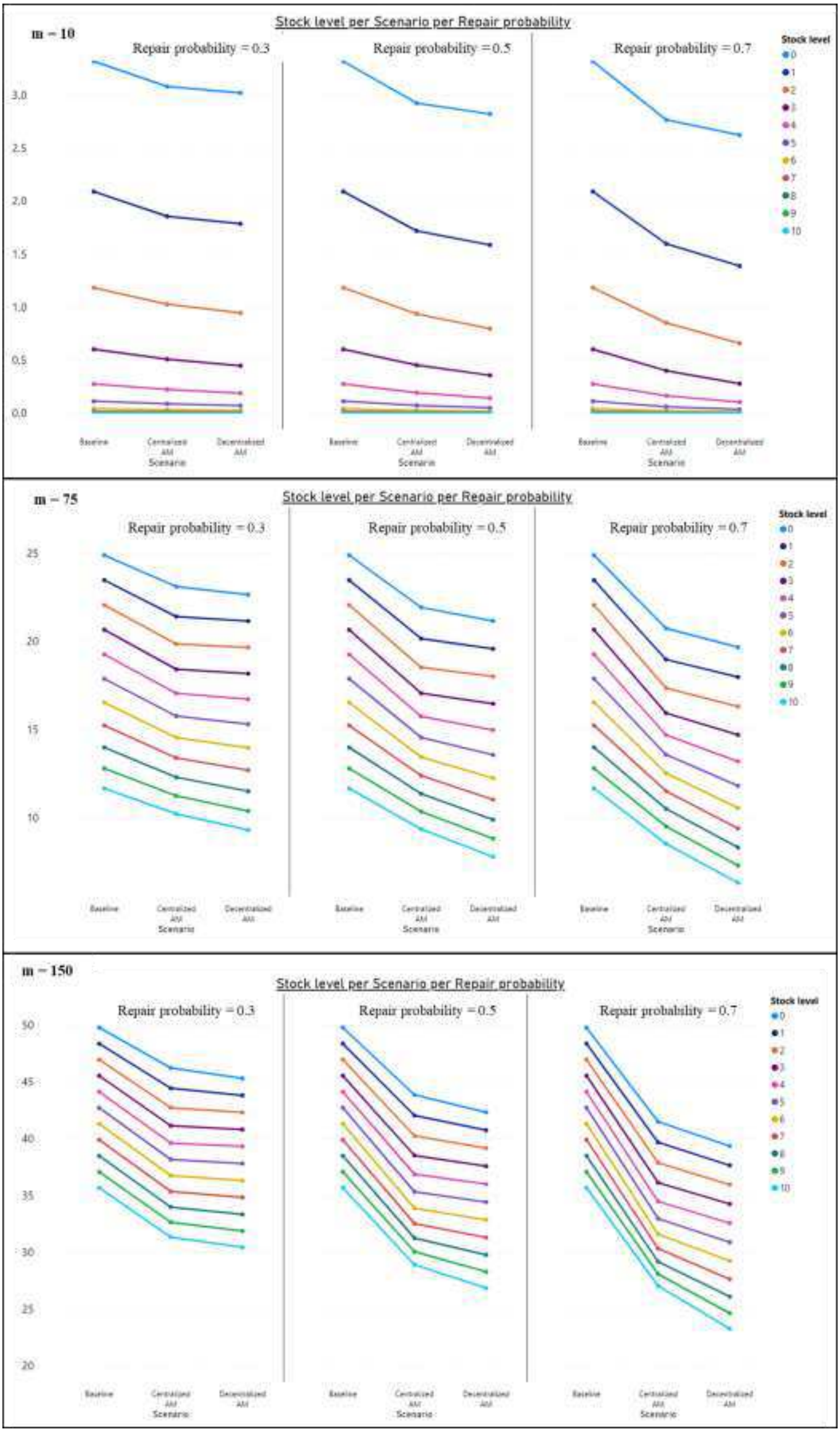

Figure 5. Demand vs. Repair probability for FSN parts.

8. Discussion and managerial implications

This work established a scenario modeling for assessing the potential use of AM to supply aircraft spare parts. These models consider various factors associated with the spare part supply chain attributes and AM system operation characteristics. The analysis showed that when AM repair time is inferior to CP repair time, the best scenario for AM manufacturing integration is scenario 3 (model 2), which considers decentralized AM location. And when AM repair time equals CP repair time (AM=CP) and AM repair probability is superior to 70%, the decentralized scenario still the optimal integration solution. However, when the AM repair time equals CP repair time and the AM repair probability is inferior to 70%, the centralized scenario is the optimal integration solution. Finally, when AM repair time is superior to CP repair time, the best scenario is the baseline scenario; thus, no change is required. The whole analysis is based on four dimensions: Stock level, demand, repair time, and repair probability. Figure 6 shows the decision tree diagram based on the whole result, and Figure 7 illustrates a decision example for stock levels 5.

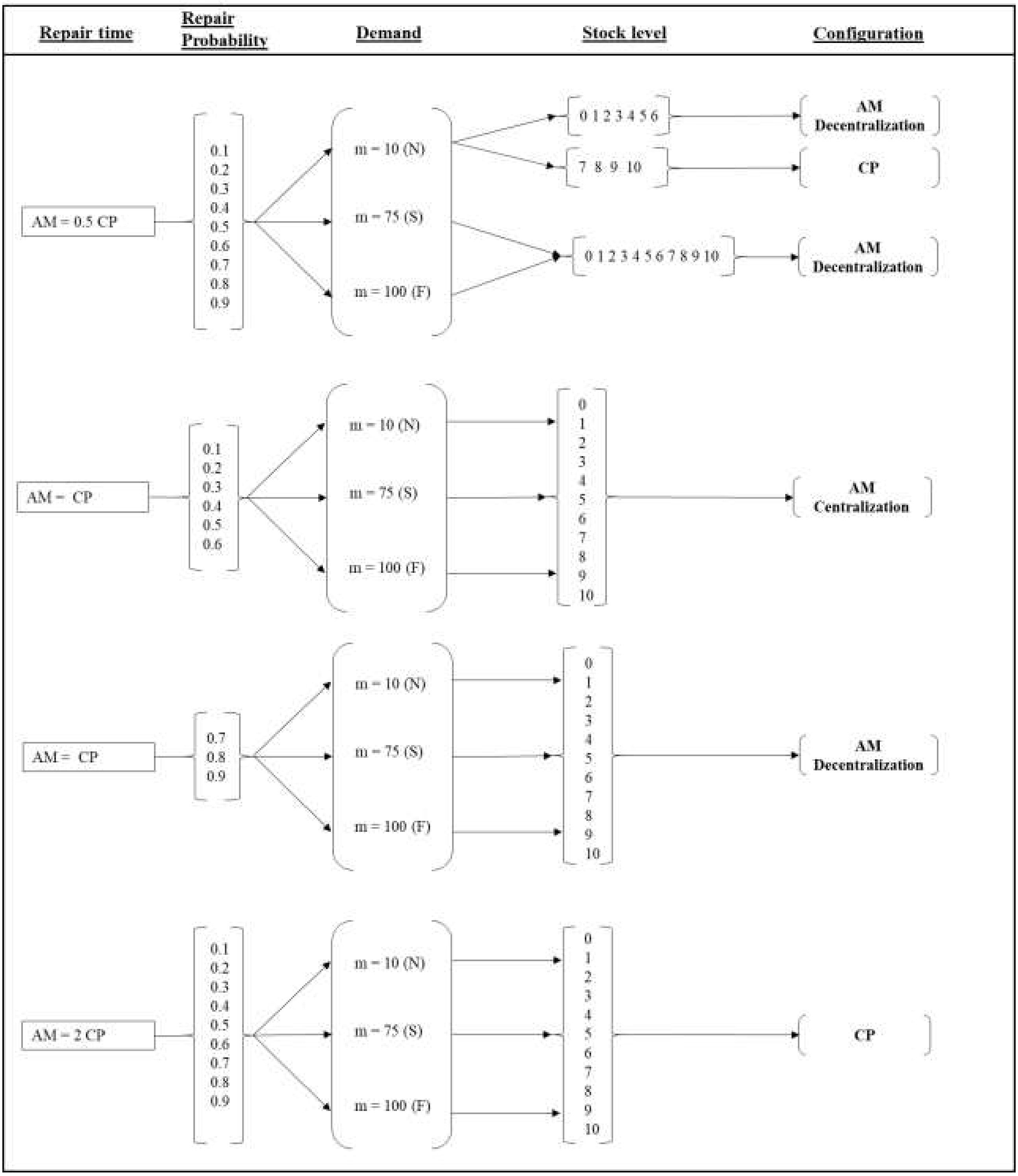

Figure 6. Decision tree diagram.

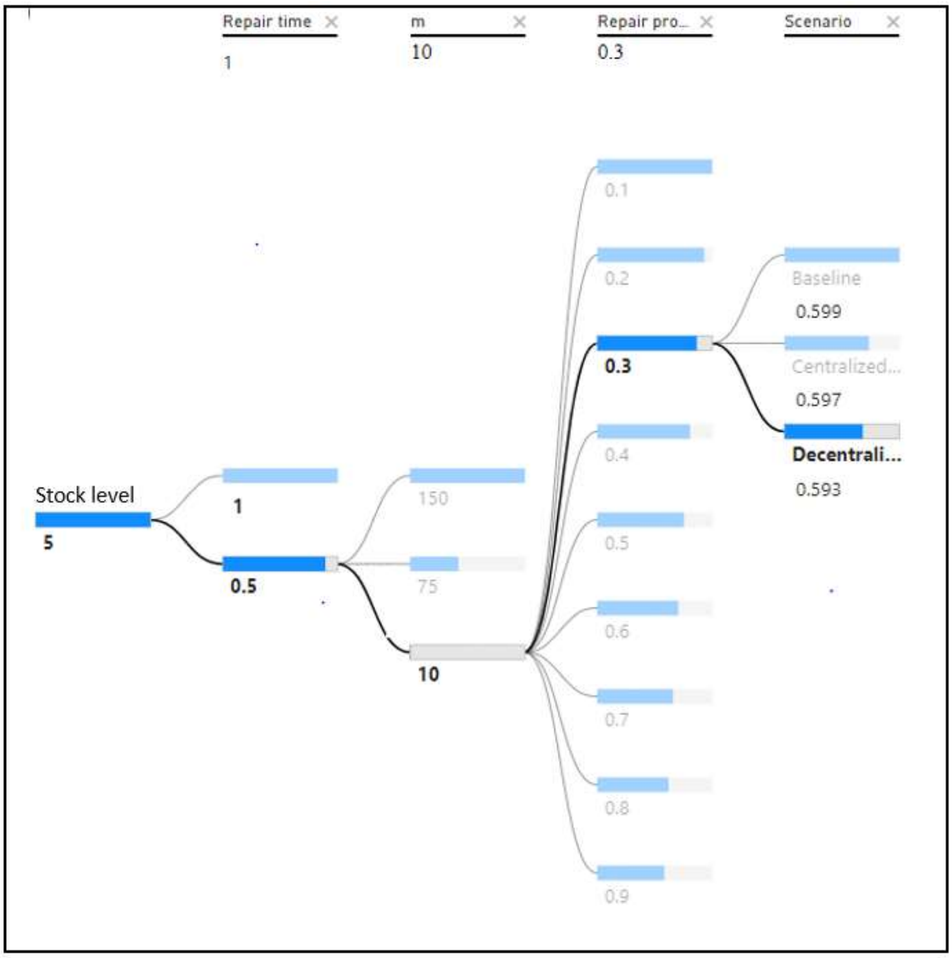

Figure 7. Decision example for stock levels 5

Knowing the AM is more appropriate for small batch sizes, the non-moving or slow-moving spare parts could be an advantageous opportunity to integrate AM. The study showed that non-moving spare parts are the most suitable categories of spare parts for the AM, followed by slow-moving and fast-moving. Therefore, some criteria should be validated, such as the repair time and the probability of parts reparation with AM. But at the same time, it highlights that this result is valid under certain conditions if we have the repair time inferior to CP and the AM probability of making parts is significant (more than 70%). Compared to the literature, this quantitative scenarios modeling study converges on the same result that the decentralized supply chain configuration is the optimal one (Walter et al. (2004); Holmström et al. (2010); Khajavi, Partanen, and Holmström (2014); Liu et al. (2014); Li et al. (2017); (Li et al., 2019); Montero et al., 2020). Decentralization usually ensures a rapid response to demand, fast deliveries (which result in reduced maintenance time), low transportation costs, and high flexibility (Alvarez and van der Heijden 2014). Having many decentralized centers and expecting to guarantee a high service level implies keeping a large amount of stock, resulting in high holding costs and reduced inventory turnover (Cantini et al., 2022). However, since the demand for spare parts is usually unpredictable, sporadic, and slow-moving, the centralized supply chain is more suitable for high demand rates (Liu et al., 2014; Li et al., 2017; Li et al., 2019).

In the literature, most of the decision-making parameters are based on the total cost, such as production cost (Holmström et al. (2010)) and total operating cost ((Walter et al. (2004); Khajavi, Partanen, and Holmström (2014); Li et al. (2017); Ashour Pour et al. (2017); (Li et al., 2019)). The total cost contains inventory, production, distribution, Inventory obsolescence, life-cycle, holding, stock-carrying, ordering, and transportation costs. Some authors use different decision-making methods. Liu et al. (2014) use a Safty inventory reduction to choose the best configuration. (Montero et al., 2020) Process model; (Cantini et al., 2022) use decision tree cost-based comparison using spare parts demand, purchasing costs, transportation costs, and backorder cost. In this study, we provide different decision parameters such as backorders, stock level, and total cost using other variables such as demand, repair time, and repair probability. This will allow managers and practitioners to decide not only on the costs but also on the inventory parameters and variables, especially if there is a tradeoff between the inventory and the cost.

Decentralized manufacturing is an alternative means of creating parts that have certain traits that centralized manufacturing does not. The most obvious positive is that decentralized manufacturing has flexibility. Factories that are decentralized produce lower volumes of parts but can more easily adjust to changes in demand and disruptions to the market as a whole. Additive manufacturing naturally fits the model of decentralized manufacturing due to its high degree of flexibility, lower volume of production, and overall potential for customization. The benefits of having a smaller yet more agile means of producing also contribute to lowering the overall costs of the supply chain.

Although the decentralization of additive manufacturing is the most dominant in the manufacture of spare parts. In the context of aeronautics, for complex and expensive parts, decentralization cannot be the most optimal option. The choice depends mainly on the variables and the deciding factors such as the repair time the level of stock as well as the probability of making the parts in additive. At a low stock level and a significant probability does not always favor decentralization but rather centralization. As shown in Figure 6, from stock level 7 centralized is the optimal option for non-moving parts which is the case of aircraft spare parts. This finding could lead to avoiding unprofitable investments at this level. The integration of the additive in aeronautics requires an in-depth analysis in order to choose the best scenario whether decentralization or centralization taking into consideration the spare parts value which is the case of aircraft spare parts.

9. Conclusion

In this paper, we analyze the potential integration of AM in the multi-echelon system. As stated in the introduction, the objective of this paper was to identify the main factors that affect the decision on a multi-echelon configuration system for integrating additive manufacturing for aircraft spare parts. Three scenario models were considered to identify the best configuration of the multi-echelon system. This work established a scenario modeling for assessing the use of AM to supply aircraft spare parts. These models consider various factors associated with the spare part supply chain attributes and AM system operation characteristics. The paper focused on demonstrating the modeling and analysis of aircraft spare parts in a multi-echelon system-based AM. This analysis showed that the best scenario for AM manufacturing integration is scenario 3 (model 2), which considers decentralized AM location. The analysis is based on the parameters chosen for the calculation in Table 1. Model 2 for the AM decentralization represents the optimal solution for integrating the AM for spare parts inventory management. Increasing the annual demand rate for the spare parts categories increases the EBO quantity and, consequently, the spare parts inventory cost. Knowing the AM is limited to small batch size, the non-moving or slow-moving spare parts could be a good opportunity for the integration of AM where the quantity of parts to manufacture is limited and may need a huge setup time and tooling. This could be the best alternative since the quantity of the EBO justifies the investment in AM. Therefore, for the fast-moving parts, the investment should be justified.

The performance of the aircraft spare parts relies on the service level provided to the customer. Hence, optimizing spare parts in the supply chain is paramount when choosing the right configuration between centralization, decentralization, or hybrid systems. Therefore, practitioners and managers need more quantitative methods to compare different supply chain configurations instead of based on their experience. The paper found in the literature focuses more on qualitative methods by using the inventory costs factors such as holding cost and transportation to evaluate the supply configuration for the AM integration. It lacks the quantitative comparison of the CP and AM, where the decision becomes difficult to be taken to provide evidence that the adoption of AM spare parts can guarantee higher performance than the CP. Thus, the theoretical contribution resides in overcoming these challenges by using the quantitative scenarios modeling carried out in this paper to provide a step-wise process to evaluate the integration of AM in the spare parts supply chain and which configuration is the most suitable. Besides, the study emphasizes the factors that impact the decision, such as the repair time, repair probability, cost, and demand rate. At a practical level, the contribution of this study is to provide companies with a quick and user-friendly method for determining how to design AM spare parts supply chain. The results of this study will help managers and practitioners optimize the allocation of stocks inside company warehouses (choosing between centralization, decentralization, and hybrid configuration), and the selection of the appropriate items' manufacturing technology (AM or CP). Decision-makers and managers can use the proposed system to monitor their spare parts inventory management and take appropriate actions based on continuous data monitoring.

As a limitation, the example calculation is carried out without lateral shipment. Considering the lateral shipment analysis in the multi-echelon system would be relevant in order to analyze the impact of spare parts shipment between RMCs on the final decision. Also, the data used for the present study is adapted from the existing literature. It would be relevant to consider a real case study to test the models in complex environments such as aerospace. As a future direction, it will be relevant to consider different parameters using an experimental design to evaluate the interaction between parameters to develop the best combination of parameters that optimize the stock level.

Appendix A: Mathematical formulation for Model 1

In this scenario, we propose the integration of AM and centralization in the CMC. Thus, the CMC will supply the RMC with repairable parts and AM parts (Figure 8).

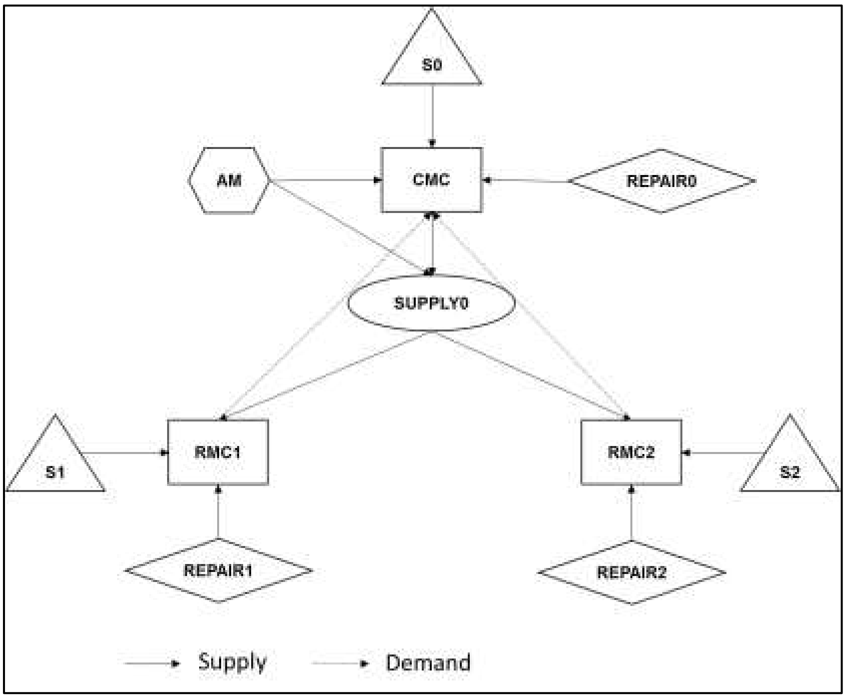

Figure 8. Inventory system with centralized AM integration

Total Expected Backorder for the Depot

First, we calculate the average demand repairable at CMC plus the fraction of the average demand not repairable from the RMC. Since we integrate the AM at CMC, let ϕ be the probability that the parts will produce by AM and $(1-\phi)$the probability that the CP will repair the parts. Thus, the average demand for repairable equals:

$$\lambda_{i0}^{*} = \left(\lambda_{i0}\rho_{i0} + \sum_{j=1}^{2} \lambda_{ij}\left(1-\rho_{ij}\right) \right)\left(1-\varphi_{i0}\right) \tag{7}$$

The average demand of repairable with AM is equal to:

$$\omega_{i0} = \varphi_{i0}\left(\lambda_{i0}\rho_{i0} + \sum_{j=1}^{2} \lambda_{ij}\left(1-\rho_{ij}\right) \right) \tag{8}$$

Let γ be the meantime to repair the parts that will be done by AM. Thus, the number of parts under repair and AM that are repairable at the CMC equals:

For repair: $$\mu_{i0}^{RP} = \nu_{i0}\lambda_{i0}^{*} \quad (9)$$

For AM: $$\mu_{i0}^{AM} = \gamma_{i0}\omega_{i0} \quad (10)$$

$$\mu_{i0} = \nu_{i0}\lambda_{i0}^{*} + \gamma_{i0}\omega_{i0} \quad (11)$$

$$\mu_{i0} = \nu_{i0}\left(\lambda_{i0}\rho_{i0} + \sum_{j=1}^{2}\lambda_{ij}\left(1-\rho_{ij}\right)\right)\left(1-\varphi_{i0}\right) + \gamma_{i0}\varphi_{i0}\left(\lambda_{i0}\rho_{i0} + \sum_{j=1}^{2}\lambda_{ij}\left(1-\rho_{ij}\right)\right) \quad (12)$$

The expected backorder at the CMC for repair is equal to:

$$\mathrm{EBO}_{i0}^{RP}\left(s_{i0}\right) = \mu_{i0}^{RP}\frac{\left(\mu_{i0}^{RP}\right)^{s_{i0}}}{s_{i0}!}e^{-\mu_{i0}^{RP}} + \left(\mu_{i0}^{RP} - s_{i0}\right)\left(1-\sum_{l=0}^{s_{i0}}\frac{\left(\mu_{i0}^{RP}\right)^{l}}{l!}e^{-\mu_{i0}^{RP}}\right) \quad (13)$$

The expected backorder at the CMC for AM is equal to:

$$\mathrm{EBO}_{i0}^{AM}\left(s_{i0}\right) = \mu_{i0}^{AM}\frac{\left(\mu_{i0}^{AM}\right)^{s_{i0}}}{s_{i0}!}e^{-\mu_{i0}^{AM}} + \left(\mu_{i0}^{AM} - s_{i0}\right)\left(1-\sum_{l=0}^{s_{i0}}\frac{\left(\mu_{i0}^{AM}\right)^{l}}{l!}e^{-\mu_{i0}^{AM}}\right) \quad (14)$$

The total expected backorder at the CMC is as follows :

$$\mathrm{EBO}_{i0}\left(s_{i0}\right) = \mu_{i0}\frac{\left(\mu_{i0}\right)^{s_{i0}}}{s_{i0}!}e^{-\mu_{i0}} + \left(\mu_{i0} - s_{i0}\right)\left(1-\sum_{l=0}^{s_{i0}}\frac{\left(\mu_{i0}\right)^{l}}{l!}e^{-\mu_{i0}}\right) \quad (16)$$

Total Expected Backorder for the base

Let α be the meantime between shipment and receipt for the parts that will be done by AM. Let's assume that the demand follows a Poisson process. Since the sum of Poisson processes is a Poisson process (Sherbrooke 1968), the average demand at the RMC will be composed of repairable parts at the base and the average fraction demand resupplied by CMC. Thus, the number of repairs is calculated as follows.

For repairable:

$$\mu_{ij}^{RP} = \lambda_{ij}\left[\rho_{ij}\nu_{ij} + (1-\varphi_{i0})(1-\rho_{ij})\left(\tau_{ij} + \frac{EBO_{i0}^{RP}(s_{i0}|\mu_{i0})}{\lambda_{i0}}\right)\right] \quad (17)$$

For AM:

$$\mu_{ij}^{AM} = \lambda_{ij}\varphi_{i0}\left[(1-\rho_{ij})\left(\alpha_{ij} + \frac{EBO_{i0}^{AM}(s_{i0}|\mu_{i0})}{\omega_{i0}}\right)\right] \quad (18)$$

Thus, the total number of repairs and AM equals:

$$\mu_{ij}^{RP} = \lambda_{ij}\left(\left[\rho_{ij}\nu_{ij} + (1-\varphi_{i0})(1-\rho_{ij})\left(\tau_{ij} + \frac{EBO_{i0}^{RP}(s_{i0}|\mu_{i0})}{\lambda_{i0}}\right)\right] + \varphi_{ij}\left[(1-\rho_{ij})\left(\alpha_{ij} + \frac{EBO_{i0}^{AM}(s_{i0}|\mu_{i0})}{\omega_{i0}}\right)\right]\right) \quad (19)$$

Where $(1-\varphi_{i0})(1-\rho_{ij})\left(\tau_{ij} + \frac{EBO_{i0}^{RP}(s_{i0}|\mu_{i0})}{\lambda_{i0}}\right)$ is the number of repair parts from CMC to RMC, and $\varphi_{i0}\left[(1-\rho_{ij})\left(\alpha_{ij} + \frac{EBO_{i0}^{AM}(s_{i0}|\mu_{i0})}{\omega_{i0}}\right)\right]$ is the number of parts from CMC to RMC. The quantity $EBO_{i0}^{RP}(s_{i0}|\mu_{i0}^{RP})$ is the expected number of resupplies remaining at the depot at a random point in time for repair and $EBO_{i0}^{AM}(s_{i0}|\mu_{i0}^{AM})$ is the expected number of resupplies outstanding at the depot for AM. The quantity $\frac{EBO_{i0}^{RP}(s_{i0}|\mu_{i0}^{RP})}{\lambda_{i0}}$ represents the average delay added to resupply requests daily, resulting from the fact that the CMC does not always have stock on the shelf. t_{ij} represents the order-and-ship time from the CMC to the RMC. The quantity $\frac{EBO_{i0}^{AM}(s_{i0}|\mu_{i0}^{AM})}{\omega_{i0}}$ represents the average delay added daily to resupply requests, resulting from the fact that the depot does not always have stock on the shelf for AM. And the α_{ij} represents the order-and-ship time from the CMC to the RMC for AM. The expected backorder at the RMC for repair is as follows:

$$\mathrm{EBO}_{\mathrm{ij}}^{\mathrm{RP}}\left(s_{ij}\right)=\mu_{\mathrm{ij}}^{\mathrm{RP}}\frac{\left(\mu_{\mathrm{ij}}^{\mathrm{RP}}\right)^{s_{ij}}}{s_{ij}!}e^{-\mu_{\mathrm{ij}}^{\mathrm{RP}}}+\left(\mu_{\mathrm{ij}}^{\mathrm{RP}}-s_{ij}\right)\left(1-\sum_{l=0}^{s_{ij}}\frac{\left(\mu_{\mathrm{ij}}^{\mathrm{RP}}\right)^{l}}{l!}e^{-\mu_{\mathrm{ij}}^{\mathrm{RP}}}\right) \tag{20}$$

The expected backorder at the RMC for AM is as follows:

$$\mathrm{EBO}_{\mathrm{ij}}^{\mathrm{AM}}\left(s_{ij}\right)=\mu_{\mathrm{ij}}^{\mathrm{AM}}\frac{\mu_{\mathrm{ij}}^{\mathrm{AM}}}{s_{ij}!}e^{-\mu_{\mathrm{ij}}^{\mathrm{AM}}}+\left(\mu_{\mathrm{ij}}^{\mathrm{AM}}-s_{ij}\right)\left(1-\sum_{l=0}^{s_{ij}}\frac{\left(\mu_{\mathrm{ij}}^{\mathrm{AM}}\right)^{l}}{l!}e^{-\mu_{\mathrm{ij}}^{\mathrm{AM}}}\right) \tag{21}$$

The total expected backorder at the RMC is equal to:

$$\mathrm{EBO}_{\mathrm{ij}}\left(s_{\mathrm{ij}}\right)=\mu_{\mathrm{ij}}\frac{\left(\mu_{\mathrm{ij}}\right)^{s_{\mathrm{ij}}}}{s_{\mathrm{ij}}!}e^{-\mu_{\mathrm{ij}}}+\left(\mu_{\mathrm{ij}}-s_{\mathrm{ij}}\right)\left(1-\sum_{l=0}^{s_{\mathrm{ij}}}\frac{\left(\mu_{\mathrm{ij}}\right)_{ij}^{l}}{l!}e^{-\mu_{\mathrm{ij}}}\right) \tag{22}$$

Appendix B: Mathematical formulation for Model 2

In this scenario, we propose that CMC support the RMC only for the parts that are not repairable at the RMC. Nevertheless, the parts obtained by the use of AM will be manufactured at the RMC. Thus, the RMC center will have AM machines to cover the demand that will be potential for the AM (Figure 9).

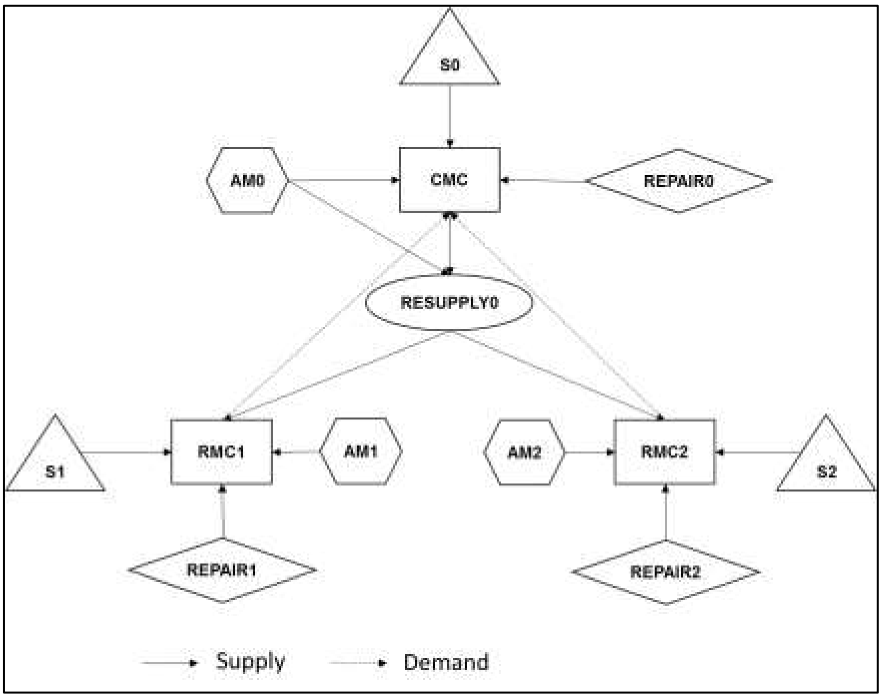

Figure 9. Inventory system with decentralized AM integration.

Total Expected Backorder for the CMC:

First, we calculate the average demand repairable at CMC plus the fraction of the average demand that is not repairable from the RMC. Since we integrate the AM at CMC, let ϕ be the probability that the parts will be done by AM and $(1-\phi)$the probability that the parts will be done by CP. Thus, the average demand is as follows:

Average demand repairable with no AM at the CMC:

$$\lambda_{i0}^{RP*} = \lambda_{i0}\rho_{i0}\left(1-\varphi_{i0}\right) \tag{22}$$

Fraction average demand repairable from the base with no AM:

$$\lambda_{i0}^{RP**} = \sum_{j=1}^{2}\lambda_{ij}\left(1-\rho_{ij}\right) \tag{23}$$

Average demand repairable with AM at CMC:

$$\omega_{i0} = \varphi_{i0}\lambda_{i0}\rho_{i0} \tag{24}$$

Thus, the number of parts that is not repairable at the CMC is as follows:

For repair:

$$\mu_{i0}^{RP} = \nu_{i0}\lambda_{i0}^{RP*} + \nu_{i0}\lambda_{i0}^{RP*} \tag{25}$$

For AM: $$\mu_{i0}^{AM} = \gamma_{i0}\omega_{i0} \tag{26}$$

Thus, the total number of repairs at CMC:

$$\mu_{i0} = \nu_{i0}\lambda_{i0}^{RP*} + \nu_{i0}\lambda_{i0}^{RP**} + \gamma_{i0}\omega_{i0} \tag{27}$$

$$\mu_{i0} = \nu_{i0}\lambda_{i0}\rho_{i0}\left(1-\varphi_{i0}\right) + \nu_{i0}\sum_{j=1}^{2}\lambda_{ij}\left(1-\rho_{ij}\right) + \gamma_{i0}\varphi_{i0}\lambda_{i0}\rho_{i0} \tag{28}$$

Thus, the total Expected Backorder for the depot.

$$\mathrm{EBO}_{i0}\left(s_{i0}\right) = \mu_{i0}\frac{\left(\mu_{i0}\right)^{s_{i0}}}{s_{i0}!}e^{-\mu_{i0}} + \left(\mu_{i0} - s_{i0}\right)\left(1 - \sum_{l=0}^{s_{i0}}\frac{\left(\mu_{i0}\right)_{ij}^{l}}{l!}e^{-\mu_{i0}}\right) \tag{29}$$

Total Expected Backorder for the base:

Let's assume that demand follows a Poisson process. The average demand at the RMC will be composed of repairable parts at the base and the average fraction demand resupplied by CMC. Thus, a number of repairs are as follows:

Average demand repairable at RMC with no AM

$$\lambda_{ij}^{*} = \lambda_{ij}\rho_{ij}\left(1-\varphi_{ij}\right) \tag{30}$$

Average demand repairable at RMC with AM

$$\omega_{ij} = \varphi_{ij}\lambda_{ij}\rho_{ij} \tag{31}$$

The number of repairs with no AM at RMC is as follows:

$$\mu_{ij}^{RP*} = \left(1-\varphi_{ij}\right)\lambda_{ij}\rho_{ij}\nu_{ij} \tag{32}$$

The number of repairs resupplied with no AM from CMC to RMC is as follows:

$$\mu_{ij}^{RP**} = \lambda_{ij}\left(1-\varphi_{ij}\right)\left(1-\rho_{ij}\right)\left(\tau_{ij} + \frac{\mathrm{EBO}_{i0}^{RP}\left(s_{i0} \middle| \mu_{i0}\right)}{\lambda_{i0}}\right) \tag{33}$$

Thus, the total repair is as follows:

$$\mu_{ij}^{RP} = \lambda_{ij}\left(1-\varphi_{ij}\right)\left[\rho_{ij}\nu_{ij} + \left(1-\rho_{ij}\right)\left(\tau_{ij} + \frac{\mathrm{EBO}_{i0}^{RP}\left(s_{i0} \middle| \mu_{i0}\right)}{\lambda_{i0}}\right)\right] \tag{34}$$

The number of repairs with AM at CMC is as follows:

$$\mu_{ij}^{AM} = \lambda_{ij}\varphi_{ij}\gamma_{ij}\rho_{ij} \tag{35}$$

The total number of repairs at CMC is as follows:

$$\mu_{ij}^{RP} = \lambda_{ij}\left[\left(1-\varphi_{ij}\right)\left(\rho_{ij}\nu_{ij} + \left(1-\rho_{ij}\right)\left(\tau_{ij} + \frac{EBO_{i0}^{RP}\left(s_{i0}|\mu_{i0}\right)}{\lambda_{i0}}\right)\right) + \varphi_{ij}\gamma_{ij}\rho_{ij}\right] \tag{36}$$

The quantity $EBO_{i0}^{RP}\left(s_{i0}|\mu_{i0}^{RP}\right)$ is the expected number of resupplies outstanding at the CMC at a random point in time for repair. The quantity $\frac{EBO_{i0}^{RP}\left(s_{i0}|\mu_{i0}^{RP}\right)}{\lambda_{i0}}$ represents the average delay added daily to resupply requests, resulting from the fact that the CMC does not always have stock on the shelf. The expected backorder at the RMC for repair is as follows:

$$EBO_{ij}^{RP}\left(s_{ij}\right) = \mu_{ij}^{RP}\frac{\left(\mu_{ij}^{RP}\right)^{s_{ij}}}{s_{ij}!}e^{-\mu_{ij}^{RP}} + \left(\mu_{ij}^{RP} - s_{ij}\right)\left(1-\sum_{l=0}^{s_{ij}}\frac{\left(\mu_{ij}^{RP}\right)^{l}}{l!}e^{-\mu_{ij}^{RP}}\right) \tag{37}$$

The expected backorder at the RMC for AM is as follows:

$$EBO_{ij}^{AM}\left(s_{ij}\right) = \mu_{ij}^{AM}\frac{\left(\mu_{ij}^{AM}\right)^{s_{ij}}}{s_{ij}!}e^{-\mu_{ij}^{AM}} + \left(\mu_{ij}^{AM} - s_{ij}\right)\left(1-\sum_{l=0}^{s_{ij}}\frac{\left(\mu_{ij}^{AM}\right)^{l}}{l!}e^{-\mu_{ij}^{AM}}\right) \tag{38}$$

The total expected backorder at the RMC is as follows:

$$EBO_{ij}\left(s_{ij}\right) = \mu_{ij}\frac{\left(\mu_{ij}\right)^{s_{ij}}}{s_{ij}!}e^{-\mu_{ij}} + \left(\mu_{ij} - s_{ij}\right)\left(1-\sum_{l=0}^{s_{ij}}\frac{\left(\mu_{ij}\right)_{ij}^{l}}{l!}e^{-\mu_{ij}}\right) \tag{39}$$

Appendix C. Expected Backorder for different scenarios for xxxxx162

						Stock level					
Item	Model	Type	m	Repair time	AM prob	0	1	2	3	4	5
1	1	EBO_Baseline	10	0,5	0,1	3,32	2,09	1,18	0,60	0,27	0,11
1	2	Centralized AM	10	0,5	0,1	3,24	2,01	1,13	0,57	0,25	0,10
1	2	Centralized AM	10	0,5	0,5	2,92	1,72	0,93	0,45	0,19	0,07
1	2	Centralized AM	10	0,5	0,9	2,61	1,49	0,77	0,35	0,14	0,05
1	2	Centralized AM	10	0	0,1	3,32	2,06	1,17	0,60	0,27	0,11
1	2	Centralized AM	10	0	0,5	3,32	2,02	1,15	0,59	0,27	0,11
1	2	Centralized AM	10	0	0,9	3,32	2,06	1,17	0,60	0,27	0,11
1	2	Centralized AM	10	2	0,1	3,48	2,18	1,26	0,66	0,31	0,13
1	2	Centralized AM	10	2	0,5	4,11	2,68	1,65	0,94	0,49	0,23
1	2	Centralized AM	10	2	0,9	4,74	3,35	2,19	1,31	0,72	0,36
1	3	Decentralized AM	10	0,5	0,1	3,22	1,99	1,10	0,55	0,24	0,09
1	3	Decentralized AM	10	0,5	0,5	2,82	1,58	0,79	0,35	0,14	0,05
1	3	Decentralized AM	10	0,5	0,9	2,42	1,19	0,53	0,21	0,07	0,02
1	3	Decentralized AM	10	0	0,1	3,32	2,08	1,18	0,60	0,27	0,11
1	3	Decentralized AM	10	0	0,5	3,32	2,05	1,16	0,60	0,27	0,11
1	3	Decentralized AM	10	0	0,9	3,32	2,01	1,15	0,59	0,27	0,11
1	3	Decentralized AM	10	2	0,1	3,52	2,27	1,34	0,71	0,34	0,15
1	3	Decentralized AM	10	2	0,5	4,31	3,01	2,00	1,24	0,70	0,36
1	3	Decentralized AM	10	2	0,9	5,11	3,76	2,72	1,87	1,19	0,69
1	1	EBO_Baseline	75	0,5	0,1	24,88	23,47	22,06	20,65	19,26	17,88
1	2	Centralized AM	75	0,5	0,1	24,29	22,74	21,30	19,89	18,51	17,15
1	2	Centralized AM	75	0,5	0,5	21,92	20,16	18,52	17,05	15,74	14,55
1	2	Centralized AM	75	0,5	0,9	19,56	17,92	16,47	15,15	13,93	12,80
1	2	Centralized AM	75	0	0,1	24,88	23,24	21,74	20,32	18,93	17,57
1	2	Centralized AM	75	0	0,5	24,88	23,07	21,31	19,66	18,17	16,83
1	2	Centralized AM	75	0	0,9	24,88	23,24	21,74	20,32	18,93	17,57
1	2	Centralized AM	75	2	0,1	26,07	24,32	22,71	21,20	19,78	18,41
1	2	Centralized AM	75	2	0,5	30,80	28,98	27,19	25,46	23,81	22,27
1	2	Centralized AM	75	2	0,9	35,54	33,89	32,39	30,96	29,54	28,13
1	3	Decentralized AM	75	0,5	0,1	24,14	22,70	21,27	19,83	18,42	17,03
1	3	Decentralized AM	75	0,5	0,5	21,16	19,58	18,00	16,46	14,97	13,56
1	3	Decentralized AM	75	0,5	0,9	18,18	16,32	14,53	12,87	11,38	10,07
1	3	Decentralized AM	75	0	0,1	24,88	23,45	22,01	20,58	19,16	17,77
1	3	Decentralized AM	75	0	0,5	24,88	23,30	21,73	20,18	18,69	17,28
1	3	Decentralized AM	75	0	0,9	24,88	23,03	21,23	19,57	18,09	16,77
1	3	Decentralized AM	75	2	0,1	26,37	24,94	23,50	22,07	20,65	19,26
1	3	Decentralized AM	75	2	0,5	32,33	30,75	29,18	27,63	26,14	24,73
1	3	Decentralized AM	75	2	0,9	38,29	36,43	34,64	32,98	31,50	30,18
1	1	EBO_Baseline	150	0,5	0,1	49,77	48,36	46,94	45,53	44,12	42,71
1	2	Centralized AM	150	0,5	0,1	48,58	46,94	45,44	44,01	42,59	41,18
1	2	Centralized AM	150	0,5	0,5	43,85	42,03	40,24	38,51	36,86	35,32
1	2	Centralized AM	150	0,5	0,9	39,12	37,37	35,75	34,25	32,83	31,46
1	2	Centralized AM	150	0	0,1	49,77	48,02	46,40	44,89	43,45	42,02
1	2	Centralized AM	150	0	0,5	49,77	47,94	46,12	44,31	42,51	40,75
1	2	Centralized AM	150	0	0,9	49,77	48,02	46,40	44,89	43,45	42,02
1	2	Centralized AM	150	2	0,1	52,13	50,33	48,56	46,88	45,29	43,78
1	2	Centralized AM	150	2	0,5	61,60	59,78	57,96	56,14	54,33	52,54
1	2	Centralized AM	150	2	0,9	71,07	69,32	67,71	66,20	64,75	63,33
1	3	Decentralized AM	150	0,5	0,1	48,28	46,84	45,40	43,96	42,53	41,09
1	3	Decentralized AM	150	0,5	0,5	42,32	40,74	39,15	37,57	35,99	34,41
1	3	Decentralized AM	150	0,5	0,9	36,36	34,48	32,61	30,75	28,92	27,13
1	3	Decentralized AM	150	0	0,1	49,77	48,33	46,89	45,45	44,02	42,58
1	3	Decentralized AM	150	0	0,5	49,77	48,18	46,60	45,02	43,44	41,86
1	3	Decentralized AM	150	0	0,9	49,77	47,89	46,02	44,16	42,32	40,54
1	3	Decentralized AM	150	2	0,1	52,75	51,31	49,87	48,43	47,00	45,56
1	3	Decentralized AM	150	2	0,5	64,66	63,08	61,50	59,91	58,33	56,75
1	3	Decentralized AM	150	2	0,9	76,58	74,71	72,84	70,97	69,14	67,36

Appendix C. Expected Backorder for different scenarios for xxxxx163

						Stock level					
Item	Model	Type	m	Repair time	AM prob	0	1	2	3	4	5
2	1	EBO_Baseline	10	0,5	0,1	3,83	2,53	1,51	0,82	0,41	0,18
2	2	Centralized AM	10	0,5	0,1	3,73	2,42	1,44	0,77	0,38	0,16
2	2	Centralized AM	10	0,5	0,5	3,33	2,03	1,16	0,60	0,28	0,11
2	2	Centralized AM	10	0,5	0,9	2,94	1,74	0,95	0,46	0,20	0,07
2	2	Centralized AM	10	0	0,1	3,83	2,49	1,49	0,82	0,40	0,18
2	2	Centralized AM	10	0	0,5	3,83	2,42	1,46	0,81	0,40	0,18
2	2	Centralized AM	10	0	0,9	3,83	2,49	1,49	0,82	0,40	0,18
2	2	Centralized AM	10	2	0,1	4,03	2,64	1,61	0,91	0,46	0,21
2	2	Centralized AM	10	2	0,5	4,83	3,29	2,14	1,30	0,74	0,38
2	2	Centralized AM	10	2	0,9	5,63	4,17	2,90	1,86	1,11	0,61
2	3	Decentralized AM	10	0,5	0,1	3,73	2,42	1,42	0,75	0,36	0,16
2	3	Decentralized AM	10	0,5	0,5	3,30	1,96	1,05	0,51	0,22	0,08
2	3	Decentralized AM	10	0,5	0,9	2,87	1,52	0,73	0,31	0,12	0,04
2	3	Decentralized AM	10	0	0,1	3,83	2,52	1,51	0,82	0,40	0,18
2	3	Decentralized AM	10	0	0,5	3,83	2,48	1,48	0,81	0,40	0,18
2	3	Decentralized AM	10	0	0,9	3,83	2,42	1,46	0,81	0,40	0,18
2	3	Decentralized AM	10	2	0,1	4,05	2,73	1,69	0,96	0,50	0,23
2	3	Decentralized AM	10	2	0,5	4,90	3,53	2,43	1,59	0,95	0,53
2	3	Decentralized AM	10	2	0,9	5,76	4,32	3,22	2,30	1,55	0,96
2	1	EBO_Baseline	75	0,5	0,1	28,75	27,30	25,86	24,41	22,97	21,54
2	2	Centralized AM	75	0,5	0,1	28,00	26,37	24,89	23,44	22,00	20,58
2	2	Centralized AM	75	0,5	0,5	25,01	23,15	21,40	19,79	18,34	17,02
2	2	Centralized AM	75	0,5	0,9	22,02	20,29	18,74	17,33	16,02	14,79
2	2	Centralized AM	75	0	0,1	28,75	27,02	25,45	23,97	22,52	21,09
2	2	Centralized AM	75	0	0,5	28,75	26,86	25,00	23,21	21,54	20,01
2	2	Centralized AM	75	0	0,9	28,75	27,02	25,45	23,97	22,52	21,09
2	2	Centralized AM	75	2	0,1	30,24	28,41	26,69	25,10	23,59	22,14
2	2	Centralized AM	75	2	0,5	36,23	34,34	32,47	30,63	28,85	27,15
2	2	Centralized AM	75	2	0,9	42,21	40,48	38,91	37,43	35,97	34,53
2	3	Decentralized AM	75	0,5	0,1	27,94	26,47	25,00	23,53	22,07	20,61
2	3	Decentralized AM	75	0,5	0,5	24,73	23,12	21,51	19,90	18,33	16,79
2	3	Decentralized AM	75	0,5	0,9	21,52	19,64	17,78	15,99	14,32	12,79
2	3	Decentralized AM	75	0	0,1	28,75	27,28	25,81	24,34	22,87	21,42
2	3	Decentralized AM	75	0	0,5	28,75	27,13	25,52	23,92	22,34	20,80
2	3	Decentralized AM	75	0	0,9	28,75	26,86	25,00	23,21	21,54	20,01
2	3	Decentralized AM	75	2	0,1	30,35	28,88	27,41	25,94	24,48	23,02
2	3	Decentralized AM	75	2	0,5	36,77	35,16	33,54	31,94	30,36	28,83
2	3	Decentralized AM	75	2	0,9	43,19	41,31	39,45	37,66	35,98	34,46
2	1	EBO_Baseline	150	0,5	0,1	57,49	56,05	54,60	53,16	51,72	50,27
2	2	Centralized AM	150	0,5	0,1	56,00	54,27	52,70	51,22	49,76	48,32
2	2	Centralized AM	150	0,5	0,5	50,01	48,13	46,25	44,42	42,64	40,94
2	2	Centralized AM	150	0,5	0,9	44,03	42,20	40,48	38,89	37,38	35,93
2	2	Centralized AM	150	0	0,1	57,49	55,66	53,94	52,35	50,83	49,36
2	2	Centralized AM	150	0	0,5	57,49	55,60	53,72	51,83	49,95	48,08
2	2	Centralized AM	150	0	0,9	57,49	55,66	53,94	52,35	50,83	49,36
2	2	Centralized AM	150	2	0,1	60,48	58,60	56,75	54,96	53,25	51,63
2	2	Centralized AM	150	2	0,5	72,45	70,56	68,67	66,79	64,90	63,02
2	2	Centralized AM	150	2	0,9	84,42	82,59	80,87	79,27	77,76	76,29
2	3	Decentralized AM	150	0,5	0,1	55,89	54,42	52,95	51,48	50,01	48,54
2	3	Decentralized AM	150	0,5	0,5	49,47	47,85	46,24	44,62	43,01	41,39
2	3	Decentralized AM	150	0,5	0,9	43,05	41,16	39,27	37,39	35,50	33,64
2	3	Decentralized AM	150	0	0,1	57,49	56,02	54,55	53,08	51,61	50,14
2	3	Decentralized AM	150	0	0,5	57,49	55,88	54,26	52,65	51,03	49,42
2	3	Decentralized AM	150	0	0,9	57,49	55,60	53,72	51,83	49,95	48,08
2	3	Decentralized AM	150	2	0,1	60,70	59,23	57,76	56,29	54,82	53,35
2	3	Decentralized AM	150	2	0,5	73,54	71,93	70,31	68,69	67,08	65,46
2	3	Decentralized AM	150	2	0,9	86,38	84,49	82,60	80,71	78,83	76,96

Appendix C. Expected Backorder for different scenarios for xxxxx164

						Stock level					
Item	Model	Type	m	Repair time	AM prob	0	1	2	3	4	5
3	1	EBO_Baseline	10	0,5	0,1	3,96	2,59	1,50	0,78	0,36	0,16
3	2	Centralized AM	10	0,5	0,1	3,83	2,44	1,39	0,71	0,33	0,14
3	2	Centralized AM	10	0,5	0,5	3,29	1,89	1,01	0,49	0,21	0,08
3	2	Centralized AM	10	0,5	0,9	2,75	1,50	0,74	0,32	0,12	0,04
3	2	Centralized AM	10	0	0,1	3,96	2,53	1,46	0,76	0,36	0,15
3	2	Centralized AM	10	0	0,5	3,96	2,43	1,39	0,74	0,36	0,15
3	2	Centralized AM	10	0	0,9	3,96	2,53	1,46	0,76	0,36	0,15
3	2	Centralized AM	10	2	0,1	4,23	2,73	1,62	0,88	0,43	0,19
3	2	Centralized AM	10	2	0,5	5,30	3,63	2,35	1,42	0,80	0,42
3	2	Centralized AM	10	2	0,9	6,38	4,85	3,47	2,29	1,39	0,78
3	3	Decentralized AM	10	0,5	0,1	3,88	2,50	1,42	0,72	0,33	0,14
3	3	Decentralized AM	10	0,5	0,5	3,53	2,10	1,10	0,51	0,22	0,08
3	3	Decentralized AM	10	0,5	0,9	3,19	1,71	0,81	0,35	0,13	0,05
3	3	Decentralized AM	10	0	0,1	3,96	2,58	1,49	0,77	0,36	0,15
3	3	Decentralized AM	10	0	0,5	3,96	2,52	1,44	0,75	0,36	0,15
3	3	Decentralized AM	10	0	0,9	3,96	2,44	1,40	0,74	0,36	0,15
3	3	Decentralized AM	10	2	0,1	4,13	2,75	1,64	0,88	0,43	0,19
3	3	Decentralized AM	10	2	0,5	4,82	3,36	2,20	1,35	0,76	0,39
3	3	Decentralized AM	10	2	0,9	5,51	3,96	2,79	1,88	1,19	0,69
3	1	EBO_Baseline	75	0,5	0,1	29,71	28,24	26,76	25,29	23,82	22,35
3	2	Centralized AM	75	0,5	0,1	28,71	27,00	25,45	23,96	22,49	21,02
3	2	Centralized AM	75	0,5	0,5	24,68	22,75	20,87	19,10	17,46	15,95
3	2	Centralized AM	75	0,5	0,9	20,65	18,83	17,17	15,65	14,22	12,86
3	2	Centralized AM	75	0	0,1	29,71	27,89	26,22	24,68	23,18	21,70
3	2	Centralized AM	75	0	0,5	29,71	27,77	25,83	23,91	22,05	20,28
3	2	Centralized AM	75	0	0,9	29,71	27,89	26,22	24,68	23,18	21,70
3	2	Centralized AM	75	2	0,1	31,73	29,81	27,98	26,26	24,65	23,11
3	2	Centralized AM	75	2	0,5	39,78	37,83	35,89	33,96	32,06	30,20
3	2	Centralized AM	75	2	0,9	47,84	46,01	44,35	42,80	41,30	39,82
3	3	Decentralized AM	75	0,5	0,1	29,07	27,57	26,07	24,57	23,07	21,57
3	3	Decentralized AM	75	0,5	0,5	26,50	24,85	23,21	21,57	19,93	18,31
3	3	Decentralized AM	75	0,5	0,9	23,92	22,02	20,13	18,25	16,42	14,66
3	3	Decentralized AM	75	0	0,1	29,71	28,21	26,71	25,21	23,71	22,21
3	3	Decentralized AM	75	0	0,5	29,71	28,07	26,43	24,79	23,15	21,52
3	3	Decentralized AM	75	0	0,9	29,71	27,81	25,92	24,04	22,21	20,45
3	3	Decentralized AM	75	2	0,1	31,00	29,50	28,00	26,50	25,00	23,50
3	3	Decentralized AM	75	2	0,5	36,14	34,50	32,86	31,22	29,58	27,96
3	3	Decentralized AM	75	2	0,9	41,29	39,39	37,50	35,62	33,78	32,02
3	1	EBO_Baseline	150	0,5	0,1	59,42	57,95	56,48	55,00	53,53	52,06
3	2	Centralized AM	150	0,5	0,1	57,41	55,58	53,92	52,37	50,88	49,40
3	2	Centralized AM	150	0,5	0,5	49,36	47,41	45,47	43,53	41,63	39,77
3	2	Centralized AM	150	0,5	0,9	41,30	39,38	37,55	35,84	34,22	32,69
3	2	Centralized AM	150	0	0,1	59,42	57,51	55,68	53,96	52,35	50,80
3	2	Centralized AM	150	0	0,5	59,42	57,48	55,53	53,58	51,64	49,69
3	2	Centralized AM	150	0	0,9	59,42	57,51	55,68	53,96	52,35	50,80
3	2	Centralized AM	150	2	0,1	63,45	61,51	59,57	57,67	55,82	54,04
3	2	Centralized AM	150	2	0,5	79,56	77,61	75,67	73,72	71,77	69,83
3	2	Centralized AM	150	2	0,9	95,67	93,75	91,92	90,20	88,59	87,05
3	3	Decentralized AM	150	0,5	0,1	58,14	56,64	55,14	53,64	52,14	50,64
3	3	Decentralized AM	150	0,5	0,5	52,99	51,35	49,71	48,06	46,42	44,78
3	3	Decentralized AM	150	0,5	0,9	47,85	45,95	44,05	42,15	40,25	38,35
3	3	Decentralized AM	150	0	0,1	59,42	57,92	56,42	54,92	53,42	51,92
3	3	Decentralized AM	150	0	0,5	59,42	57,78	56,14	54,50	52,85	51,21
3	3	Decentralized AM	150	0	0,9	59,42	57,52	55,62	53,72	51,82	49,93
3	3	Decentralized AM	150	2	0,1	62,00	60,50	59,00	57,50	56,00	54,50
3	3	Decentralized AM	150	2	0,5	72,29	70,64	69,00	67,36	65,72	64,07
3	3	Decentralized AM	150	2	0,9	82,58	80,68	78,78	76,88	74,98	73,08

Appendix C. Expected Backorder cost for different scenarios

						Stock level										
Item	**Model**	**Type**	**m**	**Repair time**	**AM prob**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
xxxxx162	1	EBO_Baseline	10	0,5	0,9	$1,327.12	$835.39	$472.27	$239.97	$108.92	$44.02	$15.90	$5.16	$1.52	$0.41	$0.10
xxxxx162	2	Centralized AM	10	0,5	0,9	$1,043.07	$596.78	$309.06	$139.96	$55.10	$19.00	$5.80	$1.58	$0.39	$0.09	$0.02
xxxxx162	3	Decentralized AM	10	0,5	0,9	$969.59	$477.09	$211.84	$82.84	$28.04	$8.25	$2.14	$0.49	$0.10	$0.02	$0.00
xxxxx163	1	EBO_Baseline	75	1	0,9	$ 114,986.13	$ 109,208.41	$ 103,431.27	$ 97,657.17	$ 91,893.53	$ 86,156.98	$ 80,476.55	$ 74,892.99	$ 69,452.78	$ 64,198.30	59158.05031
xxxxx163	2	Centralized AM	75	1	0,9	$ 114,986.13	$ 108,061.86	$ 101,792.68	$ 95,868.85	$ 90,083.35	$ 84,378.16	$ 78,772.57	$ 73,313.07	$ 68,046.87	$ 63,005.89	58198.73041
xxxxx163	3	Decentralized AM	75	1	0,9	$ 114,986.13	$ 107,450.62	$ 100,018.94	$ 92,856.03	$ 86,157.07	$ 80,058.67	$ 74,582.23	$ 69,642.57	$ 65,100.09	$ 60,814.97	56678.72158
xxxxx164	1	EBO_Baseline	150	2	0,9	$ 267,410.43	$ 260,778.85	$ 254,147.27	$ 247,515.69	$ 240,884.11	$ 234,252.54	$ 227,620.96	$ 220,989.38	$ 214,357.81	$ 207,726.26	201094.7812
xxxxx164	2	Centralized AM	150	2	0,9	$ 430,519.32	$ 421,894.78	$ 413,649.09	$ 405,921.04	$ 398,664.55	$ 391,730.25	$ 384,972.03	$ 378,294.02	$ 371,647.33	$ 365,011.33	358378.5763
xxxxx164	3	Decentralized AM	150	2	0,9	$ 371,600.57	$ 363,050.57	$ 354,500.61	$ 345,950.88	$ 337,402.29	$ 328,857.79	$ 320,325.07	$ 311,820.57	$ 303,374.07	$ 295,031.85	286856.2671

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c. All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Youssef Abidar and Amin Chaabane.

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