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SPARE PARTS INVENTORY MANAGEMENT FOR THE NEXT GENERATION FINNISH DEFENSE FORCE FIGHTER FLEET

by

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December 2017

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SPARE PARTS INVENTORY MANAGEMENT FOR THE NEXT GENERATION FINNISH DEFENSE FORCE FIGHTER FLEET

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LIST OF ACRONYMS AND ABBREVIATIONS

AA	Achieved Availability
AI	Inherent Availability
AO	Operational Availability
AFB	Air Force Base
BOM	Bill of Material
CLS	Contractor Logistics Support
CONOPS	Concept of Operations
CrED	Critical, Essential and Desirable
DAU	Defense Acquisition University
DLA	Defense Logistics Agency
DOD	Department of Defense
EDI	Electronic Data interchange
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
F/A-18 C/D	Hornet fighter
FDF	The Finnish Defense Forces
GAO	The U.S. Government Accountability Office
HX	The Finnish Fighter Program
IMM	Integrated Materials Management
LCC	Life Cycle Cost
LRT	Logistics Response Time
MDT	Mean Down Time
MLDT	Mean Logistics Delay Time
MMT	Mean Maintenance Time
M&S	Modeling and Simulation
MTBF	Mean Time Between Failures
MTBM	Mean Time Between Maintenance
MTTR	Mean Time To Repair

O&S	Operating and Support
PBL	Performance Based Logistics
PM	Project Manager
PSI	Product Support Integrator
RfI	Request for Information
RfQ	Request for Quotation
ROP	Reorder Point
SDLM	Standard Depot Level Maintenance
SS	Safety Stock
VEN	Vital, Essential and Non-essential
VMI	Vendor Managed Inventory

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I. INTRODUCTION

This research will suggest factors Finland should consider to better manage spare parts inventories in its upcoming fighter aircraft fleet acquisition. The topic is timely, because the Finnish Defense Forces (FDF) is in the process of procuring the fighters to replace the present F/A-18 C/D-fleet. The next step in the FDF procurement process will be the Requests for Quotations (RfQs) from the manufacturers, which the FDF expects to submit in February 2018. This study will concentrate on factors in spare parts inventory management that the FDF should consider in defining the requirements for the future fighter fleet's spare parts inventory management system.

A. RESEARCH QUESTIONS

1. What are the key spare parts inventory management factors in the near future fighter that will affect the FDF fighter fleet's performance?

2. What are the essential questions and requirements that the FDF should consider—in terms of spare parts inventory management—in formulating its Request for Quotation for fourth or fifth generation fighter manufacturers?

B. ADDITIONAL QUESTIONS

1. How should the future fighter spare parts inventory management be arranged to meet the operational user's requirements?

2. What are useful processes in modern corporate supply chain and inventory management that could be implemented into the future fighter spare parts management?

This study seeks to answer these questions by means of theories of modern supply chain and inventory management studies. This study takes into consideration the following aspects: a fighter assets' required operational availability and fighter units' performance requirements, spare parts classification approaches, demand forecasting, known spare parts inventory management processes, and key findings in previous inventory management studies. It reviews inventory classification, which is a key element of defining the different significance that the various stock-keeping units may have in the fighter maintenance. In addition to a traditional ABC-classification it suggest a classification approach that addresses demand variability, lead time and also define demand-based inventory classification parameters that present the item's criticality in terms of fighter operations performance.

Because of the importance and the criticality of some aircraft spare parts, the study reviews the inventory review models for the replenishment policies. Because this study precedes issuing the RfQ, by definition it lacks exact data from the fighter candidates' manufacturers, so I use generic examples and estimates to process the data where necessary. The actual values of the factor parameters are not essential in this study, but rather, the process and the overall management concept. The estimates will be based on case examples in the U.S. Navy and Air Force and the experiences of the FDF with the current and previous fighter system, the Hornet-fighter fleet, as well as on other published studies regarding the subject. The study reviews self-sufficiency, outsourcing and pooling, and estimates the advantages and disadvantages of them for the Finnish Defense Forces. It also addresses vendor managed inventory policy (VMI) as a theoretical option of managing the supply chain and the inventory of the Finnish fighters' spare parts. The study next compares the possible advantages and disadvantages between the present system and a highly outsourced inventory and supply chain management system. The conclusion presents the essential findings: the key elements that the FDF should consider when producing the requirements for the RfQs.

C. THE PURPOSE OF THE FINNISH FIGHTER FLEET

Finland's defense force deters threats and attacks by offensive use of military forces to meet operational requirements (Defmin, 2017). Finland's defense capability has been developed to meet the changes in the modern operating environment, which is increasingly fluid, unpredictable, uncertain, interdependent, and resource-constrained (Defmin, 2017). By means of defense cooperation, the Finnish Defense Forces enhances its performance and utilizes, maintains and further develops its defense capability. The "transformation of the character of battle is influenced by the demand of interoperability which encompasses comprehensive battlespace management that covers all domains of warfare (land, sea, air, space, information), long-range strike and missile defence capabilities, and cyber capabilities." (Puranen et al., 2015) Finland's military capabilities must be ready to meet future conventional military threats as well as a wide range of asymmetric threats. To be able to meet these threats effectively, the continuous development of the military capabilities and comprehensive international cooperation are and will be essential.

The Finnish Air Force's major air asset, the F-18 C/D Hornet fleet, working together with air defense and intelligence, surveillance, and command systems, is critical in influencing and engaging air, land, and sea targets (Defmin, 2017). Puranen et al. (2015) suggest that the "three major factors … limit the service life of the fleet: weakening comparative capabilities, structural fatigue and challenges in obtaining system support for the aircraft" (p. 11). Changes to the operating environment and concept of operations, and the need to maintain the air defense and the offensive engagement capabilities will demand the modernization of the air defense, including a new fighter fleet, by 2030 (Defmin, 2017; Puranen et al., 2017).

A multi-role fighter offers the advantage of flexibility in adapting into and forming the air operation during the mission (Puranen, et al., 2015). This operational superiority and flexibility create the conditions to apply the fighter's capabilities wherever needed across the area of responsibility (Defmin, 2017). Experts suggest that, "In the future multi-role fighters will be the most important component in establishing Finland's air defense capability. They also play a central role in creating freedom of action for the Defense Forces as well as in achieving and maintaining sufficient control of the air after having repulsed a first strike" (Puranen, et al., 2015, p. 35).

The Finnish Air Force has two operational fighter wings, Karelia Air Command and Lapland Air Command, which are in continuous readiness to exercise command and control of air operations. The main operating bases are located in Rissala and Rovaniemi. The air commands have also multiple dispersed operational locations, airfields and road trips, across their area of responsibility. These locations enable the surveillance, command and control operations to cover the Finnish airspace. The Air Commands cooperate continuosly with the Defense Forces units, and train conscripts and reservists, while sustaining and developing the high expertise among the active duty personnel. The

Air Commands also provide support to other authorities (Ilmavoimat, 2017). The Air Commands' Aircraft Maintenance Squadrons (AMS) cooperate closely with Fighter Squadrons (FS) at the base level and enable everyday flight training, exercises and fighter operations by being responsible of fighter fleet's daily inspections, base-level fighter support and maintenance management and execution. Basically, the Air Command's Aircraft Maintenance Squadrons are divided into three operational units: Line Maintenance Flight, Aircraft Maintenance Flight and Base Support Flight. In addition to aircraft maintenance, these units account for maintaining aircraft weapons systems, aircrew flight gear, ground equipment and aircraft rescue and firefighting.

The modern multi-role fighter is a key air defense asset and enabler. It is a system that contains several sophisticated, complex and expensive subsystems that must be maintained to sustain high performance for decades to meet the challenges and fluctuations in operating environment. The Finnish Defense Forces Logistics Command is responsible for producing the joint logistics services and contributing to the building, maintaining and using of the Defense Forces' capabilities. (Puolustusvoimat, n.d.) The Joint Systems Centre is one of the sub organizations in the Logistics Command and is responsible of life cycle management, maintenance and acquisition processes of the Defense Forces' and the Frontier Guard's systems. The Joint Systems Centre is also responsible of the materiel availability of the systems as well as the technical inspection and the systems safety (Puolustusvoimat, n.d.).

D. THE HX PROJECT

The purpose of Finland's "HX Fighter Program is to replace the operational capability of the Air Force F/A-18 aircraft" (Puranen, et al., 2015). The Finnish Defense Forces' Logistics Command sent a Request for Information (RfI) on fighter, weapons and equipment systems regarding the HX fighter project to the governments of seven countries (France, Germany, Great Britain, Israel, Norway, Sweden and the United States) to be forwarded to their respective industries (Defmin, 2017). The purpose of the RfIs was to clarify what capabilities and potential will be available to meet Finland's air defence's estimated future needs. A request for a quotation (RfQ) will be drawn up on the basis of the responses received. The weapons and equipment will be procured on a separate contract alongside the aircraft and RfQs on them will be sent in spring 2018 (see Figure 1.). The decision on the weapons and equipment will be made as part of the decision on the aircraft type. Procurement contracts are scheduled to be signed in spring 2021 (Defmin, 2017).

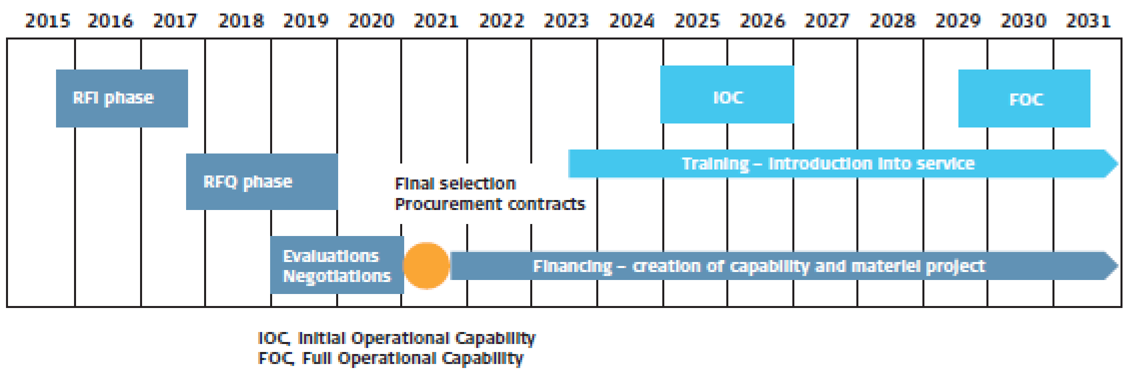

Figure 1. HX programme schedule. Source: Defmin (2017).

E. THE IMPORTANCE OF THE SPARE PARTS INVENTORY MANAGEMENT

In spare parts logistics you can use the same saying as in logistics as a whole: The right things are needed in the right place at the right time. A sufficient spare parts inventory is a basic requirement for fighter performance, but the costs of maintaining invenotry restricts the amount of spare parts in stock. The inventory policy affects the costs: the acquisition cost, the inventory holding cost and the shortage cost. There are also several other direct or indirect cost elements connected to decided inventory policy: administrative personnel and ordering costs, transportation costs and costs caused by facilities. Inventory holding costs include capital costs of the investment, operational costs and depreciation costs (Ferrer, Supply chain analysis for logistics professionals, 2016). Shortage costs occur when the required demand can not be satisfied from on-hand spare parts. Besides additional costs, in fighter operations environment, spare parts shortages cause decrease fighter's in operational availability increasing the down time.

The U.S. Government Accountability Office's (GAO) researched the Navy's inventory management challenges in 2008. The outcome of the report was that the Navy's spare parts inventory exceeded the current requirements by 40%. According to GAO (2008), the Navy had "not adjusted inventory management practices to incorporate flexibility for accommodating demand fluctuations." The same GAO report "identified three specific areas—initial provisioning management, on-order management, and retention management—where current practices contributed to the Navy having significant amounts of inventory in excess of current requirements" (GAO, Management actions needed to improve the cost efficiency of the Navy's spare parts inventory (GAO-09-103), 2008, p. 25). The challenge in having an appropriate inventory appeared especially in the aviation support equipment. Even though the amount of parts in aviation exceeding current requirements was only 15% of the total annual average, the value of those parts represented 75% ($5.6 billion) of the total excess value (GAO, Management actions needed to improve the cost efficiency of the Navy's spare parts inventory (GAO-09-103), 2008, p. 12). The GAO report indicated that the inventory management in especially the field of aircraft spare parts played a remarkable role in costs allocated to military forces.

Fighter spare parts inventory management is an essential part of air asset performance. To be able to use inventory effectively, the spare part "categorization is needed to create a manageable number of parts groups to focus management efforts" (Paakki, Huuskonen, & Pirttila, 2011, p. 164). The inventory management together with the supply chain is a complex ensemble and consists of many parties. The utilization and maintenance of a modern multirole fighter requires a vast amount of sophisticated special spare parts and exchange devices which in turn involves a lot of actors with specific skills. Along with internal inventory processes, external factors (e.g., suppliers, demand) and pervasive factors (e.g., variabilility) can affect inventory management of spare parts (Paakki, Huuskonen, & Pirttila, 2011).

Fighter operations require heavy utilization of equipment, spare parts and exchangeable devices to ensure the maximization of performance and managing spare part inventories effectively, to include their timely delivery, is critical to prevent grounding aircraft (Louit, Pascual, Banjevic, & Jardine, 2011). In turn, however, excessive inventories can lead to excessive spending and tie up resources unnecessarily (Ferrer, Supply chain analysis for logistics professionals, 2016).

F. THE IMPORTANCE OF DEMAND MANAGEMENT

To be able to support fighters with spare parts efficiently, it is useful to discuss the factors affecting the demand. There are models that address the key factors of demand management. When conducting a demand analysis, one should generate some key questions to ensure that the logistics strategy meets the strategic intent. Success in spare parts management depends highly on the reliability of the demand information and of what the management personnel does with the information. The demand information is driving by the 4W's and 2H's (who, what, when, where, how, how much): (Crum & Palmatier, 2003)

- Who are the top end users (customers)? Which end users have demand we can forecast?
- What are the top spare parts? What spare parts are the most critical for the firghter fleet's performance? What spare parts demand can we forecast?
- When are the spare parts ordered? Is demand seasonal?
- Where are the spare parts ordered from?
- How are the spare parts fulfilled? Are they made to order or stock? How are they shipped?
- How much is ordered for each spare part on timely basis?

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II. THE LITERATURE REVIEW

This chapter addresses the key theories, thoughts and findings regarding spare parts inventory management. It presents these findings to provide an informed foundation for considering different alternatives for fighter spare parts inventory management policies.

A. SPARE PARTS FORECASTING

A spare part is a "an extra piece that can be used to replace a piece that breaks, esp. in a machine" ("Spare Part," n.d.). There are several studies concerning the best practices to improve spare parts forecasting. Spare parts for a modern fighter fleet are have different costs, replenishment arrangements, lead times, service and maintenance requirements, and demand patterns. Classifying fighter spares is an important contributor to an effective inventory policy (Bacchetti & Saccani, 2011).

In fighter operation, several factors influence the demand and therefore cause additional complexity in managing spare parts inventories. These factors include larger numbers of parts, greater variance in parts importance and demand pattern, greater fighter availability required (downtime can significantly degrade the nation's defense), and the risk of inventory excessive costs and obsolescence. There are some common key findings available from previous studies:

> Successful spares planning and forecasting need more effective collaboration and sharing of information (fleet data, engineering change orders, part reliability, service bulletins) across the supply chain. The adoption of best practices for spares planning bills of material (BOM), demand aggregation, and software enabling capabilities shows a low maturity level. This is impacting internal and external key performance indicators across the service value chain. (Marx, 2011, p. 3)

Spare parts can be classified classified depending on their expenditure, importance for the user, or some other characteristic. One way to classify aircraft spare parts is to divide them into three or four types among rotables, repairables, expendables and consumables (Garg, 2013; Gu and Li, 2015). Each type of spare part can require a different replenishment policy. Predicted failure rates typical drive the replenishment of rotables and repairables, while expendibles and consumables typically benefit from a standard reorder point system (Gu & Li, 2015) (See Table 1.) Rotables can be rotated among aircraft and repairables have same character than rotable parts, but are more inexpensive. Consumables can be used once or are disposable components (Garg, 2013, p. 19).

Table 1. Definitions of rotables, repairables, expendables and consumables. Adapted from (Gu & Li, 2015).

Rotables	Complex components. Normally unlimited number of repairs. Normally no scrap is expected. Controlled by individual serial number. Exchange during maintenance. Example: Engines, engine components, weapons systems components, airframe parts.
Repairables	Components which can be technically and economically repaired. Under normal conditions a follow up of each individual serial number is not necessary. Have limited number of repairs and also have a possibility of scrap. Examples: Standard hindges, brackets, seat covers
Expendables	Cannot be repaired and will be scrapped after removal and inspection result is unserviceable. 100% replacement items. Items which cannot be repaired (not economical to be repaired). Standard parts. Example: Tires, bolts, nuts, fasteners.
Consumables	Any materials used only once. Raw material. Chemical material. Items which merge on production with new product and cannot be removed. Example: Hydraulic fluid, gaskets, filters.

B. ABC CLASSIFICATION SYSTEM

The ABC system classifies the spare parts based on their importance, primarily their financial importance, for the organization. A typical ABC system classifies inventory (here, spare parts) into three classes based on volume and value. Authorities provide different ranges (e.g., Greasley, 2009; Jacobs and Chase, 2013; Stevenson, 2012), but A items are typically 15–20 percent of the volume of inventory, but represent as much as 60- 80 percent of the value; B items might account for as much as 30 percent of the volume, and can represent up to 30 percent of the value; C items are essentially the reverse of the A items, with volume of as much as 60 percent, but value as low as 15–20 percent.

The quantitative classification techniques and the ABC approach are the most common techniques in determining inventory classification (Bacchetti & Saccani, 2011).

In terms of cost efficiency, the A items must receive more attention in the inventory management process. The importance of the items decreases cradually from A to C. In terms of cost effect, the B items are relatively necessary items but the C items are non-important items. According to Aisyati et al. (2013), the steps to perform ABC classification are as follows:

1. Listing the spare parts and their demand.
2. Determining the contribution of the spare part by multiplying the demand for each item and the value or price of item.
3. Computing the percentage of spare part contribution by dividing the contribution of each spare part with the total contribution of the spare parts.
4. Sorting the spare parts so that the percentages of spare part contribution are listed from higher value to lower value. The category of spare part could be found by using the above description (p. 3)

In fighter spare parts inventory management, the cost factor plays remarkable role. For example, the engine components and the weapons systems spare parts are expensive. They are also necessary for the operational availability. In terms of cost efficiency, it is important to pay attention to control and optimize the contribution of the most expensive parts. Apart from traditional ABC, different classification techniques have been developed. In this paper I address the variables that affect the efficiency of managing the inventories in the fighter spare parts management and develop a classification that is simple and effective at prioritizing the stock-keeping units. Here are some inventory management variables that I implement in this paper's inventory classification based on Ferrer's (2016) work:

- **Demand variability** – a statistical metric, measured as the standard deviation of demand.

- **Lead time** – a measure of the time that it takes to resupply.
- **Coefficient of variation** – the standard deviation divided by the average demand during the lead time. The coefficient of variation during the lead time CV_{LT} incorporates the impact of demand variability and the impact of annual demand, normalized by the lead time.
- **Criticality** – a subjective item classification indicating the impact of its shortage. (pp. 50–51)

Criticality is particularly important in fighters aircraft spare parts management and maintenance operations for a wide variety of device and parts. The variable subjectively indicates if the item is critical to keep the fighters in operation. The classification with ABC method is one way to categorize spare parts based on their monetary value. It alone does not categorize the spare parts according to their criticality, the value for mission accomplishment and for satisfying the end users' demand. Items with large annual turnover (tires, liquids, projectiles, chaffs and flares) have impact on spare parts management cost. Items with large coefficient of variation or large standard deviation are difficult to predict demand (landing gear components, canopies) so they need large safety stocks. Items with high criticality (engine components, weapons systems components) would need greater attention from the spare parts management given the potential impact of their shortage. In addition to these variables (turnover, coefficient of variance, criticality) there could be more. (Ferrer, 2016, p. 52)

C. CRITICAL, ESSENTIAL AND DESIRABLE CATEGORIZATION

In terms of criticality, it is useful to expand the spare parts classification to differentiate the spare parts by not only their monetaty value but also by their impact on mission accomplishment. One practical way of differentiating the parts is to apply the VEN-method, which is used in classification for drugs and medical supplies. With this system the "V" is for vital medicines, the "E" is for essential medicines and the "N" is for non-essential medicines. In vital classification there are medications that can save someone's life or are important to maintain the standard level of care. These are the drugs that must be available at all times. (Galka, 2016).

In fighter operations there are also certain spare parts, analogous to "medication for aircraft," that are critical for mission accomplishment. For example, the weapons systems and engine components and parts play critical role in. Those spare parts must be available all times and they have to be installed quickly. VEN classification could be transferred into a better suitable form for fighter spare parts management: Critical (replacing Vital from the medical model), Essential and Desirable (replacing non-essenstial in the medical model). CrED analysis is based on critical values and shortage cost of the spare part. There could be serious impacts for fighter fleet's operational availability when critical spare parts are not available even for a short period. If essential parts are not available beyond a few days, the performance of the air asset can be adversely affected. The shortage of desirable items would not adversely affect fighter fleets' performance even if shortage is prolonged. To be able to accomplish fighters' mission, the parts necessary to keep aircraft flying and the weapons systems ready to operate are essential. In many cases these parts are not only critical for the mission accomplisment but they are also expensive. For example, the canopy is irreplaceable part of the flying aircraft and therefore a critical spare part. Depending on the fighter type, it may also be a relatively expensive spare part.

To combine mission availability and spare parts inventory management cost effects, it is useful to cross-tabulate the spare parts ABC- and CrED analyses in the same matrix. From the resultant matrix combination, several new categories can be created (see Table 2). CrA items are those that are most critical to keep aircraft flying, and also have the largest monetary impact on the organization. As such, they require intensive focus in terms of inventory management. CrB-items are also critical for the fighter asset's performance, but their monetary value is less than CrA items'. CrC items are inexpensive items that still have a remarkable impact on fighters' performance. In addition to spare parts' criticality and cost factor, the spare parts may be given other classification criteria elements to enable sufficient inventory management. Spare parts may be listed and sorted by countless number of factors. Table 3 shows a simplified example of some possible factors regarding the spare parts multi-criteria classification.

Table 2. Spare parts classification model using cross-tabulated ABC and CrED analyses

Classification		**A**	**B**	**C**
		80% value 20% volume	15% value 30% volume	5% value 50% volume
Cr	Critical for mission	CrA	CrB	CrC
E	Essential for mission	EA	EB	EC
D	Desirable for mission	DA	DB	DC

Matrix is combination of ABC analysis and CrED analysis.

Table 3. Example of parts list using several classification criteria elements

Part #	Criticality (Cr, E, D)	Price (A, B, C)	Supply Risk (H, L)	Demand	Turnover	Std Dev	Lead Time	Demand (LT)	Std Dev (LT)	CV (LT)
P00000001										
P00000002										
P00000003										

Using weighted criteria parameters, the overall prioritizing of spare parts can be managed. In this example, there are only few key parameter functions.

D. KRALJIC'S CLASSIFICATION MODEL

In Kraljic's (1983) model, the acquisition (and the related inventory) strategy for an item depends on two dimensions: profit impact and supply risk. Supply risk assesses the risk that the item will be, for any number of reasons, limited or unavailable, while profit risk assesses the impact to the organization's profits. (See Figure 2.) Items presenting high risk on both dimensions suggest managing the acquisition using a strategic partnership between buyer and supplier; items with a high supply risk and low profit impact should be managed carefully to ensure their supply, perhaps by redesiging products that limit the sources of supply, and even at the cost of paying more for the item; items with high profit impact but low supply risk should be managed to concentrate the buyer's market leverage and drive cost reductions; finally, items low on both dimensions suggest the optimal acquisition strategy involves trying to automate the resupply process so as to avoid unnecessary acquisition costs while taking advantage of the more available supply (Kraljic, 1983).

Because managing spares typically involves acquiring them from suppliers, Krajic's logic can be adapted to the fighter asset's spare parts management and the ABC-CrED analysis. Strategic items, those high on both dimensions (engine components, weapons systems components, airframe parts), should be managed carefully in partnership with key suppliers; bottleneck items, those with high supply risk but perhaps lower impact on costs (lower cost parts that are spesific and dependent on only few suppliers), should be managed to ensure availability, but also perhaps to expand the supply base by redesiging the part; leverage items, those more broadly available, but at lower costs, can be competed regularly to drive down costs; while management of non-critical items, those with low risk on both diminsions, might best be decentralized.

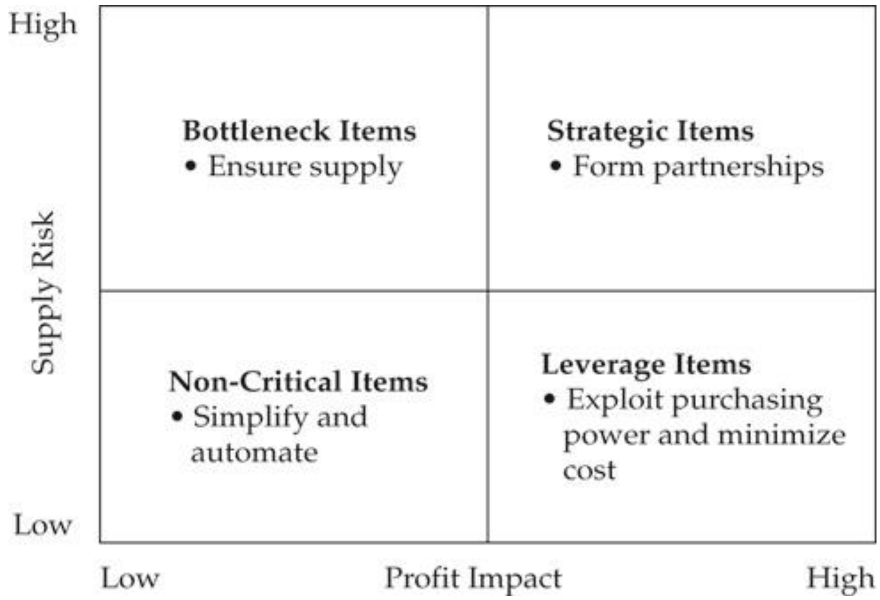

Figure 2. Krajic’s classification model. Source: Kraljic (1983).

E. CONTINUOUS AND PERIODIC REVIEW MODELS

This study reviews two inventory policy approaches for fighters’ spare parts: the continuous and periodic review models

1. Continuous Review Model

According to Aisyati, et al. (2013), a continuous review policy monitors the inventory level for an item, and when the inventory of that item drops to a reorder point (r), such that the remaining inventory will likely cover the expected demand during the supplier’s restocking lead time, along with an extra amount of safety stock to address variability during that lead time, an order is placed for an economically optimal quantity (Q). They suggest this model is appropriate for aircraft spares.

The spare parts classification system (ABC-CrED) categorizes the spare parts based on their criticality and cost effect. The continuous review model is practical in managing the inventory of spare parts that have relatively high impact on mission accomplishment. The continuous review policy may provide for significant savings in important classes' parts management compared to alternative approaches. (Aisyati;Jauhari;& Rosyidi, 2013)

2. Periodic Review Model

The periodic review model reviews physical inventory at specific intervals of time and orders the quantity necessary to achieve a desired target, or maximum, level of inventory. The safety stock of periodic review model is larger than that of continuous review model. This safety stock is important to meet demand at lead time period (L). One of the Periodic Review Models is the P model. This model is characterized by a fixed, optimal order interval (T) and the quantity order based on the difference of the maximum inventory level (R) and the on hand inventory. (Aisyati;Jauhari;& Rosyidi, Developing inventory policy for aircraft spare parts using periodic review model, 2015) Aisyati et al. (2015) focused on determining the optimal review period and by investigating the optimal inventory level for each consumable class C spare parts by employing periodic review policy. The results from that study indicated that the periodic review in consumable spare parts lowered the total inventory cost compared to the original policy where all the parts were reviewed in same period.

According to several studies, the periodic review policy can be applied more easily in managing inventory than continuous review policy. This is because by using periodic review, the user has to put less effort into controlling the inventory level. The optimal decision is made based on by the most desirable value, usually the lowest total cost possible. (Aisyati;Jauhari ja Rosyidi, Developing inventory policy for aircraft spare parts using periodic review model 2015)

3. Combining the Continuous and Periodic Systems for Aircraft Spares

As noted, the continuous system appears more appropriate for items in the inventory classes CrA, CrB, EA and EB, where the parts have a higher impact on the mission and the budget (engine and weapons systems components, airframe parts). The periodic system might be more appropriate for consumable items in inventory classes CrC, EC, DA, DB and DC, where consumption does not vary much or the monetary value does not restrict having sufficient safety stock. These consumables include for example periodic maintenance material, tires, liquid fluids, projectiles, chaffs and flares.

F. VENDOR MANAGED INVENTORY)

Vendor Management Inventory (VMI) is "a distribution channel operation system where the manufacturer (vendor) [monitors and manages] the inventory" at the end user (Moghaddam, Martinez, Koochak-Yazdi, & Murad, 2011). According to Ferrer (2016), in a VMI partnership, the original equipment manufacturer's representative makes spare parts inventory replenishment decisions. The aircraft or spare part manufacturer monitors the fighter fleet's inventory levels and makes resupply decisions regarding order criticality, order quantities, shipping modalities and timings. VMI shifts the spare parts demand forecast and current inventory level information from the end user directly to manufacturer and reduces information delays. The manufacturer knows both how many fighter spare parts are in stock, and how many it must provide. Knowing this information confidence reduces both excess inventory and variability in the supply chain (Ferrer, Supply chain analysis for logistics professionals, 2016). The manufacturer sees additional benefits, including greater visibility into inventory levels, greater ability to match demand to the need for increased capacity, and reduced delivery variability. (Moghaddam;Martinez;Koochak-Yazdi, & Murad, 2011).

There is evidence that aircraft maintenance and repair organizations responsible for keeping the aircraft flying use excessive amount of capital in spare parts (Or, 2004). Due to continuous demand for reducing the expenses through cost savings in maintenance and repair processes, many operators in aviation business consider outsourcing support activities by applying Vendor Managed Inventory (VMI) models. For example, Boeing promotes its spare parts support programs for its customers through Integrated Materials Management (IMM), where Boeing buys back airlines' spare parts inventories and manages the customers' maintenance and supply chain processes (Or, 2004). The objective is to satisfy the airlines' performance requirements by carrying out the maintenance processes to meet the required service level (Or, 2004). The number of VMI programs is expected to increase in the near future, since the aviation operators are more and more goal-oriented and will increasingly concentrate on their core competences, transporting passengers and freight and marketing these services, while outsourcing spares to third parties (Or, 2004).

The goal of the optimal inventory management in fighter units is to make sure that the fighter fleet's spare parts inventory manager only purchases what the warfighters will use. By working closely with suppliers, the inventory manager places timely, appropriate-sized orders (Angelin, 2016). With "smaller batches, the burden of inventory management is shifted to the material partner, who pushes inventory" to the user, "based on real-time demand" (Angelin, 2016). "Instead of forecasting yearly maintenance projects, or last-minute requirements, and buying spares to ensure maintenance projects will go as planned, the customer will be in constant communication with its material partner" (Angelin, 2016). The warfighter updates the inventory status and its supplier will "constantly maintain the inventory, making frequent shipments. The vendor managed inventory is usually handled through modern technology. This technology is called EDI (electronic data interchange)" which connects with the supplier's Enterprise Resource Planning (ERP) system. (Angelin, 2016)

The Finnish Defense Forces might benefit from VMI by arranging the inventory management of the most sophisticated and complex spare parts like engine and weapons systems components with the vendor. The vendor should be responsible of providing the spare part in agreed time and at agreed cost. By managing the storage maintenance and the spare part life time updates the vendor can provide the end user with direct and indirect cost savings. When the vendor has visibility in estimated demand, the safety stock may be kept as low as possible. This arrangement might benefit the end user most in classification classes CrA, CrB, EA and EB.

G. PERFORMANCE-BASED LOGISTICS

This section draws heavily from the Defense Acquisition University's websites, Defense Acquisition Guidebook (September 16, 2013) and Performance Based Logistics (PBL) Guidebook (March 30, 2017). Performance-Based Logistics is

> performance-based life cycle product support, where outcomes are acquired through performance-based arrangements that deliver Warfighter requirements and incentivize product support providers to reduce costs through innovation. These arrangements are contracts with industry or intragovernmental agreements. (DAU, 2017)

According to the PBL Guidebook (2017), PBL strategies have been implemented for years especially in commercial aviation, where the airline operator buys a level of system availability. This availability can be measured by service level - which is the percentage of hours in operational period - of the system, subsystem or component. The objective of the performance-based support is to "develop and implement strategies … that optimize total system availability while minimizing cost and logistics footprint." (DAU, 2013, p. 44)

When considering outsourcing the maintenance or the spare parts management of complex systems, like fighter aircraft and their weapons systems, it is necessary to build the support, maintenance and logistics strategy "on the best features [available in] the public and private sectors" (DAU, 2013, p. 411). As the Defense Acquisition University explains:

> The Performance-Based Life-Cycle Product Support Implementation Framework captures the range of capability solutions that could be employed. The framework is incremental, in that each alternative builds on the previous category. In all cases the [systems] sustainment parameters are projected and measured during the design process and then re-assessed once the system is operational so appropriate actions can be taken to achieve the Materiel Availability objective. (DAU, 2013, p. 411)

The four Performance Based Logistics category features are described next, drawing heavily from the Defense Acquisitions Guidebook (2013) (see Figure 3).

> **Category 1**: [Category level 1] is the traditional support concept where the program buys the various individual support elements. The government develops the requirements, integrates, procures, and balances the [product] support elements to achieve the material availability outcome. The contractor metrics are usually cost and schedule…Most of the fiscal risks are on the government side and the PM works with the [product support] element functional offices, government infrastructure/supply chain, and contractors to determine and ensure corrective actions are taken" (p. 411)

Category 2: At level 2, fiscal risks begin to transition, but only in narrow but critical supply chain functional areas. Typical functions falling within this level include providing material, inventory management, transportation, and/or maintenance where the provider is accountable for the responsiveness required to meet customer requirements. This level generally concentrates on providing parts with the government making design decisions. Part availability, mean down time (MDT) or logistics response time (LRT) are the typical metrics for Level 2 implementations where the time it takes the supplier to deliver the part, commodity or service to the user determines their payment. [More program] risks are shared because there are fewer providers with whom to coordinate. (p. 411)

Category 3: This level expands the provider's fiscal risk level by transferring life-cycle support activities to the product support integrator (PSI), making them accountable for sustaining overall system materiel availability. Category 3 typically focuses on maintaining the required availability of key components or assemblies, such as a wing flap or auxiliary power unit, but can include the entire system. In Category 3, there is an additional PSI focus on life-cycle support, training, maintenance, repair and overhaul including logistics planning and execution, in-service engineering, configuration management and transportation. In Category 3, the PSI may also make repair [or] replace decisions. The preferred metric is materiel availability. At this level, the product support integrator is assigned specific life-cycle responsibility, solely or in partnership, for the breadth of processes affecting materiel availability. This includes aspects of sustainment engineering and configuration control, since reliability and maintenance of equipment and effectiveness of the supply chain influences continually affordable operational availability. (p. 412)

Category 4: This level transfers life-cycle support and design performance responsibilities making the product support integrator responsible for assuring operational availability (Ao) or operational capability. Typically this level applies to systems in the form of operational capability. [The] PSI is assigned responsibility, solely or in partnership, for the breadth of processes that influence Materiel Readiness. This gives the PSI the flexibility to adopt any practices and technology enablers needed to meet required performance levels, including the number of systems deployed and where they are located or staged (p. 412).

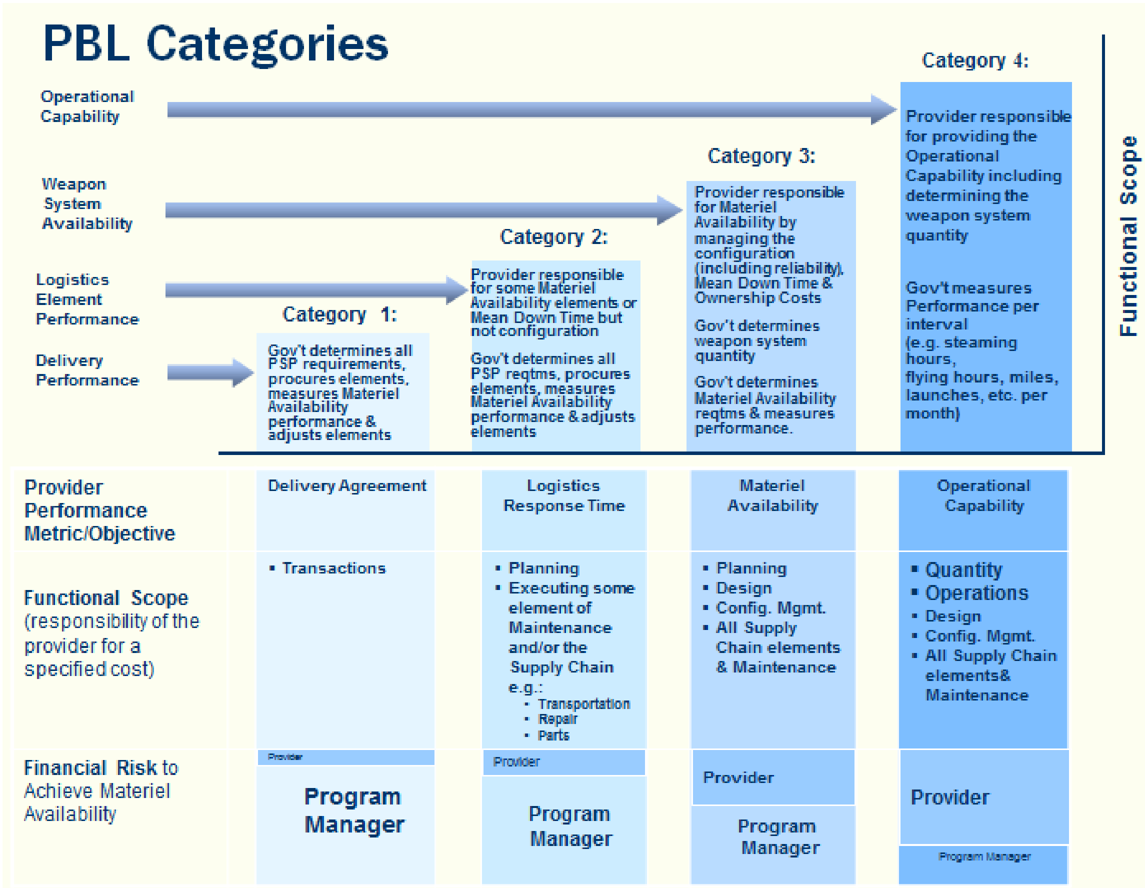

Figure 3. Performance-Based Life-Cycle Product support implementation framework. Source: DAU (2013).

The important factor in determining performance based logistics policy is to synchronize and link the support supplier's and warfighter's metrics. The warfighter's requirements for the performance metrics drive the manufacturer's and the logistics metrics (availability, reliability, maintainability and supportability). In turn, the cost metrics often drive the warfighter's requirements. Due to complex mutual dependence, continuous information sharing and reporting is essential. In the long term, it is also "important that the initial identification of performance outcomes be consistent with the program's life cycle" sustainment (Fast, 2017). Requirements "for materiel readiness outcomes should be established early in the material solution analysis and then carried through as program baseline goals until system retirement" (Fast, 2017). As a part of performance based logistics, product support is necessary to plan to enable the life cycle management, “to maintain the readiness and operational capability of fighters and the related weapons systems, subsystems, and components. The package of product support functions related to weapon system readiness and which can be performed by both public and private entities” (Estevez, 2011).

The Finnish Defense Forces might benefit from PBL by ordering operational availability or capability from the provider. The provider would be responsible of managing the configurations and quantities of the spare parts to meet the fighter fleet’s operational capability demands. This arrangement, as well as VMI, might benefit the end user most in high criticality or high cost classification classes: CrA, CrB, EA and EB.

H. LEAD TIME EFFECTS

Lead time is the time between placing an order and receiving the ordered item or service available for use. In fighters’ spare parts management, the lead time depends heavily on the spare parts character like complexity and cost, the spare parts management processes like ordering and transportation processes, the required testing and inspections, and where the spare parts are being stored. Depending on the complexity and character of the spare part, there are often many separate function phases connected together in the fighters’ spare parts supply chain (see Figure 4). The lead time uncertainty and variations affect the working orders and resource allocations in different phases and increase the total logistics delay time. The increased logistics delay time means larger safety stock in order to satisfy the required performance level. Some of the parts are “plug and play” and their lead time is short whereas some parts require longer lead times. Nevertheless, for operational user, the warfighter, the accuracy of the lead time expectation is the key issue: the vast variation in expected availability date and the actual availability date has negative impact on fighter asset’s operational availability. The inventory optimization is challenging when there is a high level of uncertainty in lead time forecasting. The variation may cause unplanned excessive inventories and thus increase in inventory costs.

In worse case, it may cause unwanted stock-outs and thus ground aircraft.

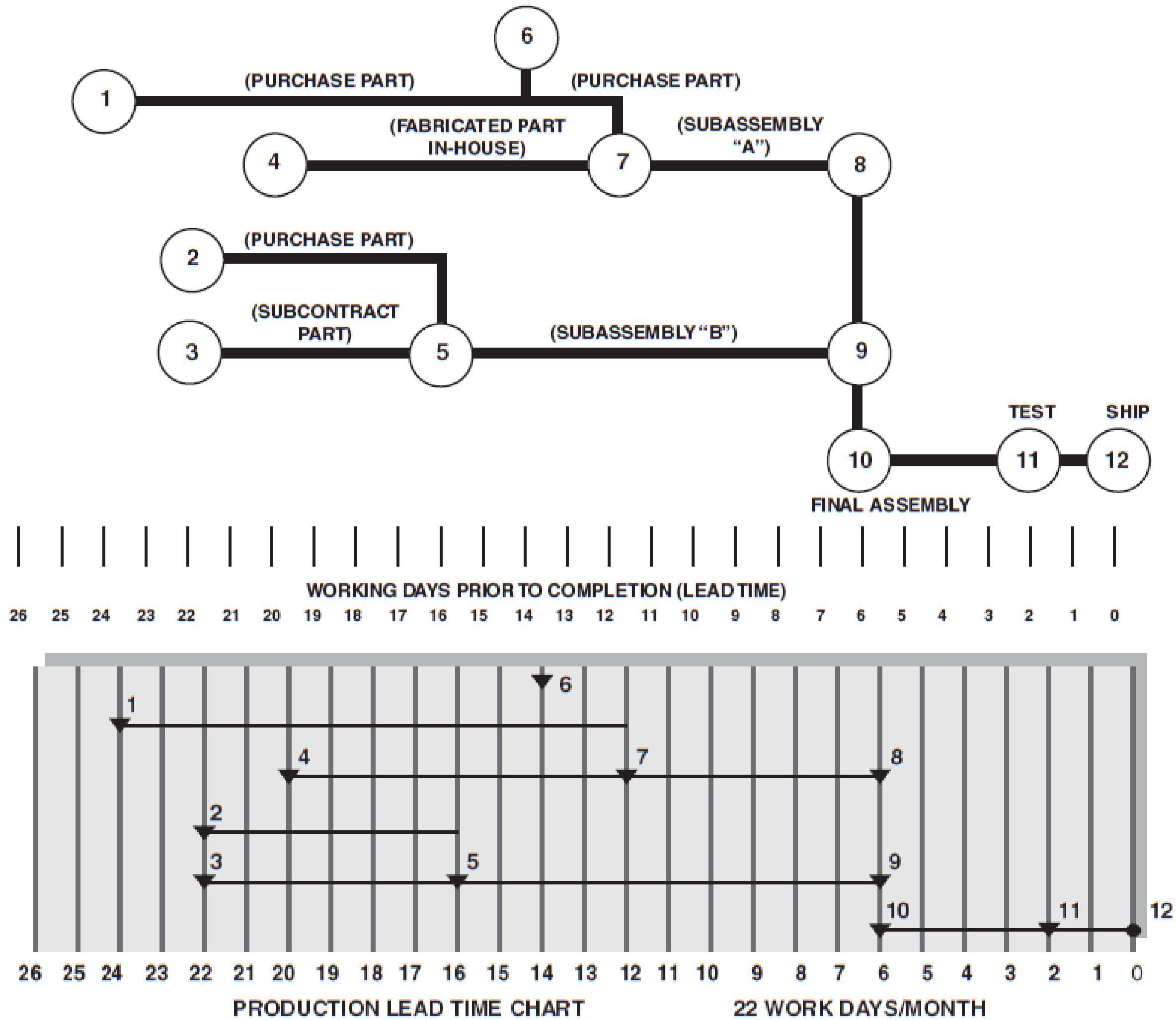

Figure 4. Production lead time. Source: Parker (2011)

III. METHODOLOGY AND EMPIRICAL DATA

This study built its foundation regarding aviation spare parts inventory management from research articles, reports and previous studies. The study next analyzes this information to determine what key elements of inventory management the Finnish Defense Forces should consider when creating a future fighter fleet spare parts management system. The key driver analyzing and processing the information is the need to maximize the future fighter fleet's operational availability in affordable cost.

1. Operational Availability

"Military Logistics support deals with everything required to provide war fighters with the right stuff at the right time at the right place at the right cost. The goal of military logistics support is to maintain the highest possible level of readiness, commonly expressed as operational availability" (Apte & Kang, 2006, p. 2). "Operational Availability indicates the percentage of time that a system or group of systems within a unit are operationally capable of performing an assigned mission and can be expressed as (uptime/(uptime + downtime)). Determining the optimum value for Operational Availability requires a comprehensive analysis of the system and its planned use as identified in the Concept of Operations (CONOPS), including the planned operating environment, operating tempo, reliability alternatives, maintenance approaches, and supply chain solutions. Development of the Operational Availability metric is a requirements manager responsibility." (DoD, 2009, p. 2)

"Operational availability is the fraction of time a weapon system is operational or mission capable" (Kang, 2017). Operational availability is a function of three (sometimes four) factors: the mean time between maintenance (MTBM), the maintenance down time (MDT), the mean maintenance time (MMT) and the mean logistics down time (MLDT). Using these factors as variables, operational availability can be expressed with a formula: Ao = MTBM/(MTBM+MDT), or MTBM/(MTBM+MMT+MLDT) (see Figure 5) (Fast, 2017). Mean "down time is the [total average] time [something] is not operational," including time required for repair, administrative tasks, various lead times, and other delays (Kang, 2017). Obviously, "operational availability can be improved by increasing MTBM (increasing reliability) and / or decreasing MDT (reducing repair or cycle-time)" (Kang, 2017). As a result, "two key issues to improve [fighter] systems readiness are reliability improvement and cycle-time reduction" (Kang, 2017). "A_O is affected by how long it takes to replace a failed system with a spare. Sensitivity analysis on A_O must include clear definitions of the varied operational states being considered as most systems will have different A_O values." (DoD, Department of Defense reliability, availability, maintainability and cost rationale report manual, 2009, p. 15)

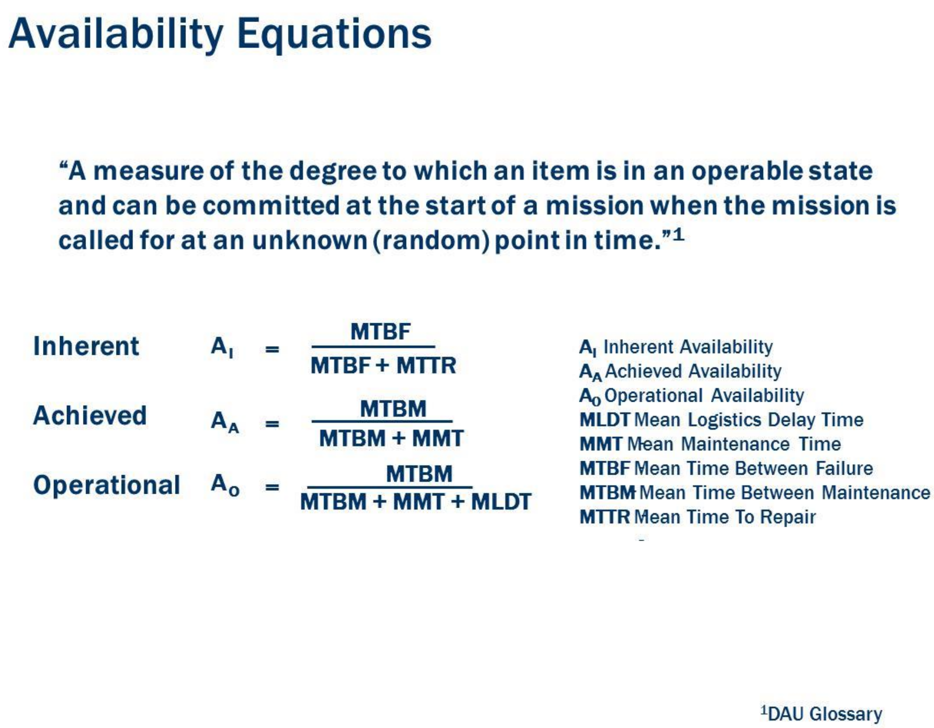

Figure 5. Explanations and equations of inherent, achieved and operational availability. Source: Fast (2017).

The importance of decreasing the mean down time (MDT) can be explained by a simple example regarding the cycle-time reduction in fighter aircraft logistics. This example draws heavily from an example at the Naval Postgraduate School (Kang, 2017). Let us suppose that the Finnish Air Force currently has 60 F/A-18C/D Hornet fighters. If Standard Depot Level Maintenance (SDLM) requires one year (MDT = 1 year) and occurs every four years, then using the formulas above, operational availability is 4 years /(4 years + 1 year) = 0.8 or 80%. In this situation only 48 of the 60-aircraft fleet is mission-capable on average, while 12 aircraft will be undergoing scheduled maintenance. Reducing the maintenance (MDT) to 6 months would increase operational availability to 0.89 (4 years / (4.5 years), meaning 53 aircraft would be available for the mission and only 7 would be undergoing maintenance. As Kang's example notes, if each F/A-18 aircraft is valued at $50 million U.S. dollars, this is the equivalent of having five additional aircraft (worth $250 million) in the fleet.

2. The Operations and Support Costs

The operations and support (O&S) costs represent a relatively large portion of the fighter life cycle cost. For example, "in 2011, the U.S. Air Force spent fifty billion dollars on operations and maintenance programs, which includes facility upkeep and upgrades as well as training and administrative costs" (Iwata & Mavris, 2013, p. 187). "Improvements to maintenance and logistics systems are expensive to perform in real life, so a modeling and simulation (M&S) environment capable of analyzing logistics systems allows for the testing of efficient changes" (Iwata & Mavris, 2013, p. 187).

The "logistics system to support fighter operations is complex" even though the "steps of the overall process are simple: Inspect and identify broken parts, replace aging or broken parts, perform turnaround tasks, send out broken parts, and stock new spare parts. The difficulty arises when considering the details" (Iwata & Mavris, 2013, p. 188). Aircraft require many sophisticated, unique systems and parts, and "these parts are delivered through various supply chain networks. There are different management strategies to govern the system. Furthermore, these activities face human and geographical constraints. For a fighter aircraft with many critical and highly technical parts, the maintenance and logistics system is vast, and making the right decisions while balancing the competing needs of improving performance, reducing costs and enhancing safety is challenging" (Iwata & Mavris, 2013).

3. Low Demand Spare and Service Parts

Very often the most critical spare parts may be low in demand. Low demand may derive from high mean time between failures of the part. It may often be challenging to predict the demand, also. This increases variation in demand determining at different stages of the inventory management chain. The increased variation in turn means excessive safety stock. The research organization RAND presented a series of what it termed "best practices in developing proactive supply strategies for Air Force low-demand service parts" in its Project Air Force paper in 2010 (Chenoweth, Arkes, & Moore, 2010). The research reviewed "Air Force purchases of low-demand spare parts [and analyzed] how much the Air Force spends on low-demand parts" (Chenoweth, Arkes, & Moore, 2010). The purpose of the research was to "identify and synthesize best commercial purchasing and supply chain management practices used for developing supply strategies for such items and to recommend how the Air Force could improve its supply strategies for such items" (Chenoweth, Arkes, & Moore, 2010).

The "benefits of improved supply strategies for low-demand parts can be quite substantial, because such parts purchased before demands occur usually remain in inventory longer and tie up resources that could have been used productively elsewhere. Low-demand parts have higher unit inventory management costs because their fixed management costs must be apportioned over fewer quantities" (Chenoweth, Arkes, & Moore, 2010, p. 31). The RAND study found that "having supply strategies and suppliers in place for low-demand parts may be more cost-effective than holding many of these parts in inventory. If customers give suppliers responsibility for delivering parts to a schedule, suppliers can decide whether to hold the parts in inventory or produce them in response to actual demands" (Chenoweth, Arkes, & Moore, 2010, p. 32). In general, the RAND study "found that the best time for developing supply strategies for low-demand parts is before production begins" (Chenoweth, Arkes, & Moore, 2010, p. 28).

The acquisition process of the low demand parts may be divided into phases (see Figure 6). Chenoweth, Arkes & Moore, (2010) explain the phases of this process; they begin stating that in the first phase of product life cycle, the design phase,

> …plans become concrete with detailed drawings and product specifications, material selection, and development of manufacturing processes. Much of the product's ultimate cost is determined in this phase… Logisticians develop support concepts for field services, levels and sources of repair, supply (inventory), and suppliers. They analyze how much repair will be done internally at organic facilities or in contracting support. They also consider the use of Contractor Logistics Support (CLS) and Performance-Based Logistics (PBL) (p. 34.)

The Finnish Defense Force is in phase 1, which adds importance to both this study, and their efforts to develop an effective inventory management strategy for spare parts. Decisions made now will have cost consequences for decades to come.

Chenoweth, Arkes & Moore (2010) next explain the second phase of the process:

> In the second phase, production, products are manufactured… Lean production techniques allow suppliers to provide needed parts at a prescribed time and sequence to be assembled into final products at the same rate as production. Setting production schedules translates into certain parts requirements… The aftermarket services phase begins once the first products that are sold require maintenance or their parts begin to fail, typically while production is still ongoing. As the number of products in operation increases, demands for aftermarket services also increase. Service parts, including low-demand service parts, may compete for parts with new production on manufacturing lines during the production phase of a product, but they are easier to produce during this phase as well. (p. 35)

Finally, they (2010) conclude describing the third phase:

> In the third phase, postproduction, production of new products has ceased and only the aftermarket phase continues… Many different low-demand parts would exhibit infrequent demands over the duration of the product's operating life. Demands for low-demand parts are intermittent, variable, and economically unattractive to companies (p. 35)

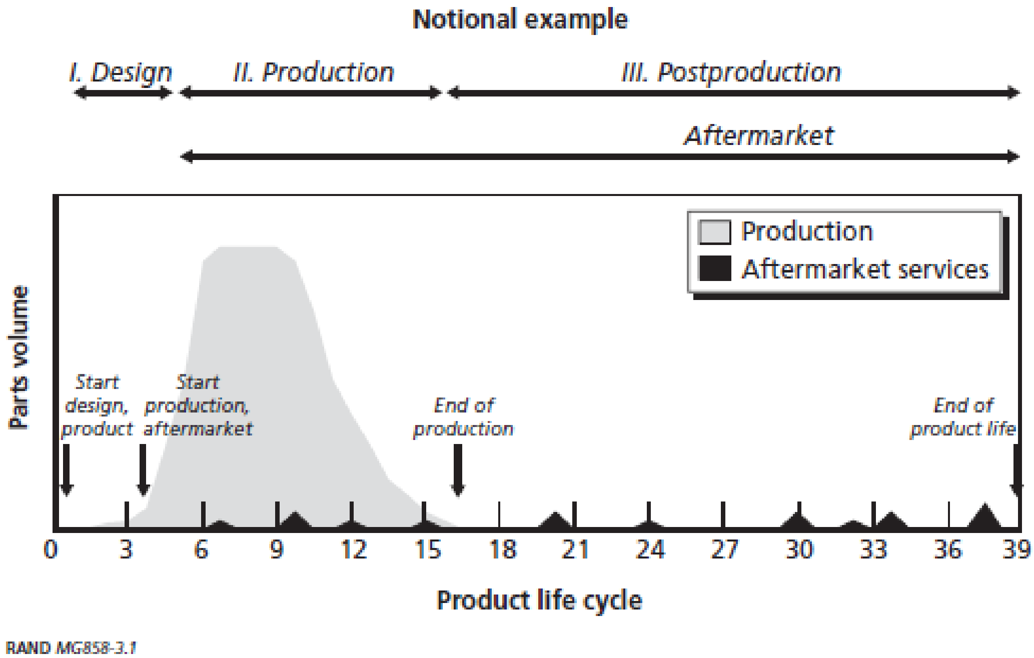

Figure 6. Product life cycle adapted from the RAND study: Developing proactive supply strategies for Air Force low-demand service parts. Source: Chenoweth, Arkes, & Moore (2010), p. 33.

The RAND study (2010) identified several strategies to ensure availability of low-demand parts throughout the phases of a product's life cycle:

1. Involve buyers and suppliers in the design of new systems, products, and parts.
2. Reduce complexity by using common subsystems and parts.
3. Monitor and manage obsolescence by identifying soon-to-be-obsolete parts, technologies, and processes.
4. Commit suppliers to postproduction aftermarket services in the production contract.
5. Secure access to technical data in the production contract.
6. Provide incentives for supply of low-demand parts.
7. If a supplier does not currently exist, develop one.
8. Purchase or retire whole products just for parts.
9. Buy lifetime supply of parts before the supplier exits the business Chenoweth, Arkes, & Moore, 2010, p. 58)

The Finnish Air Force like other air forces has some special features in spare parts management. Many of the fighter fleet's spare parts are hi-tech, sophisticated, "specialized, incorporating expensive materials, are sole-source, with long lead times, and are subject to technology obsolescence" (Chenoweth, Arkes, & Moore, 2010, p. 59). Demand includes "low-demand items with high unit prices and a need for reserve stocks to support" (p. 59) an unexpected and sudden increase in demand. "Having enough low-demand parts in inventory is very expensive and not economically viable as a strategy. Many low-demand parts will not be demanded, but those that might ground aircraft if they are unavailable" (p. 59).

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IV. ANALYSIS

In this chapter, I describe and analyze the process of how to determine the required spare parts and compute the spare parts requirements in a given operational environment. The requirements and the management of the spare parts have an inseparable relationship between fighter fleet's readiness and also the life cycle cost of the fighter asset. The roles and meanings of initial spares, demand supporting spares, investment spares, spares pipelines and the balance with spare provisioning and spare procurement all have multi-dimensional operability and cost effects on the system. As the United States Government Accountability Office (GAO) (2010) reports, reinforcing Chenoweth, Arkes & Moore's (2010) assertions, "The best opportunities for minimizing investment in unneeded inventory while still meeting required inventory levels are at the front end of the process when the agency is making decisions on what and how much to purchase." (p. 38) The GAO, in their review of the Defense Logistics Agency (DLA), also offered potentially helpful advice for the FDF, that an organization should "have effective policies and practices in place to modify planned purchases as appropriate when demands for parts change." (GAO, Defense Logistics Agency needs to expand on efforts to more effectively manage spare parts (GAO-10-469), 2010, p. 38) GAO (2010) recommended that the DLA take the following actions to improve their spare parts management and reduce capital invested in secondary spare parts inventory:

1. Establish an action plan for completing the agency's evaluation of identified demand planning issues, and include goals, objectives, resources, and time frames in this action plan.

2. Develop an approach for working with suppliers to assess the root causes of inaccurate production lead time estimates and implement corrective actions linked to these root causes.

3. Reinforce and reinvigorate effective internal controls aimed at evaluating and making adjustments to the military services' estimated additional requirements, including both supply support requests and special program requirements.

4. Conduct a program evaluation of the demand data exchange initiative to determine what, if any, additional actions should be taken to (1) improve communication and data exchange internally and with military customers

and suppliers and (2) expand the initiative across the enterprise (for example, to other customers, items, and processes).

5. Evaluate the effectiveness of the agency's process for identifying and reducing potential over-procurements and determine the feasibility of applying the process on a wider scale. (GAO, Defense Logistics Agency needs to expand on efforts to more effectively manage spare parts (GAO-10-469), 2010, p. 39)

The GAO (2010) also recommended the spare parts end users "to establish goals and metrics for tracking and assessing the cost efficiency of inventory management in accordance with DOD's policy requiring DLA and the services to minimize investment in secondary item inventory while providing inventory needed." GAO (2010) also recommended the services to integrate the "goals and metrics into existing management and oversight processes." The GAO report confirms, that the information flow, overall understanding of the players' roles in the spare parts management chain, the integrated management processes and the best possible spares demand estimate are the key functions of cost-effective inventory management.

In distribution systems, there is often a lot of variability built in, which leads to excessive fluctuation in lead times, uncertainty and lack of trust. An inadequate inventory management system causes end-users to adjust their behavior response by keeping excess inventory, using discrete spare parts inventory systems to ensure required performance and make things happen. To maintain the required service level, the most effective way of improving the inventory management efficiency is to reduce variability.

A. POOLING AND STOCK CONSOLIDATION:

Why will stock consolidation reduce total inventory? One interesting concern is to identify the effects of inventory management solutions – inventory design, storage and distribution system – on an end user. The inventory manager must evaluate the trade-offs in different consolidation, or pooling, options. The pooling may occur "in three dimensions: time, place and product aggregation" (Ferrer, Open architecture, inventory pooling and spare maintenance assests, 2007). In time aggregation, the inventory addresses demand across time; in place aggregation, the inventory addresses demand across locations; and in product aggregation, "a product or component is designed to meet the demand associated with one or more applications or customer needs" (Ferrer, Open architecture, inventory pooling and spare maintenance assests, 2007, p. 27). All of these pooling dimensions are worth studying in terms of gaining operational savings by reducing the safety stock. The inventory manager should determine what kind of effect does the pooling generate to operational availability by increasing the need for transportation.

I present a mathematical justification of consolidating *n* decentralized fighter spare parts inventory depots into one, while maintaining the same service level (in this case 90%). I assume that the transportation time is negligible and that the demand at each depot is independent of others. We know that the safety stock (SS) is a product of the service level (z) multiplied by the standard deviation of the demand, or $SS = z \times \sigma$. We also know that the EOQ was never intended to apply in situations where the demand is unpredictable. (Kang, 2017, p. 61) When there is uncertainty present, there is also a risk associated with any course of action. That is why one has to be careful in making assumptions with various demand patterns each having high variability. It is known that when two or more variables with independent randomness are compounded, the result is less variable.

If the demand of depot1 is normally distributed with a mean of μ_1 and a variance of σ_1^2, the required safety stock level at a 90% (SL(z) 0.90 = z 1.2816) service level is $\mu_1 + 1.28\ \sigma_1$.

If the demand of $depot_2$ is normally distributed with a mean of μ_2 and a variance of σ_2^2, the required stock is $\mu_2 + 1.28\ \sigma_2$. Thus, the total required stock level at two decentralized stock points is $\mu_1 + \mu_2 + 1.28\ (\sigma_1 + \sigma_2)$.

If these two inventory control points (depots) are consolidated, the demand would be normally distributed with a mean of $\mu_1 + \mu_2$ and a variance of $\sigma_1^2 + \sigma_2^2$. The required stock level is $\mu_1 + \mu_2 + 1.28$ sqrt $(\sigma_1^2 + \sigma_2^2)$. Thus, the inventory savings from stock consolidation will be 1.28 sqrt $[(\sigma_1 + \sigma_2) - (\sigma_1^2 + \sigma_2^2)]$ that is always greater than or equal to 0. Now we can generalize it for n depots. It is true that stock consolidation will always reduce the inventory level at depots. However, the pipeline inventory may go up due to increase in transportation time after consolidation.

The standard deviation is a measure of variability. A higher stock level is needed if the standard deviation is larger. Also, the higher the service level is, the larger safety stock is needed. The more variability one has the more inventory savings one will achieve through consolidation. Instead of maintaining two separate depots, one consolidated stock point will substantially reduce the inventory level, which means monetary savings. Also, by means of standardizing processes and components, one needs to maintain inventory of fewer items instead of many. Immediate cost savings may be achieved from consolidation effects.

Inventory models can provide quantitative decision-making aids in a limited number of cases. They do not cover all the real-life problems where thousands of individual but interrelated parts and actors must be managed and controlled.

B. CASE F-HX: SPARE PARTS INVENTORY MANAGEMENT

I present a simplified case to explain the differences of decentralized and consolidated inventory models. This case is based on the in-class case by Prof Keebom Kang at Naval Postgraduate School’s Logistics Strategy course in summer 2017. In this case, there are 60 twin-engine F-HX aircraft in the Finnish Air Force. The fighter fleet is divided into two operational bases: AFB1 has an inventory of 30 aircraft and AFB2 also has an inventory of 30 aircraft. An engine consists of 6 modules. The MTBF and cost of the modules are listed in the table below. The operational tempo is estimated to be 200 flight hours per aircraft per year. When an engine fails, the faulty engine is removed and tested at its Air Force Base. The faulty module is replaced with a spare module, and then sent for depot repair. The average module repair turnaround time is 15 days. To simplify the problem let’s assume that the time needed for the engine test and module replacement is negligible. Let’s also assume that the failure times follow an exponential distribution. The inventory carrying rate in this case is 20% per year. Table 4 summarizes key information for the example case.

Table 4. The components, MTBF, protection level, number and cost of F-HX engine modules. Adapted from Kang (2017)

Components	MTBF	Protection Level	k	Cost $
Compressor	2000	0.9	120	$1,000,000
Fan	1500	0.9	120	$1,000,000
HPT	1,000	0.9	120	$500,000
LPT	1,200	0.9	120	$500,000
Combustor	2,500	0.9	120	$750,000
Afterburner	500	0.9	120	$750,000

1. Decentralized Inventory Model, Turnaround 15 days

In the first case, each airbase carries and maintains its own inventory at the airbase maintenance facility. What is the total dollar value of the module spare parts pool at given protection level when the both airbases operate independently?

First I need to determine how many failures of each of the engine modules I expect to face during the average turnaround time, 15 days. As can be seen, due to fact that the modules are different among themselves during the mean time between failures (MTBF), some modules tend to fail more frequently than the others. Obviously, they require larger inventory to meet the need during the turnaround duration. In this case k is the number of systems. This means, that k_1 presents the number of systems at airbase 1. Therefore, k_2 presents the number of systems at airbase 2. The average failure rate of the system is presented by λ. The time range is presented by t. The time range is defined by the turnaround time in function of flight hours. This means, that if turnaround time is 15 days, 8.22 flight hours are lost due to turnaround of that particular system. The expected number of failures is presented by μ.

$\mu = k \lambda t$

$k_1 = 60$

$k_2 = 60$

MTBF = 1/ λ => λ = 1/MTBF

t = 200 flhrs * 15/365 years = 200*15/365 = 8.22

Table 5 summarizes these calculations.

Table 5. Decentralized model. Adapted from Kang (2017).

Decentralized model									
Components	MTBF	Protection Level	k	λ	t	k λ t	**Required spares**	Cost	Total Cost
Compressor	2000	0.9	60	0.00050	8.22	0.25	**1**	$1,000,000	$1,000,000
Fan	1500	0.9	60	0.00067	8.22	0.33	**1**	$1,000,000	$1,000,000
HPT	1,000	0.9	60	0.00100	8.22	0.49	**1**	$500,000	$500,000
LPT	1,200	0.9	60	0.00083	8.22	0.41	**1**	$500,000	$500,000
Combustor	2,500	0.9	60	0.00040	8.22	0.20	**1**	$750,000	$750,000
Afterburner	500	0.9	60	0.00200	8.22	0.99	**2**	$750,000	$1,500,000
									$5,250,000

The failure rates of modules during the turnaround time vary between 0.20 failures (combustor) and 0.99 failures (afterburner). The natural conclusion is that each Air Base needs to store more afterburners (2+2) than combustors (1+1). To meet the required protection level each base should have the inventory shown in the table in the "Required spares" column. The total dollar value of the module spare parts with two independent airbases at 90% protection level is 2 * $5,250,000 = $10,500,000.

2. Consolidated Inventory Model, Turnaround 15 days

What difference does it make if the airbases consolidate their inventories and instead of having two separate inventories held only one inventory? What is the total dollar value of the module spare parts pool at given protection level when the spare parts management is consolidated between the two airbases? Table 6 summarizes the following calculations, which follow the same basic logic as the previous calculations, but for a combined inventory.

$\mu = k \lambda t$

$k = k_1 + k_2 = 120$

$\lambda = 1/\text{MTBF}$

t = 200 flhrs * 15/365 years = 200*15/365 = 8.22

Table 6. Consolidated model with 15 days turnaround time. Adapted from Kang (2017)

Consolidated model									
Components	MTBF	Protection Level	k	λ	t	k λ t	**Required spares**	Cost	Total Cost
Compressor	2000	0.9	120	0.00050	8.22	0.49	**1**	$1,000,000	$1,000,000
Fan	1500	0.9	120	0.00067	8.22	0.66	**2**	$1,000,000	$2,000,000
HPT	1,000	0.9	120	0.00100	8.22	0.99	**2**	$500,000	$1,000,000
LPT	1,200	0.9	120	0.00083	8.22	0.82	**2**	$500,000	$1,000,000
Combustor	2,500	0.9	120	0.00040	8.22	0.39	**1**	$750,000	$750,000
Afterburner	500	0.9	120	0.00200	8.22	1.97	**4**	$750,000	$3,000,000
									$8,750,000

I can determine the spare modules needed to satisfy the required protection level by using the Poisson distribution method. When the inventory is consolidated between the bases, we can notice, that there is a reduction in the spare parts needed even though the protection level remains the same. The total dollar value of the module spare parts with consolidated airbases at 90% protection level is $8,750,000. So by consolidating the inventory management, the airbases were able to reduce their inventory value by 16.7%. Also, the stock facility operating costs are expected to decrease after consolidation. On the other hand, presumably, there will become additional transportation costs and administrative delays due to consolidation. I consider these costs next.

3. Consolidated Inventory Model, Turnaround 20 days

Next, let’s assume that the consolidated inventory management increases the average turnaround time by five days and the additional transportation, handling and administrative costs are $300 per failure. Is the consolidation still the more preferable option? Table 7 summarizes this set of calculations.

$\mu = k \lambda t$

$k = k_1 + k_2 = 120$

$\lambda = 1/MTBF$

t = 200 flhrs * 20/365 years = 200*20/365 = 10.96

Table 7. Consolidated model with 20 days turnaround time. Adapted from Kang (2017)

Cosolidated model, 20 day turnaround time									
Components	MTBF	Protection Level	k	λ	t	k λ t	**Required spares**	Cost	Total Cost
Compressor	2000	0.9	120	0.00050	10.96	0.66	**2**	$1,000,000	$2,000,000
Fan	1500	0.9	120	0.00067	10.96	0.88	**2**	$1,000,000	$2,000,000
HPT	1,000	0.9	120	0.00100	10.96	1.32	**3**	$500,000	$1,500,000
LPT	1,200	0.9	120	0.00083	10.96	1.10	**2**	$500,000	$1,000,000
Combustor	2,500	0.9	120	0.00040	10.96	0.53	**1**	$750,000	$750,000
Afterburner	500	0.9	120	0.00200	10.96	2.63	**5**	$750,000	$3,750,000
									$11,000,000

The total dollar value of the module spare parts with consolidated airbases at 90% protection level and 20-day turnaround time is $11,000,000. The total number of failures per year must be determined to find the total cost effect caused by transportation and other failure rate related cost functions. It can be calculated for each component using the simple formula: (Annual operating hours/ MTBF)* number of units.

Table 8. Failure rates per year

Components	Failures per Year
Compressor	12
Fan	16
HPT	24
LPT	20
Combustor	9.6
Afterburner	48
	129.6

The total amount of failures is 129.6 per year. The additional transportation and administrative annual costs in this case is $300 * 129.6 = $38,880. The annual inventory holding cost difference depends on the average amount of spare parts in stock. The required spare parts modules in decentralized inventory and consolidated 20-day turnaround inventory are as follows:

Table 9. Cost comparison between decentralized model (15 days turnaround) and consolidated model (20-day turnaround). Adapted from Kang (2017)

Components	Required spares Decentralized	Cost	Required spares Consolidated	Cost
Compressor	2	$2,000,000	2	$2,000,000
Fan	2	$2,000,000	2	$2,000,000
HPT	2	$1,000,000	3	$1,500,000
LPT	2	$1,000,000	2	$1,000,000
Combustor	2	$1,500,000	1	$750,000
Afterburner	4	$3,000,000	5	$3,750,000
		$10,500,000		**$11,000,000**

In this case, the inventories between the 15-day decentralized model and 20-day consolidated model are rather similar in volume. The five-day change in turnaround time has an obvious effect on the required spare parts inventory. The longer the turnaround time is, the more there have to be spare parts in stock to maintain required protection level. The annual inventory carrying cost difference in 20% inventory carrying rate in this case is $500,000 * 0.2 = $100,000. When the transportation and administrative cost factors are added, the decentralized inventory management is $138,800 more inexpensive annually. Once again, the facility cost function has not been taken into consideration. If the facility – or other – savings exceed $138,800 annually, the consolidated option becomes more cost-effective.

4. Complete Spare Engines In Airbases

What if the airbases keep spare engines instead of spare modules in consolidated stock? What is the engine MTBF? What is the value and annual cost of the required spare engine inventory pool? In this case, drawn from Kang (2017), when a module fails, maintenance personnel remove the faulty engine, install a new (spare) engine, and send the faulty to the repair depot. Assume the depot turnaround time in this case is 15 days, the spare engine protection level is 90%, and an engine costs \$4.5 million, equal to the sum of the module costs.

The expected amount of engine failures during the depot turnaround time can be determined by adding up the sum of the failure rates of engine modules and multiplying that factor by number of engines and operating hours during turnaround time ($\mu = k \lambda t$).

$k = 120$

$\lambda = 1/2000 + 1/1500 + 1/1000 + 1/1200 + 1/2500 + 1/500 = 0.00540$

$t = 200$ flhrs * 15/365 years = 200*15/365 = 8.22

$\mu = k \lambda t = 120 * 0.00540 * (200 * 15/365) = 5.33$

When the expected amount of engine failures during the turnaround time is 5.33, according to Poisson distribution, to protect the fighter fleet's performance with 90% protection level, there have to be at least eight spare engines available all times. (See Table 10 for the calculations.)

Table 10. Spare engines calculation. Adapted from Kang (2017)

Complete spare engines calculation				
Number of engines	Failure rate	Turnaround time	Expected number of failures during t	
k	λ	t	k λ t	
120	0.00540	8.21918	5.32602864	
Protection level	0.90		Required Spare engines	8

The total dollar value of the spare engines at 90% protection level is 8 * $4,500,000 = $36,000,000. The potential engine failure rate λ(engine) is the sum of the failure rates of its modules. Due to that fact, the number of spare engines needed is relatively high when compared to the amounts of modules needed.

C. F-HX LIFE CYCLE COST DETERMINATION

"Life cycle cost (LCC) can be defined as the total cost to the government of a program over its full life, including costs for research and development, testing, production, facilities, operations, maintenance, personnel, environmental compliance, and disposal" (Barber, 2015, pp. B-4). Life cycle cost estimate is a pivotal source of information for the spare parts inventory policy determination and acquisition process. For a new fighter aircraft acquisition program, it is necessary to make thorough life cycle cost estimation for future funding. Based on the fighter manufacturers' and the end users' estimates of cost and required performance parameters and metrics the program may be modified and the decisions related to the mission impact can be made. Maintenance and spare parts constitute a remarkable part of the fighter's life cycle cost, so the cost estimate is essential in assessing overall system affordability (DAU, 2013). The typical modern fighter system's life expectancy is 20–30 years (Jones, White, Ryan, & Ritschel, 2014, p. 454) and a remarkable part of the life cycle costs are attributed to operations and support –that is: fuel, spare and "repair parts, maintenance, [outsourced] and contract services [and] the costs of all personnel associated with the fighter system" (Jones, White, Ryan & Ritschel, 2014). "Operating and Support (O&S): Cost of operating and supporting the fielded system, including all direct and indirect costs incurred in using the system, e.g., personnel, maintenance (unit and depot), and sustaining investment (replenishment spares). The bulk of life cycle costs occur in this category" (Barber, 2015, p. B4).

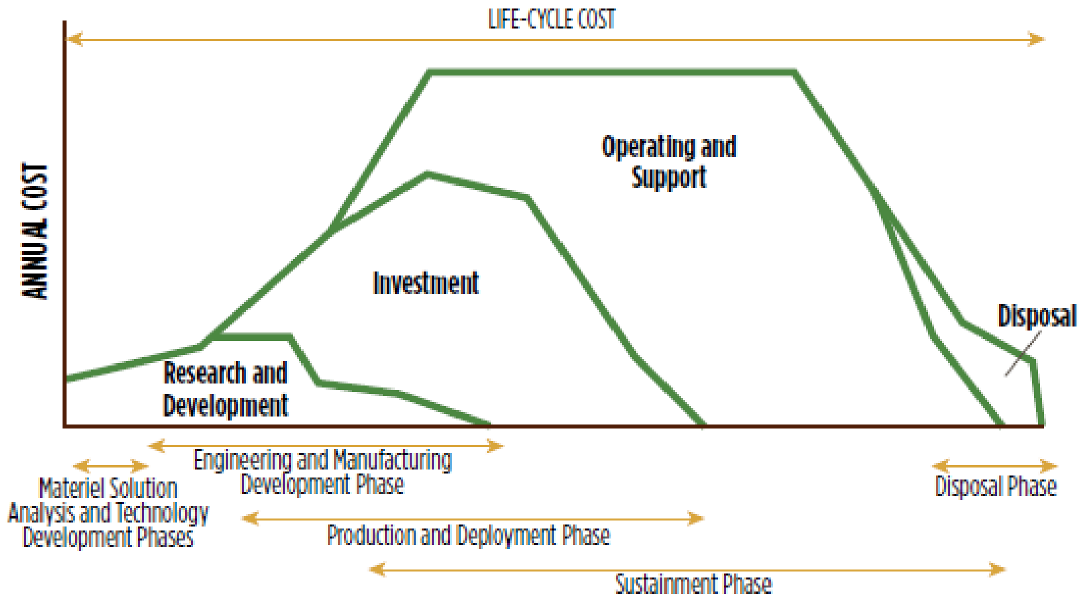


Figure 7. Illustrative system life cycle. Note: This figure depicts the ratio as nominal. Source: Jones, White, Ryan, & Ritschel (2014).

To make the appropriate decisions regarding the spare parts, maintenance and the life cycle costs of the fighter system, the decision makers need to get the correct information. The notion of operation and support costs being 70% of life cycle costs has been widely used in the U.S. Department of Defense's acquisition directives (see Figure 7) (Jones, White, Ryan, & Ritschel, 2014). Still, it is important to analyze the actual sustainment costs of each particular fighter candidate system. The latest studies show, that the operations and support costs of modern technology weapons systems vary a lot. The expected lives of modern fighter systems may be extended significantly by future modifications, which also extend their capabilities through future updates, thus having a remarkable impact on long-term sustainment costs (Barber, 2015). These future modifications and performance updates should be taken into consideration when predicting the actual operations and support costs. Defining the realistic picture of the variability of the life cycle proportions supports the decision makers understand the expected sustainment costs.

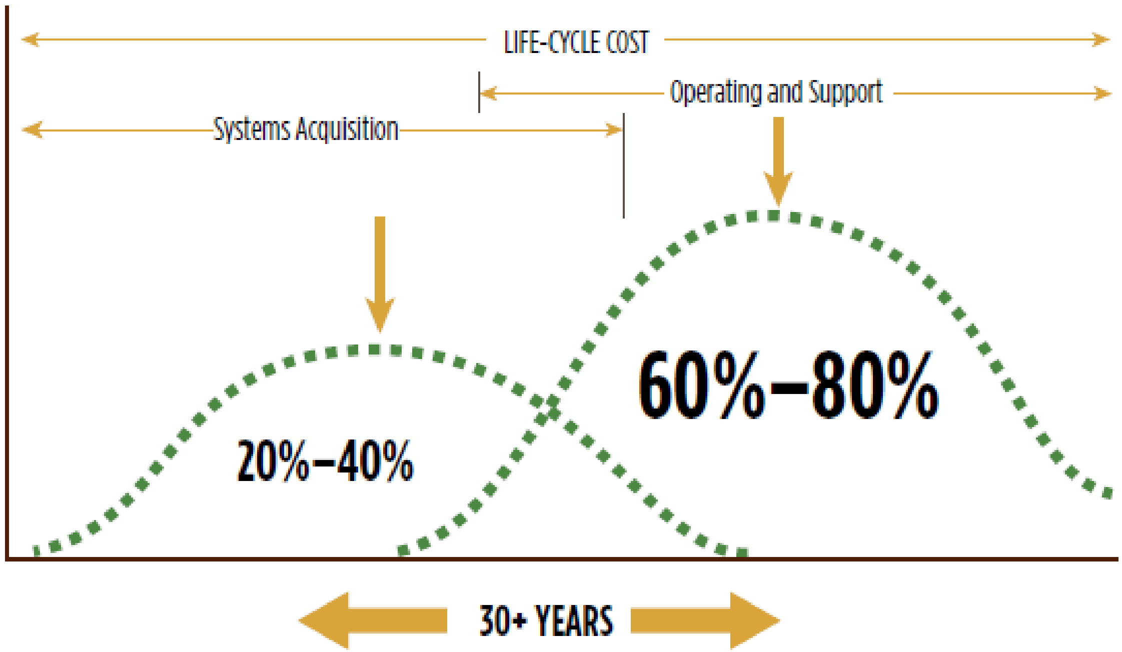
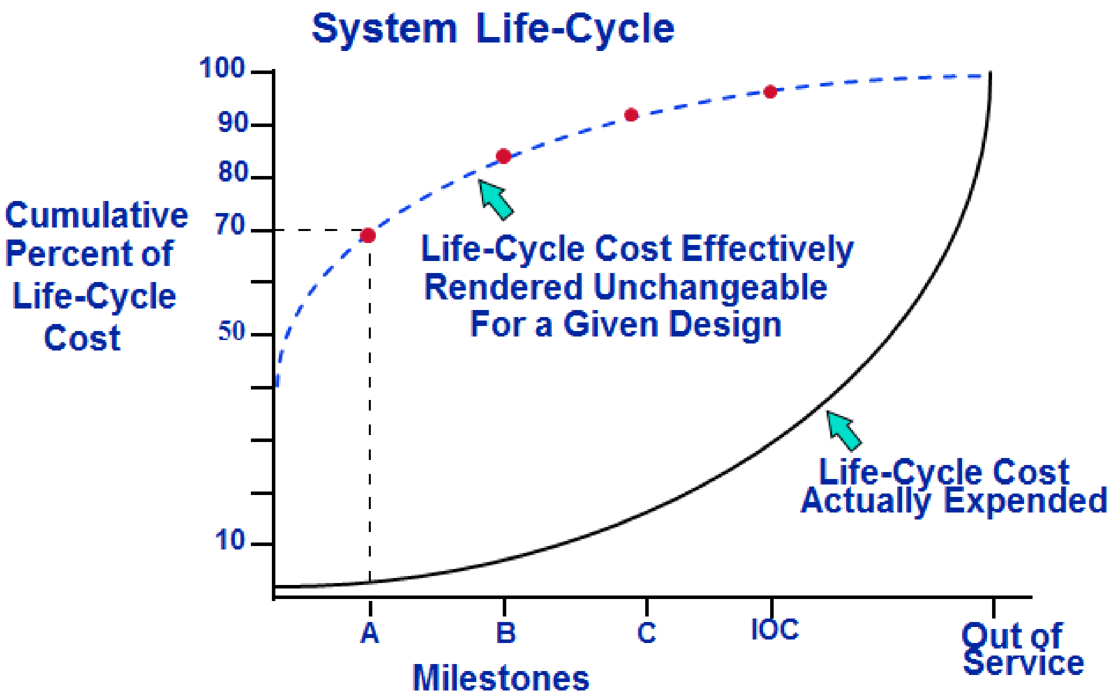


Figure 8. Nominal life cycle cost distribution. Source: Jones, White, Ryan, & Ritschel (2014)

For the current fighter type aircraft group (eight fighter types used in the U.S. Airforce and Navy), the mean operations and support cost proportion is 53%. The estimates regarding the future weapons systems indicate that the "new systems will have more life cycle costs devoted to acquisition than to sustainment" (Jones, White, Ryan, & Ritschel, 2014). The lowest estimates of the systems operations and support proportions are 41% (Jones, White, Ryan, & Ritschel, 2014, p. 456). This can be partly explained with very high research and development costs and acquisition costs of the modern fighters.



Source: Prof William Fast's class material from MN3301: Acquisition of Defense Systems (SP17_WF), Affordability AoA and CAIV (3-02), NPS.

Figure 9. Early decisions affect life cycle cost (based on historical data).

In sophisticated and complex systems, like modern fighters, the thorough estimation process for the life cycle cost is essential. If the system is software-based, requires continuous life time updates and its life cycle is 20–30 years, the operations costs tend to rise during the life time. That is why it is important to determine and agree the spare parts management future costs in purchasing process to meet the required service level over the fleet's life time.

Whatever the operations and support proportion of the life cycle cost were, the decisions concerning spare parts inventory management have multiple direct and indirect influences on life cycle cost. The accurate or best estimate of cost information supports the acquisition decision process as well as the defining the spare parts inventory management monetary demands. Earlier I discussed the differences in the spare parts inventory management by carrying separate or consolidated inventories. There is also a great difference in the monetary value of the spare parts inventory, whether the inventory consists of complete spare parts units, like complete engines, or spare parts modules, like engine parts. Having modules instead of complete systems in stock is a more inexpensive way of carrying inventory necessary for the required protection level. The most economical way of carrying spare parts inventory seems to be the one where spare part modules were stored in consolidated stocks. But what else should be taken into consideration?

Table 11. Example of parameters in LCC table. Adapted from Kang (2017)

HX O&M Cost Estimation		
# of HX Squadrons	2	
# of HX/ Squadron	30	
# of engines/ HX	2	
Operating hrs	200	hrs/yr
Protection Level for Critical Components	90%	
Protection Level for non-Critical Components	80%	
Operating cost/ hr	$ 2,000	
Depot charge per failure	$ 5,000	
Transportation per failure	$ 300	
Avg Depot TAT	15	days
Annual Inventory rate (including initial spare purchase)	20%	per yr
Preventive maintenance (PM)	$ 750,000	per AC
PM TAT	90	days
Time between PM	3	yrs
Life Cycle	30	years

By using life cycle cost calculation models (see Table 11) I have defined some key parameters to accomplish life cycle cost estimations. First, the main interest focuses on the number of systems reviewed. In this case there are 60 fighters involved in two squadron’s operations. Each aircraft carries two engines. The required parameters for determining the life cycle cost include: the usage rate of the asset, the required performance availability (Protection level), the cost components, the timing and delay factors and the annual cost of the capital.

Table 12. HX engine system's reliability, classification, availability and cost elements. Adapted from Kang (2017)

Engine Components	MTBF	λ	Unit cost	Unit classification	Protection level	# of units per AC	# of units per squadron (30 AC)	Average turnaround (days)	
Compressor	2000	0.00050	$1,000,000	Critical	0.9	2	60	15	
Fan	1500	0.00067	$1,000,000	Critical	0.9	2	60	15	
HPT	1,000	0.00100	$500,000	Critical	0.9	2	60	15	
LPT	1,200	0.00083	$500,000	Critical	0.9	2	60	15	
Combustor	2,500	0.00040	$750,000	Critical	0.9	2	60	15	
Afterbuner	500	0.00200	$750,000	Critical	0.9	2	60	15	
Engine Components	**Op Hr during TAT**	**Avg failures during TAT (kλt)**	**Required spares**	**Total spare cost**	**Annualized spare cost**	**Failures/ System /yr**	**Tot # of failures per yr per squadron**	**Tot repair cost**	**Transportation cost**
Compressor	8.2	0.25	1	$ 1,000,000	$ 200,000	0.1	6	$ 30,000	$ 1,800
Fan	8.2	0.33	1	$ 1,000,000	$ 200,000	0.1	8	$ 40,000	$ 2,400
HPT	8.2	0.49	1	$ 500,000	$ 100,000	0.2	12	$ 60,000	$ 3,600
LPT	8.2	0.41	1	$ 500,000	$ 100,000	0.2	10	$ 50,000	$ 3,000
Combustor	8.2	0.20	1	$ 750,000	$ 150,000	0.1	5	$ 24,000	$ 1,440
Afterbuner	8.2	0.99	2	$ 1,500,000	$ 300,000	0.4	24	$ 120,000	$ 7,200
				$ 5,250,000	**$ 1,050,000**		**65**	**$ 324,000**	**$ 19,440**

After entering the system data elements to the life cycle cost database, the demand for spare parts to meet the warfighter's requirement and the annual cost effects may be estimated. This estimation may be combined with the other operations and support cost elements to support in determining the total life cycle cost of the fighter operation. By using the LCC-worksheet or database one can estimate the impacts for the system's operational availability or life cycle cost when the parameters are adjusted.

Inventory consolidation and reduction drive the inventory carrying costs down, but the main question is how to satisfy the end users' demand. In determining the life cycle cost the build decisions during the development and production phases and also the future updates and the system development should all be tied into the program plan. The modern fighter is a complex, hardware and software hybrid system whose development maintenance and life time updates include a mix of incrementally deployed hardware and software changes that influence in the fighter asset's character and performance and therefor the spare parts management policy.

V. CONCLUSION

This chapter aggregates those factors in the fighter fleet’s spare parts supply chain and inventory management that have an influence in the performance of the air defense asset and the military budgeting in a modern operating environment. By using modern supply chain theories implemented in several actors worldwide I am confident to be able to define good practices to pursue and bad practices to avoid. Therefore, by defining the key elements affecting the supply chain management, this study supports the Finnish Defense Forces to bring out spare parts management requirements for the fighter manufacturer candidates in RFQs next year. Because of supposed variation in fighter manufacture candidates’ practices in managing supply chain with the end users, there are several methods to compare. This study addressed the differences between known inventory management models and practices to improve the information base needed for RFQ. This study analyzed the factors behind the research questions and presents the answers as follows.

1. What are the key factors in the near future fighter spare parts inventory management that will affect the FDF fighter fleet’s performance?

The key question regarding the fighter fleet’s spare parts inventory management is how to make sure that there is a sustainable balance between the operational user’s demand, vendor’s supply and the cost factors. The balance requires that the spare parts supply chain plans aim to the same strategic intent that the end users plans. This requires comprehensive planning from the beginning of the acquisiton process. The demand for the fighters intended use should be shared with the inventory managers. The manufacturer should share the inventory management planners with as accurate spare parts reliability data as possible and support in defining the most efficient inventory policy. As a result, the spare parts can be classified among their criticality, cost effect, lead time and several other parameters. As an outcome, the program’s inventory managers will be able to define the most appropriate spare parts inventory plan. After the inventory plan is synchronized with the operational plan and the finanacial boundary conditions, the spare parts inventory policy can be established. Inventory policy execution requires continuous interaction, demand information sharing with the end users, evaluation and necessary adjustments to insure, that the policy satisfies the need of capacity and inventory. Besides of ensuring warfighter's performance, the inventory policy must ensure that it yields with the inventory budget.

Mean down time: Fighter fleet requires a high rate of operational availability (A_o) of the fighters. When Ao = uptime / (uptime + downtime), the most important factor concerning the spare parts inventory policy is to decrease the mean down time as much as possible. Mean down time tells the average time that the fighter is not operational. According to findings in this study, the key factors regarding the mean down time are: The times what it takes to identify that the fighter is non-operational followed by failure detection and corrective maintenance times. If corrective maintenance requires spare parts, the lead time to obtain the part is essential. In case of preventive maintenance and fighter mid life updates, the scheduling the maintenance cosidering the spare parts lead time is key factor reducing the down time.

Spare parts demand forecasting: The variability in demand increases the inventory management costs by increasing the need for a safety stock. When the demand variability and the spare part's crticality are both high, the demand input from the end user is pivotal. When the demand variability is low and the spare part's criticality is high, the statistical forecasting methods may be used to establish appropriate inventory policy. In all possible cases, the understanding of the product plan and the sharing of the demand information are important for the inventory management's performance. The more critical the spare part is for the fighters' performance and the more vaiability there is in the demand, the more important the demand information sharing is. In forecasting demand, the errors occur. One can improve the forecasting, but it alone will not solve the the demand predicting challenge. The inventory managers need to understand the behavior and the processes of the players in the supply chain (Crum & Palmatier, 2003). Decreasing the variability is one of the most effective way to gain cost efficiency in spare parts inventory management. The success in predicting demand is based on effective collaboration and information sharing between the end user and players in supply chain.

Spare parts classification and identifying the critical parts. It is essential to determine the spare parts that are critical for mission accomplishment. Those spare parts must be available all times or be obtained in required period of time. The spare parts should be classified by the value for mission accomplishment and by the monetary value. In combining the spare parts classification parameters and overall priority orders, one can cross-tabulate the spare parts monetary and criticality analyses in the same matrix

The lead time management. Besides the fact that the lead time has a direct impact on mean down time, the accuracy in the lead time estimates is as important. When the lead time can be predicted precisely, the variation in maintenace process decreases. This in turn increases the efficiency of the inventory management system which has an impact on operational availability of the fighters. Inventory managers must understand the processes behind the lead times among different types of spare parts classes. By understanding how much of the lead time is caused by transportation, by ordering and other administrative processing delays or by some other time consuming factors, the repleshment policies can be adjusted to meet the demand.

In a long term inventory management, the life cycle support plan of the fighter fleet should be included in the acquisition planning. The life cycle support plan should include the evaluation of spare parts, goals, objectives, resources, and time frames to cover the fighter life time. (DAU, 2013) It should enable to maintain the fighter fleet in a ready condition required by the protection level, throughout its operational phase within life cycle cost estimate. It should include the spare parts inventory management plan, that is consistent with the fighter support strategy. The plan should describe sustainment influences on fighters' maintenance, update and technical development "activities to develop, implement, and deliver support [packages] that [maintain] affordable system operational effectiveness over the system life cycle and seek to reduce cost without sacrificing necessary levels of program support." (DoDI, 2015)

What are the essential questions and requirements that the FDF should consider – in terms of spare parts inventory management - in formulating its Request for Quotation for 4+ or 5th generation fighter manufacturers to maximize the operational availability?

According to the findings in this study, to find the most appropriate outcome and balance between the fighters' performance and cost attributes, the FDF decision makers need to get accurate information and parameters from the manufacturers regarding the fighters availability, reliability, ownership cost and the expected mean down time. These parameters may be approached with following questions:

- What is the fighter system's estimated operational availability (A_o) and fully mission capability rate?
- What is the fighter system's estimated mission reliability? What are the key metrics for mean down time (MDT)?
- What are the fighter system's and its subsystems' estimated logistics reliability? What are the key metrics for mean time between failures (MBTF)?
- What is the fighter system's estimated time between unscheduled maintenance action? What are the key metrics for mean corrective maintenance time?
- What is the fighter system's estimated time between scheduled maintenance action? What are the key metrics for mean time to repair
- What is the fighter system's estimated maintenance support time? (Maintenance man hours per operating hour)
- What is the fighter system's estimated depot maintenance need?
- How is the lifetime supply of spare parts guaranteed?
- What kind of spare parts classification model is used? What spare parts are the most critical for fighter performance?

- How and at what degree can the buyer involve in the design of fighter system, maintenance and spare parts management beginning in the early phase of procurement process?
- At what degree and at what cost can the spare parts management be arranged using Preformance Based Logistics (PBL) principles?
- At what degree and at what cost can the spare parts management be arranged using Vendor Managed Inventory (VMI) policy?
- At what degree and at what cost can the spare parts management be arranged using spare parts inventory pooling with other users?
- What is the cost per spare part unit?
- Are there aftermarket services for certain spare parts classes?
- What is the spare parts supply issue effectiveness?
- What is the spare parts order cycle time?
- What is the spare parts lead time?
- What is the spare parts back order rate?
- What is the spare parts delivery time for different spare parts classes (for critical / essential / low priority items)?
- What is the spare parts delivery accuracy and the expected amount of damages in transit?

2. How should the future fighter spare parts inventory management be arranged to meet the operational user's requirements?

To meet the warfighter's demand, the future fighter spare parts inventory management should be arranged in function of operational availability and cost. As presented in chapter IV, by consolidating the spare parts inventories managements, one may gain holding cost savings. Decentralized inventory management is traditionally more preferable for the warfighters, since it is assumed that then the spare parts are faster available. Dispersed locations also usually mean better protection for the hostile acts than a centralized location. Still, when managing complex and sophisticated aircraft and weapons systems, great amount of spare parts requires continuous attention and maintenance. Consolidating may be the only option in certain spare parts classes. Nevertheless, in terms of cost efficiency, the physical location of the spare parts' stock keeping units is not the major concern, but the inventory management. The dispersed inventory may be managed as an ensemble, which reduces the need for safety stock. Also, it is worth paying attention to the reliability of the units, the parts that the fighter or weapons system consists of. The sub units with lower reliabilities decreases the system's reliability. The less the system's reliability is, the more systems are needed in safety stock to meet the operational user's performance requirements. If the system is broken down in sub units in storage, the overall inventory holding cost savings may be gained.

When considering the excessive use of Vendor Managed Inventory (VMI) policy, Contractor Logistics Support (CLS) policy and Performance-Based Logistics (PBL) policy in streamlining the spare parts inventory management, the operational security issues may restrict the freedom of action in inventory management planning. Anyway, in terms of spare parts management performance, decreasing the demand variation is the key. The greater the variation is and the more inventory management levels there are, the more expensive and inefficient the system is. When there are many levels in a supply chain and the demand is hard to predict, every level needs safety stock to meet the demand to meet the warfighter's requirements. Moving up the supply chain from fighter units to manufacturer, every level has greater uncertainty in demand, which means greater variation, which, in turn, means greater safety stock. This bullwhip effect causes inefficiency in the supply chain system.

3. What are useful processes in the modern corporate supply chain and inventory management that could be implemented into the future fighter spare parts management?

According to my studies and findings, the most interesting and appropriate modern supply chain and inventory management process for the Finnish future fighter spare parts management could be a combination of category 3 or 4 Performance Based Logistics (PBL) and full or partial Vendor Managed Inventory (VMI).

In category 3 (system availability) PBL the vendor is responsible of producing materiel availability for the end user whereas in category 4 the vendor is responsible for providing the required operational capability for the fighter fleet (see Figure 2.) The difference is in the comprehensiveness in the vendor's responsibilities of providing the support. In category 3, the FDF should determine the required quantity of fighter asset and the associated weapons systems ready for operations. The vendor is responsible of maintaining the required availability of the spare parts and the fighter system's materiel availability. The vendor should place a Product Support Integrator (PSI) element in the Finnish Defense Forces Logistics Command's Joint Systems Centre to cooperate with the Finnish counterpart in the spare parts management. In addition to maintaining the required protection level the cooperation should include the full spectrum of support activities: "life-cycle support, training, maintenance, repair and overhaul including logistics planning and execution, in-service engineering, configuration management and transportation" (DAU, Performance Based Logistics (PBL) Overview , n.d.). In the cooperation, the Finnish counterpart determines the required materiel availability and sets the required level of performance. The interface between the responsibilities should be determined unambiguously to avoid overlapping or redundant functions. The vendor would be allowed to apply intensive leverage on the fighter asset's availability and the partnership support would last over the asset's life time, including the future performance updates in the fighter or weapons systems.

In PBL category 4 (operational capability) partnership the vendor applies the category 3 functions over the spare parts management added by the materiel quantity planning and execution (see Figure 2.). The PSI is accountable of arranging the fighter spare parts support to assuring the fighter fleet's operational availability. In this application, the partner has greater independence and flexibility to manage the functions required to meet the fighters' performance level.

Presumably, the performance based logistics increases the operations and support costs portion in fighter asset's life cycle cost since the vendor provides relatively strong life time involvement in the program. On the other hand, if the PBL costs are devoted to the acquisition portion, hence increasing the unit price of the system, the cost effect may lower the operation and sustainment portion (see Figures 6. And 7.). Also, the vendor is responsible to determine the cost effects of the future preventive maintenance programs, modifications and mid-life updates, which makes the life cycle cost planning more predictable. Nevertheless, there is evidence in several studies and in DOD documents, that the earlier the life cycle cost elements were determined, decided and agreed, the smaller the relative operational cost impact was (see Figure 8.). This means higher price per fighter but lower cost per flight hour. Also, the thoroughgoing understanding of the modern fighter's complex systems and their interdependences is the key element in planning and executing cost efficient spare parts management. The product support integrator element may support the FDF with significant contribution in planning and executing the spare parts management.

In Vendor Managed Inventory the vendor, spare parts supplier, manufacturer or the spare parts producer manages the fighter fleet's spare parts inventory. The vendor monitors the spare parts inventory and replenishes it to meet the set availability requirements. The vendor has unbiased view and understanding over the complex fighter spare parts features, their mutual dependencies in the complex fighter system and their estimated reliability factors so it can optimize the safety stock to meet the protection level that the warfighter has set. This has several advantages in increasing the performance. The supply chain's reaction time and the flexibility to the warfighters demand variations are better. This is compelling asset in reducing the risks for unwanted stock outs and also the risk for excessive inventories. Also, the supply chain is short: the risk for bullwhip effect decreases. By outsourcing the inventory management for vendors, the end user's spare parts management and maintenance personnel may concentrate on fighter performance core businesses by improving the maintenance processes. On the other hand, the VMI requires continuous information sharing and access to classified details of the fighter operations. The vendor has accurate information of the fighter asset's operational availability

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