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A framework for control and agenda for future research

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Abstract

This paper presents a framework for planning and control of the spare parts supply chain in organizations that use and maintain high-value capital assets. Decisions in the framework are decomposed hierarchically and interfaces are described. We provide relevant literature to aid decision making and identify open research topics. The framework can be used to increase the efficiency, consistency and sustainability of decisions on how to plan and control a spare parts supply chain. Applicability of the framework in different environments is investigated.

Keywords: Spare parts management, System availability, Decision framework, Decision support models

1. Introduction

Many industries depend on the availability of high-value capital assets to provide their services or to manufacture their products. Companies in these industries use capital assets in their primary processes and hence downtime can among others result in (i) lost revenues (e.g. standstill of machines in a production environment), (ii) customer dissatisfaction and possible associated claims (e.g. for airlines and public transportation) or (iii) public safety hazard (e.g. military settings and power plants). Usually the consequences of downtime are very costly.

A substantial group of companies in these industries both use and maintain their own high-value capital assets. Examples include airlines, job shops and military organizations. Within these companies, a *Maintenance Organization* (MO) is responsible for maintaining the capital assets. Besides maintenance activities, supply and planning of resources, such as technicians, tools and spare parts, are required. A *Maintenance Logistics Organization* (MLO) is responsible for matching the supply and demand of the spare parts required to conduct maintenance.

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Because the capital assets are essential to the operational processes of the companies involved, downtime of the assets needs to be minimized. Downtime of a system is usually divided into (i) diagnosis and maintenance time; (ii) maintenance delay caused by unavailability of the required resources for diagnosis and maintenance. Thus a high availability of spare parts is important as it influences maintenance delay directly (in the case of corrective maintenance) or indirectly (in the case of preventive maintenance). In this paper we focus on the responsibility of a MLO to minimize maintenance delay due to unavailability of required spare parts.

In MLO's, decisions are to be taken at the strategic, tactical and operational level. This paper presents a framework in which the connection between these decisions is outlined. We remark that the framework we provide will need refinement and alterations for every particular organizations. Nevertheless, this framework can be used to increase the efficiency, consistency and sustainability of decisions on how to plan and control the spare parts supply chain.

To decompose decisions in a hierarchical framework is a well established tradition in operations management. Initial models consider especially the production environment (Hax and Meal, 1975; Bitran and Hax, 1977; Hax, 1978; Bitran et al., 1981, 1982) and were motivated by the fact that it is computationally infeasible to solve one single all encompassing model. Later it was recognized that the hierarchy in such models is also useful because (i) in reality the power to make decisions is distributed over several managers or agents and (ii) the information available for different decisions has varying levels of detail (Dempster et al., 1981; Meal, 1984; Schneeweiss and Schröder, 1992; Schneeweiss, 1998, 2003; Schneeweiss and Zimmer, 2004). For the production environment, hierarchical frameworks are now part of standard textbooks (Silver et al., 1998; Hopp and Spearman, 2001). Other successful applications include traffic control (Head et al., 1992) and supply chain management (Schneeweiss and Zimmer, 2004; Ivanov, 2009).

Our main contribution is the development of a framework for MLO's as described above. This paper describes a clustering of the involved decisions and a hierarchy per cluster. We also provide references to literature that can support decisions in the framework and identify areas that received limited or no attention in the literature. As such, the second contribution of this paper is the clustering of maintenance spare parts literature and the identification of open research topics.

To the best of our knowledge, the only other paper in which a framework for spare parts control has been proposed is Cavalieri et al. (2008). This framework focusses exclusively on the inventory control of spare parts and provides rules of thumb concerning decisions in the framework. We take a broader perspective by incorporating a repair shop and its control and provide references to state-of-the-art techniques for supporting decisions in the framework.

Two review papers have been written on spare part management (Kennedy et al., 2002; Guide Jr. and Srivastava, 1997). These papers provide an enumerative review of the state-of-the-art at the time of writing. In this paper we do not attempt to provide an exhaustive review of contributions on these subjects. Rather we will provide relevant references for each part of the decision framework to facilitate decision making. As such, our paper groups available literature according to a practical decision framework. Thus it may be used as a convenient framework for both practitioners and academicians.

This paper is organized as follows. Section 2 describes the environment we investigate and the positioning of MLO's. Section 3 presents the framework and describes the decisions in the framework. Section 4 provides relevant references for each part of the decision framework to aid in decision making and reveals open research topics. Section 5 describes alternative framework design characteristics. In Section 6 we give concluding remarks and discuss future research.

2. Characterization of the environment

In the primary processes of the companies we consider, a substantial set of capital assets (asset base) is used for multiple purposes. Because of strategic decisions, new systems phase in and rejected systems phase out of the asset base. Maintaining this set of assets is an important task because downtime of assets immediately affects the primary processes. A capital asset is (partially) operational in case it is available for (a part of) all use purposes and a capital asset is down whenever it is in maintenance or waiting for maintenance to be conducted. Maintenance is either planned or unplanned and it is conducted within the constraints of the maintenance policy/concept.

To reduce the time an asset spends in maintenance it is common practice to maintain parts of the asset rather than the asset itself. When an asset is maintained, parts that require maintenance are taken out and replaced by *Ready-For-Use* (RFU) parts. Spare parts used at the first level maintenance are also called *Line Replaceable Units* (LRU's) (Muckstadt, 1973, 2005). The decision to designate a part as a LRU lies with the maintenance organization. LRU's that are taken out are either scrapped or sent to a repair shop for repair. Repaired parts are sent back to a ready-for-use LRU stocking location where they can be used again to replace a part. This principle is called 'repair-by-replacement' (Muckstadt, 2005) and makes the control of the spare parts supply chain a paramount task for the MLO.

MLO's try to find the optimal balance between spare parts availability, working capital and operational costs, within their span of control. Several tasks need to be conducted and decisions need to be taken in order to achieve the desired spare parts availability, possibly under constraints of working capital and/or operational costs.

In this section, an outline is given of the environment in which MLO's operate. First we characterize the process of maintaining the capital assets, second we discuss the spare parts supply chain and we end with the characterization of spare parts demand.

2.1 Characterization of system maintenance

The MO's we consider maintain a set of several high-value capital assets. The asset base is sufficiently large to generate a reasonably constant demand for maintenance activities. Examples of such asset bases include fleets of airplanes/trains or manufacturing equipment in a reasonably sized job shop. Maintenance on a capital asset is conducted according to a maintenance policy, maintenance program, maintenance planning or a modification plan. We distinguish three types of maintenance:
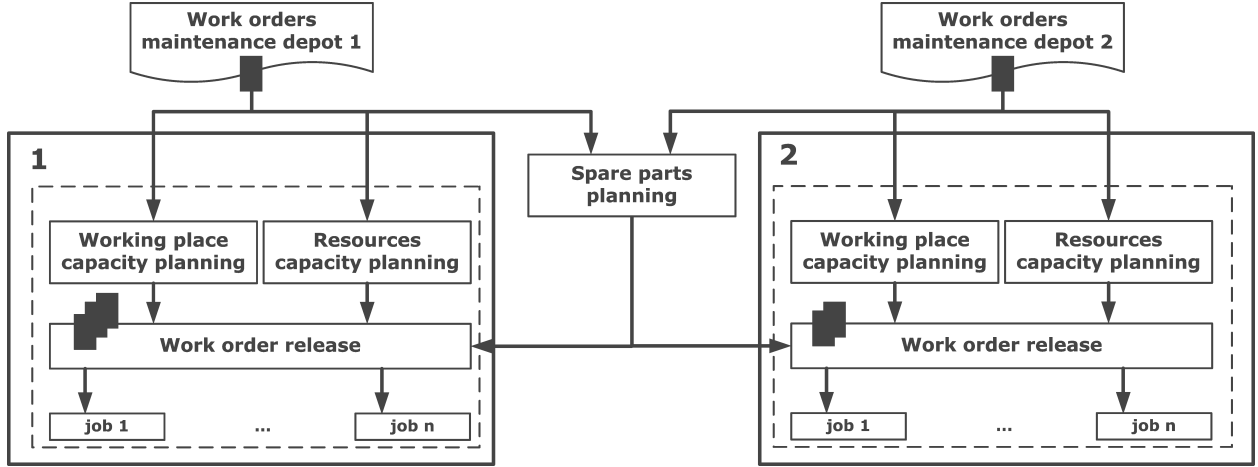
Figure 1: *Hierarchical planning framework for maintenance of high-value capital assets.*

- Preventive maintenance: maintenance that is conducted in order to prevent failure. Usually this maintenance is planned some time in advance and has to be conducted within a registered time frame during which the asset is in non-operating condition. Within this registered time frame, rescheduling of maintenance tasks is often possible. In some cases inspection can be separated in time from replacements to enable better resource and spare parts planning. Maintenance delay enlarges the time during which the asset is in non-operating condition and hence decreases the operational availability of the asset.

- Corrective maintenance: maintenance that is conducted after a failure has occurred. Corrective maintenance can be partially planned when it involves a non-critical part whose maintenance can be delayed after failure, but usually it is unplanned due to unforeseen breakdown of parts. When this happens maintenance needs to be conducted immediately as maintenance delay decreases operational availability of the asset.

- Modificative maintenance: maintenance conducted to improve the performance of the capital asset. This maintenance can be delayed until all resources are available.

MO's prepare their maintenance jobs by creating a work order. This work order contains a planning of all tasks to be completed and a list of all the resources (tools, equipment, technicians and spare parts) required to conduct the maintenance. Figure 1 presents a hierarchical planning framework for maintenance of capital assets. Note that spare parts planning (the focus of this paper) is part of this framework as a whole.

The figure is to be read top-down. Work orders generate demand for LRU's and other resources (working place, technicians, tools, equipment) needed to conduct the maintenance. A (part of a) work order is released as soon as all resources and all required LRU's to start (a part of) the work order are available. Unreleased work orders are queued, until they are released.

The MLO is responsible for the availability of LRU's needed to conduct system maintenance, the MO's are responsible for all other resources. A key performance indicator that is often used

to measure (partial) system availability is the "average number of unfinished work orders", which is related to the number of systems that are in non-operating condition. Usually performance indicators are separated for preventive, modificative and corrective maintenance work orders. Hence the MLO has to cope with multiple service level criteria.

2.2 Maintenance spare parts supply chain overview

We consider organizations in which the supply chain already exists, i.e. location and size of warehouses are predetermined. The spare parts supply chain is in general a multi-echelon system. We distinguish two types of spare parts:

1. Repairable parts: parts that are repaired rather than procured, i.e. parts that are technically and economically repairable. After repair the part becomes ready-for-use again.

2. Non-repairable parts or consumables: parts which are scrapped after replacement.

Consumable LRU's need to be replenished from outside suppliers, whereas repairable LRU's are sent to a repair shop. The LRU is repaired at the repair shop and usually one or more parts in the LRU are replaced. Parts that are replaced in the repair shop rather than at first level maintenance are called *Shop Replaceable Units* (SRU's). SRU's, like LRU's, can either be consumable or repairable and need to be replenished from external suppliers/repair shops or an internal repair shop, respectively. Hence there are multiple levels of repair.

In general there are multiple first level maintenance sites with associated spare part stocks. In general the spare parts supply chain is a multi-echelon divergent supply chain with multiple repair shops. Additionally, the supply chain has closed-loops for repairable spare parts. When demand for a LRU cannot be met from local stock, emergency procedures such as lateral transshipments or emergency shipments from upstream stocking locations may be applied.

Figure 2 presents a typical example of a spare parts supply chain within companies that both use and maintain high value capital assets. A central stocking point of spare parts supplies several local stocking points that are incident to the first level maintenance sites. There is also a stocking point of parts that still need to go to repair and a stocking point of parts required for new projects and modifications that occur during the life cycle of a capital asset. In practice these stocking points are often in one and the same warehouse, but for control reasons these stocks are distinguished.

2.3 Maintenance spare parts demand characteristics

As mentioned in the Section 2.1, maintenance on a capital asset generates demand for LRU's. The MO requests the required LRU's at the MLO by creating spare parts orders, related to a work order. The LRU's are delivered from the stocking location incident to the requesting maintenance depot. If not enough LRU's are available, then parts are delivered from the central stocking location or possibly via transshipment from a different stocking location. Each type of maintenance on the capital assets generates demand for LRU's in a different way.
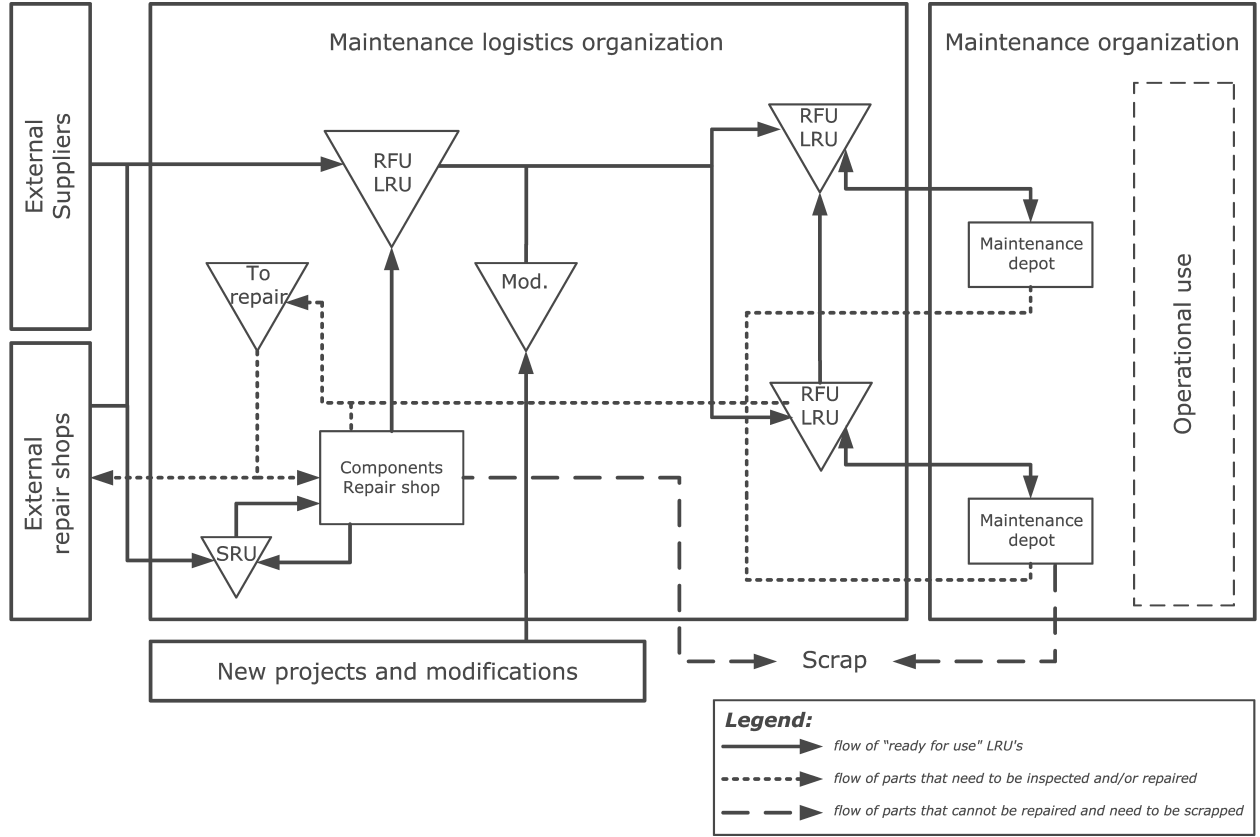
Figure 2: *Example of a maintenance spare parts supply chain*

MO's create work orders for preventive and modificative system maintenance some time before the desired start of the work order. When the work order is created, the spare parts requirements are known and fixed. The required LRU's to conduct the maintenance are requested by the MO with a desired lead time, i.e. *delivery lead time*. The desired delivery date for an LRU need not necessarily be equal to the start date of the work order, as not all maintenance tasks (including their required LRU's) commence simultaneously with the start of the work order. It is possible that the desired delivery dates of LRU's change over time as maintenance tasks are rescheduled.

Work orders for corrective maintenance are created after the probable cause(s) of breakdown is (are) diagnosed. The MO updates the work order planning and orders the required spare parts at the MLO. The desired delivery date for an LRU is then equal to the start date of the work order.

Typically, maintenance depots and MLO's make agreements on specified upper/lower bounds for key performance indicators such as (i) the average work order delay due to unavailability of spare parts, (ii) the percentage of work orders without delay (caused by unavailability of spare parts) or (iii) the maximum "number of unfinished work orders" due to unavailability of spare parts at any given time. Separate agreements are made on the availability of spare parts that do not cause immediate system downtime.

3. Framework for maintenance spare parts planning and control

In this section we present the framework for maintenance spare parts planning and control. In Figure 3 an overview and clustering of the main tasks and decisions in MLO's is presented, including their mutual connections. We separate eight different processes, which are numbered one up to eight in the figure. Within each process, we distinguish different decision levels. Decisions that are not made very frequently, i.e. once a year, are marked 'S/T' (strategic/tactical decisions); decisions made regularly, i.e. once a month or quarter, are marked 'T' (tactical decisions) and decisions made frequently, i.e. once a day/week, are marked 'O' (operational decisions).

An arc illustrates that information, e.g. data or outcome of decisions, flows from one process to another. This information is needed to make decisions in subsequent processes. We emphasize that there are many feedback loops between the various processes. For example, a feedback loop occurs when input from demand forecasting and supply structure management lead to unusually high inventory levels and demand forecasts and/or supply structures are reconsidered. For readability these feedback loops are left out of the figure.

We recall that the framework we provide will need refinement and alterations for every particular organization. The framework does serve as a useful starting point in making specific designs of maintenance spare part planning and control systems. In the remainder of this section we outline each cluster of decisions from the perspective of the performance indicators MLO's face.

3.1   Assortment management

Assortment management is concerned with the decision to include a spare part in the assortment and maintaining technical information of the included spare parts. We emphasize that the decision whether or not to include a part in the assortment is independent of the decision to stock the part. The process of managing the assortment can be found in Figure 4.

3.1.1   Define spare parts assortment

The decision whether to include a part in the assortment is usually taken shortly after procurement (initial phase) of a (sub)system. There are two options when to include a part in the assortment: before or after the first need for the part.

In case a part is included in the assortment, then there is a possibility that the part is never needed during its lifecycle. Time spent on collecting information, signing contracts with potential suppliers on unit price and (contractual) lead and/or repair times and adding the part to the database has been done without any use, which results in unnecessary operational costs.

However, in case a part is not included in the assortment there are two possible adverse consequences. First, when the part fails and a supplier is still available, the lead time of the part is higher due to data collection and negotiation actions. Second, when the part is needed there may not exist any suppliers for it anymore. In this case, the part may have to be custom made. To do this, in many cases specialized technical information regarding the form, fit and function is needed.
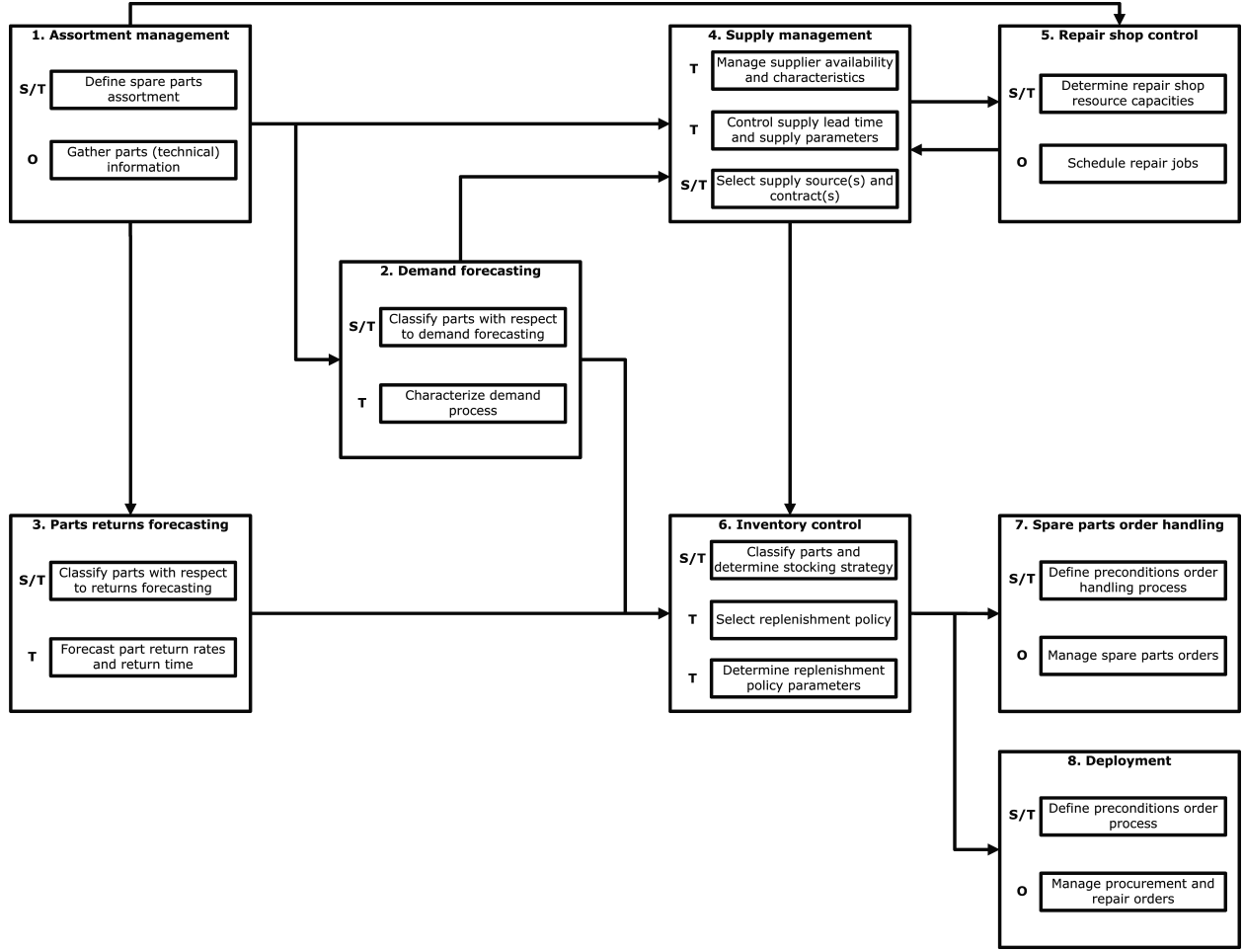
Figure 3: *Overview and clustering of decisions in maintenance logistics control.*

If a part is not included in the assortment this information is not available.

A trade-off should be made between cost of including the part in the assortment and the expected cost of extra downtime, e.g. based on the probability that the parts will be needed in the future and a simple failure mode effects and criticality analysis.

3.1.2 Gather parts (technical) information

Once a part is included in the assortment, (technical) information of the part is gathered and maintained. The MLO needs to decide whether or not to gather and maintain parts technical information that is important for spare parts planning and control: (i) criticality, (ii) redundancy, (iii) commonality, (iv) specificity, (v) substitution, (vi) shelf life, (vii) position in the configuration[1] and (viii) repairability. Additionally technical information regarding form fit and function may be

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[1]The configuration is similar to the Bill of Materials. However the configuration changes throughout the lifetime of an asset due to modificative maintenance whereas the bill of materials is a snapshot of the configuration at the time of initial manufacture.

Figure 4: *Process of managing a spare parts assortment.*

gathered. We also distinguish so called 'insurance' spare parts.

Parts criticality is concerned with the consequence of a part failure, that is the type of breakdown and reaction time. We distinguish two types of system breakdown, i.e. full or partial system breakdown. Full system breakdown means that the system is non-operational for all assigned use purposes. Parts that cause full system breakdown are denoted *critical*. Partial system breakdown means that the system is operational for only a part of the a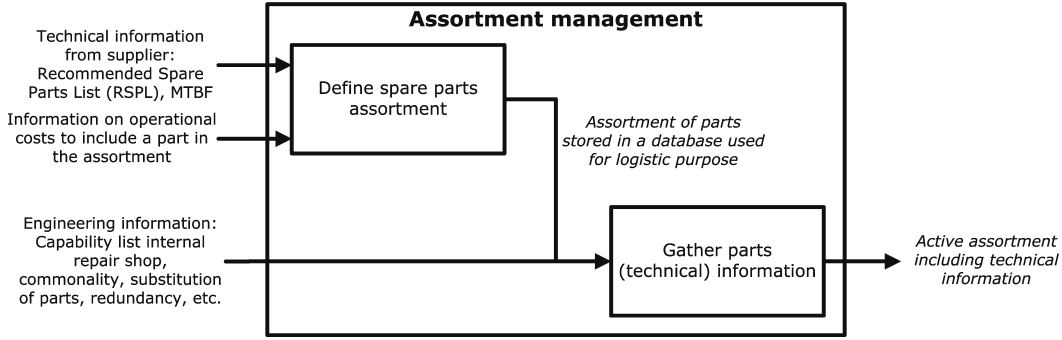ssigned use purposes. Parts that cause partial system breakdowns are denoted *partially critical*. Parts that cause no system breakdown, i.e. the system can be used for all assigned use purposes, are denoted 'non-critical'.

Parts redundancy is the duplication of system components (parts) with the intention to increase the reliability of the system. The decision to duplicate parts is either made by the OEM or the MO. Information on parts redundancy decreases the number of stocked spare parts as it is known in advance that part failure does not cause immediate system breakdown. Hence stock levels for redundant parts may be decreased.

Parts commonality concerns parts that occur in the configuration of multiple systems that are maintained by the MO. For each system the MLO's needs to meet a certain service level. Information on parts commonality is needed for customer (system) service differentiation in spare parts planning as well as for the decision where to stock parts, i.e. locally or centrally.

The specificity of a part concerns the extent to which a part is tailored for and used by a customer. Parts availability at suppliers is usually low, if not zero, for specific parts and hence this might effect the size of the buffer stock needed.

Parts are substitutional in case different parts have the same form, fit and function. This means that requests for one part can be met by a substitute part. Information on parts substitution is used to prevent stocking parts for which requests can also be met by a substitute part.

The shelf life of a part is the recommended time period during which products can be stored and the quality of the parts remains acceptable for usage. This information is used to prevent stocking to many parts that are scrapped or revised after the shelf life of the part has expired.

The configuration is a list of raw materials, sub-components, components, parts and the quantities of each that are currently in a system. Hence this list contains all the SRU's and LRU's in the system that may require maintenance during its use. The position of a part in the configuration

is needed to determine at which level parts (SRU's) can be replaced, in order to repair an LRU, and what quantity of each SRU is needed. These different levels in the configuration are also called indenture levels. The initial configuration is usually provided by or available at the OEM and coincides with the bill of materials.

Parts repairability concerns the identification whether a part is technically repairable and if so, whether or not the internal repair shop has the authorization (from the OEM) and the capability to repair the part. This information is needed to determine the parts supply structure.

Technical information on form, fit and function comes in many forms depending on the technological nature of the part involved. Sometimes this information is of a sensitive nature and the OEM may charge extra for this information and/or requires non-disclosure type contracts.

'Insurance' spare parts are parts that are very reliable, highly 'critical' to system availability and not readily available in case of failure. Often these parts are far more expensive to procure after the initial buy of the system, compared to buying at the moment of initial system purchase. Because of their high reliability, these spare parts often will not be used during the lifetime of the system. Example of an 'insurance' part is a propeller in a ship.

Parts (technical) information is sometimes provided by the OEM. However, it is also possible that the MLO needs to determine this technical information. All the technical information is used to decrease the stock value or manage supply risk. For parts that are relatively cheap and well available at suppliers, spending time on collecting and maintaining technical information is not beneficial from a cost perspective. On the other hand, for parts that are relatively expensive or not well available at suppliers, gathering parts technical information is beneficial to control supply risks and operational costs.

3.2 Demand forecasting

Demand forecasting concerns the determination of which parts will be demanded in the near future and if so, with what quantity. Future demand for spare parts is either (partially) planned or unplanned and is characterized in Section 2.3.

Demand forecasts can either be based on historical data, known future demand data or a combination of both. MLO's need to decide whether to use the information on future demand or not. Based on this decision a forecast method is chosen to forecast or, in case of planned demand only, determine future demand for spare parts. The demand forecasting process is visualized in Figure 5.

3.2.1 Classify parts with respect to demand forecasting

Two types of spare parts are considered: parts for which information on future demand is used and parts for which no future demand information is used. In case there is no information available or it is decided not to use it, then all demand is accumulated and one single demand stream is considered. Otherwise, two demand streams (planned and unplanned) are separated.
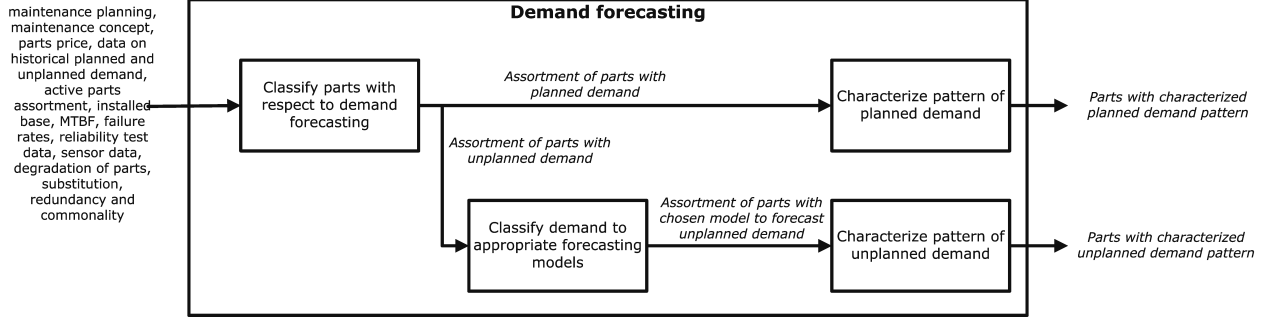
Figure 5: *Overview of the demand forecasting process.*

Using information on future demand usually decreases the overall forecast error. On the other hand, it is clear that using information on future demand increases the difficulty, the effort and hence the operational costs to forecast demand.

For parts that are relatively cheap or that have a small ratio of planned demand, using information on future demand is not beneficial from a cost perspective. In these cases the value of overstocking parts, caused by a less reliable forecast, is low. The decision to use information on future demand depends on the following criteria: (i) the price of a spare part and (ii) the ratio between planned and unplanned demand of the spare part.

Within unplanned demand another classification is made to aid the decision of using a particular forecasting technique. Two factors that determine what methods are appropriate are the interarrival time of demand moments and the variability of demand size. When time between demand moments is very long, then demand is said to be intermittent and any forecasting technique should incorporate that demand is zero in most periods. When intermittence is combined with variable demand sizes, demand is said to be lumpy. Also in this case the chosen forecast method should be appropriate for the situation.

3.2.2 Characterize demand process

After deciding whether or not to separate demand streams, the demand process needs to be characterized on behalf of the following three purposes: (i) to determine the number of parts to stock, (ii) to determine the repair shop capacity and (iii) to provide the necessary input for updating and characterizing supply contracts. MLO's forecast the unplanned demand for the next period(s), including a forecast error, for each part and stocking location combination. The demand processes of planned and unplanned demand are characterized separately.

Planned demand during the delivery lead time is deterministic, since all parts are requested at least early enough in advance. Expected planned demand after this delivery lead time is, on the contrary, not known in advance exactly and should hence be forecasted (e.g. based on historic planned demand data). Note that this forecast should be corrected for demand that is in fact known at this moment. Demand for spare parts on modificative work orders is deterministic as the delivery lead time for these work orders is flexible, i.e. these work orders can be postponed until

all resources needed to conduct the work orders are available.

Demand for spare parts could also be partially planned in advance. Parts that are needed in about $x\%$ of some types of preventive maintenance work orders are termed $x\%$-parts. Forecasting this partially planned demand is done by forecasting the probability that a part is needed for each type of work order, i.e. determine x. Combining these probabilities with the information on which types of work orders are planned to be conducted in the future, a forecast for this planned demand stream can be made.

Several methods are applicable to forecast unplanned demand. The first method to forecast unplanned demand is reliability based forecasting. The goal of this method is to forecast parts requirements based on part failure rates, a given installed base and operating conditions. This method determines the failure rate of one part and extrapolates the failure rate to the installed base and varying operating conditions. Advantage of these methods is that they can cope with changes in the installed base and operating conditions. Reliability based methods can also deal with censored data, wear patterns and different failure modes. When data of a specific (new) part is unavailable, important characteristics can still be estimated by comparing to technically similar parts. Hence it is applicable in the initial phase, the maturity phase and the end-of-life phase of a system.

The second method to forecast unplanned demand is time series based forecasting. Based on known historic requirements, extrapolations are made using statistical techniques. Examples of well-known time series based forecasting techniques are Moving average, Smoothing methods, Croston's method and bootstrapping. The reliability, i.e. forecast error, for some of these methods depends on a smoothing (forecast) parameter. MLO's need to decide which techniques to use and whether or not to set the smoothing parameters for each part separately or for groups of parts. Advantage of time series based forecasting is that only historical demand data is needed to forecast demand. Disadvantage is that manual changes to the demand forecasts need to be made in case the installed base changes, e.g. using leading indicators. The result of characterizing demand is a distribution for the demand per period per part.

Technical information about substitution is used in forecasting to determine demand for new parts that substitute old parts. Combining demand streams, for different parts that can be met by the same spare part (i.e. substitutes), increases the overall demand forecast reliability. The demand forecast for the part that can meet requests for the other parts is then based on the convolution of the demand streams of all these parts, whereas the demand forecast for the other part(s) is set to zero. Technical information on commonality of new parts is used to determine how usage in different capital assets affects demand. Information on parts redundancy is used to correct the demand forecast as well.

3.3 Parts returns forecasting

Parts requested by the MO's are either used for conducting maintenance or not. In case it is not known which part causes system breakdown, sometimes all parts that may be the cause are
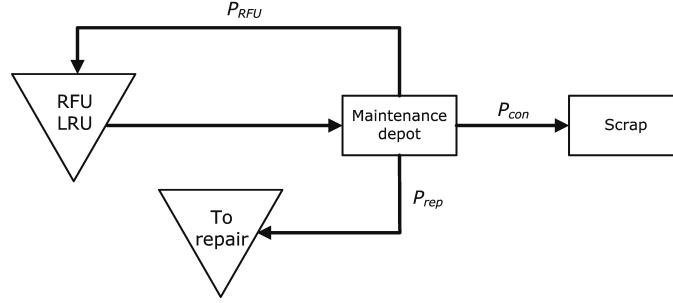
Figure 6: *Overview of different part return streams.*

requested. After it is found out which part caused the breakdown, requested parts that remain unused return ready-for-use to the original stocking point within an agreed *hand in time*. If the requested part was a repairable, a part is always returned that either (i) needs repair, (ii) is ready-for-use or (iii) is beyond repair and will be scrapped. The MLO needs to account for return rates and hand in times in their planning and control.

Consider the case of consumables. Here parts are either returned ready-for-use (with probability p_{RFU}) or not at all (with probability p_{con}), see also Figure 6. The question is now whether a part *request* should be considered a part *demand* where only the latter influences replenishment decisions. If a procurement order is placed and the part is handed in afterwards, the inventory levels grow unnecessarily. Therefore we propose to delay the registration of part demand until the hand in time has elapsed. If by that time the part has not been handed in, demand is registered and possible replenishment orders can be placed. For this system to be effective the hand in time should be small compared to the procurement lead time. This system is still convenient in case the part is cheap. Thus agreeing on effective hand in times with the MO is important.

The case of repairables is different as replenishment orders are not possible unless a failed part can be sent to a repair shop. Let p_{RFU} denote the probability that a returned part is ready-for-use, p_{rep} denote the probability that a returned part needs repair and p_{con} denote the probability that a returned part will be condemned (see Figure 6). These return fractions are used by inventory control as follows. Requests for parts can be considered as demand and with probability p_{RFU} the lead time is equal to the hand in time, with probability p_{rep} the lead time is the convolution of hand in time, return lead time and the repair lead time and with probability p_{con} the lead time is the convolution of the hand in time and the procurement lead time.

It will be evident from the above discussion that the different return rates (p_{RFU}, p_{rep} and p_{con}) can influence control in important ways. Thus the return rates need to be forecasted. To estimate return rates different techniques may be employed. The most straightforward technique is to use historic return rates, possibly corrected for special events such as unusual accidents. For most parts this technique is sufficiently accurate. For expensive parts with low demand rates, more sophisticated techniques are called for. For these parts different failure modes often correspond to different types of returns. Thus techniques from reliability engineering can be used to estimate these return rates. For a discussion of these techniques we refer to our earlier discussion in the
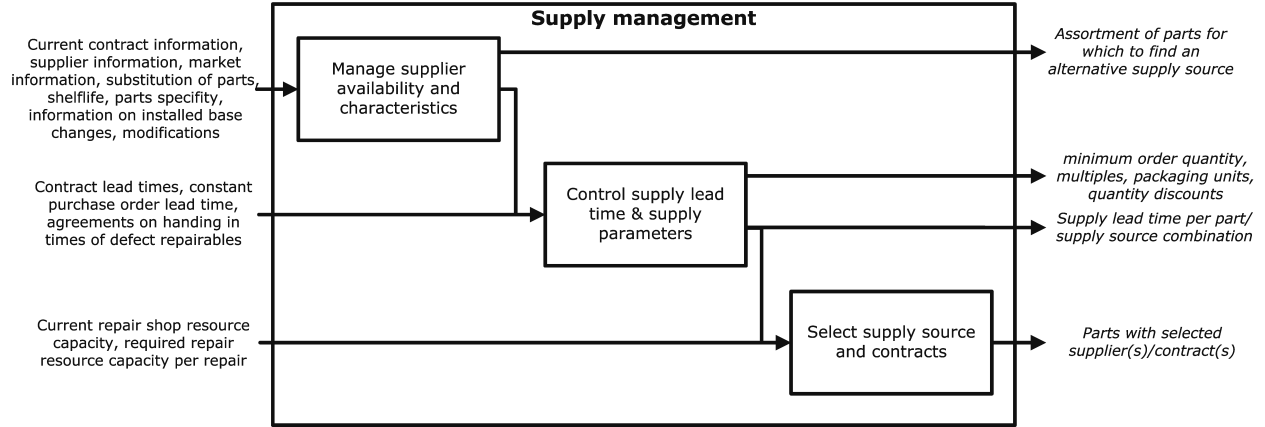
Figure 7: *Process of managing the supply structure.*

context of demand forecasting (Section 3.2.2). Note that the operational costs of using reliability based forecasting can be high and should only be used for expensive parts.

3.4 Supply management

Supply management concerns the process of ensuring that one or multiple supply sources are available to supply ready for use LRU's, as well as SRU's, at any given moment in time with predetermined supplier characteristics, such as lead time and underlying procurement contracts (price structure and order quantities). A process overview of supply management can be found in Figure 7.

3.4.1 Manage supplier availability and characteristics

The process of managing supplier availability and characteristics within MLO's is concerned with having one or more supply sources available for each spare part in the assortment, including supply characteristics. MLO's have several possible supply types: (i) internal repair shop, (ii) external repair shops, (iii) external suppliers and (iv) re-use of parts, i.e. parts that are known to become available in a short time period caused by phase out of end-of-life systems, possibly used by other companies. Moreover, within each supply type it is possible to have multiple supply sources (e.g. suppliers) as well.

Each part has either one or more supply sources, one supply source that is known to disappear within a certain time period or no available supply source at all. In the latter case, the MLO needs to find an alternative supply source for all parts that need future resupply. Alternative supply sources are e.g. a new supplier/repair shop, a substitute part or the part needs to become a repairable instead of a consumable, if technically possible.

When the only supply source of a part is known to disappear, the MLO needs to decide whether to search for an alternative supply source or to place a final order at the current supply source. The final order decision concerns the determination of a final order quantity that should cover

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demand during the time no supply source will be available. The supply availability for these parts is guaranteed through the available inventory.

Managing supply availability is also concerned with timely updating and maintaining current contracts with external suppliers. MLO's need to determine the trigger (i.e. the moment in time) when to update a contract. Updating contracts with external suppliers before expiring needs to be done some time in advance, at least the time needed to update the contract. External contracts have different reasons to expire: after a predetermined time period, after a predetermined quantity of procured/repaired parts is reached, or a combination of both.

MLO's also need to gather and maintain information on supply characteristics. Information concerning the following matters is needed to determine the supply lead time (distribution) and to select a (preferred) supply source and contract: (i) contractual or historical repair/new buy price(s) of the part, (ii) quantity discounts (iii) contractual lead and/or repair lead time, (iv) minimum order quantities and (v) multiples.

3.4.2   Control supply lead time and supply parameters

The supply lead time consists of: (i) repair or supplier lead time, (ii) procurement time, (iii) picking, transport and storage time of parts and, in case of repairables, (iv) hand in times of failed repairables. For all these components of the supply lead time, agreements are made on planned lead times.

Using planned lead times for internal repair is justified because: (i) MLO's make internal agreements with the internal repair shop on planned repair lead times and (ii) the repair shop capacity is dimensioned in such a way that internal due dates are met with high reliability. Using planned lead times for external supply is justified because MLO's agree on contractual lead times with their external suppliers. In principle, the MLO should not want their supplier to deliver the parts before (early invoicing of the parts) or after (chance of losing service level) the contractual lead time. In these cases, the MLO will consult with their suppliers in order to have the parts delivered exactly on time.

Supply by re-use of parts can be seen as a "random capacity constrained" supplier, with a contract that expires after a predetermined quantity of procured/repaired parts is reached. Thus specialized control is called for in this situation.

The supply lead time is determined for each part/supply source combination separately. We distinguish two types of supply lead times: (i) repair lead time and (ii) procurement lead time. The repair lead time can be determined by convoluting the part-times of picking, transport, storage, hand in times and repair time. The procurement lead time can be determined by convoluting the part-times of procurement, picking, storage and supplier lead time. For all parts that are known to be 'technically repairable', information that is gained from the assortment management process, the MLO needs to determine the procurement lead time, the external repair lead time and the internal repair lead time, in case internal repair is possible. For consumables only the procurement lead time needs to be determined.

3.4.3 Select supply source and contracts

The MLO needs to make sure that spare parts can be replenished at any given time. For this purpose, the MLO needs to set up contracts with one or multiple supply sources in a cost efficient way. The decision is based on the following costs incurred while selecting a supply source: (i) setup and variable costs of the repair shop capability and resources, (ii) setup costs of the contract, (iii) procurement or repair costs and (iv) inventory holding costs.

The MLO uses information on supply characteristics and supply lead times to select one or more supply sources out of all possible part/supply source combinations. Important in selecting a supply source is the decision whether to designate a spare part as repairable or consumable. Alfredsson (1997) states: "The task of determining whether an item should be treated as a discardable (consumable) or repairable item is called *level-of-repair-analysis* (LORA). If the item is to be treated as a repairable item, the objective is also to determine where it should be repaired". See also Basten et al. (2009) and MIL (1993) for analogous definitions of LORA.

The MLO's should conduct a LORA that covers characteristics such as: (i) unsuccessful repairs, (ii) no-fault-found, (iii) finite resource capacities, (iv) the possibility of having multiple failure modes in one type of component, (v) the option to outsource repairs, and (vi) the possibility of pooling parts sourcing in framework agreements.

The LORA is reconsidered each year or in case of substantial changes in the asset base. The outcome of the LORA is used to reconsider the internal repair shop resource capabilities. In many cases the LORA will reveal that it is beneficial to set up framework contracts for external procurement of parts, i.e. having economies of scope related to multiple parts. Note that MLO's need to set up a contract for repair as well as for new buy of repairables.

3.5 Repair shop control

The repair shop in the spare parts supply chain functions much like a production unit in a regular supply chain. At the interface with supply structure management, agreements are made on lead times for the repair of each LRU. Also agreements are made on the load imposed on the repair shop so that these lead-times can be realized. For example it is agreed to release no more than y parts for repair during any week.

To comply with these lead time agreements, decisions are made at a tactical and operational level. At the tactical level the capacity of the repair shop is determined and at the operational level, repair jobs are scheduled to meet their due dates. A schematic overview of repair shop control is given in Figure 8.

3.5.1 Determine repair shop resource capacities

When a repair job enters the repair shop, the sojourn time in the repair shop consists mostly of waiting time for resources such as specialists, tools and SRU's to become available. The amount of resources that are available in the repair shop determines the waiting times. For control reasons, these resource capacities need to be dimensioned in such a way that most repair jobs are completed
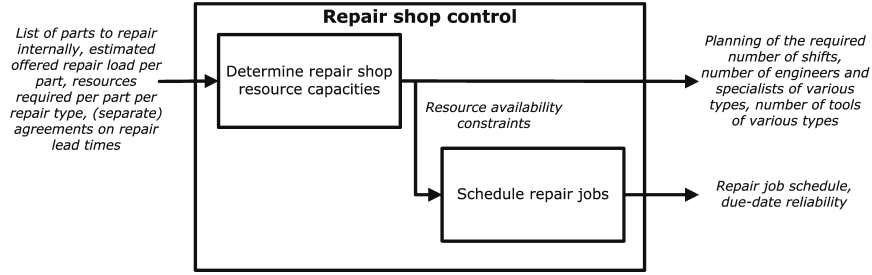
Figure 8: *Overview of repair shop control process.*

within agreed planned lead times. Within MLO's, internal repair lead time agreements are made (or targets are set) in consultation with the repair shop.

Decisions need to be taken on the amount of engineers and specialists to hire, the number of shifts, the number of SRU's to stock and the number of tools of various types to acquire. In some instances these tools are themselves major capital investments. The SRU stocking decision lies outside the responsibility of the repair shop and is part of the total inventory control decision, see also Section 3.6 for the reasoning behind this.

The resource capacity dimensioning decisions are based on the estimated repair workload, the repair workload variability (which follows from demand forecasting and parts returns forecasting) and the estimated repair time (and variability) required for an LRU when all resources are available. In making this decision, congestion effects need to be incorporated explicitly.

Since the costs of internal repair are mostly the result of the resources required for repair, the dimensioning decision together with the offered repair load can be combined to estimate the repair lead time and the cost of performing an internal repair. This information is used by supply structure management to periodically reconsider the buy/repair decision and, in case of repair, the decision where to repair the part.

3.5.2 Schedule repair jobs

During operations LRU's are released to the repair shop and need to be repaired within a the agreed planned lead time. This naturally leads to due-dates for repair jobs. The repair job scheduling function is to schedule the repair jobs subject to the resource constraints which are a consequence of the capacity dimensioning decision. Within these constraints, specific resources are assigned to specific repair jobs for specific periods in time so as to minimize the repair job tardiness. Additionally the repair shop may batch repair jobs to use resources more efficiently by reducing set-up time and costs associated with using certain resources.

3.6 Inventory control

The inventory control process is concerned with the decision which spare parts to stock, at which stocking location and in what quantities. The inventory control process is visualized in Figure 9.
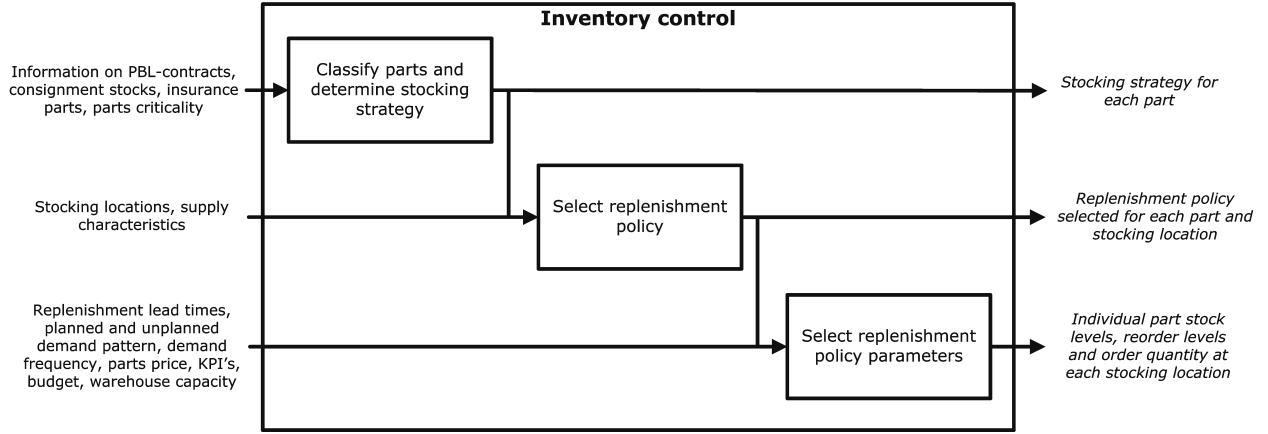
Figure 9: *Process overview of controlling inventories.*

A MLO stocks LRU's in order to meet certain service levels, agreed upon with the MO. Both the LRU and SRU inventories are centrally controlled by the MLO, that is, control of SRU and LRU inventories are integrated. In this way, the multi-indenture structure of spare parts can be used in inventory control.

The MLO should only stock parts to cover unplanned demand, or planned demand that is not known far enough ahead of time, i.e. in case the supply lead time exceeds the delivery time of the parts. Inventory control determines the desired stock levels based on the remaining demand uncertainty during the supply lead time. Planned demand that is known far enough ahead of time is delivered to order.

For control reasons, LRU's required for new projects and modifications are planned separately. We will not discuss the inventory control of these LRU's in detail here, as it is exactly known in advance which parts and quantities are needed and, without influencing system availability, modificative system maintenance work orders can be postponed until all resources (including spare parts) are available.

3.6.1 Classify parts and determine stocking strategy

The MLO has several strategies to stock spare parts and classifies the spare parts assortment into different subsets, such that each subset of spare parts has the same stocking strategy. We distinguish the following subsets of parts based on service level differentiation: (i) (partially) critical spare parts and (ii) non-critical spare parts. Both subsets are split up into two different subsets based on supply characteristics such as parts price. This classification is shown in Figure 10.

Availability of (partially) critical parts is needed to reduce system downtime. The stocking decision of (partially) critical spare parts depends on the contribution of a part to the overall service level of all (partially) critical parts. Insurance parts are a specific subset of critical parts.

The decision to stock insurance parts is not based on demand forecasts or on the contribution to a certain service level, but is based on other criteria such as supply availability, failure impact or initial versus future procurement price. The decision to stock insurance parts is typically made

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Figure 10: *Classification of parts with respect to inventory control.*

by the MO. Hence the stocking decision is not reconsidered by the MLO.

Availability of non-critical parts is needed for supporting an efficient flow of system maintenance, non-availability however does not cause immediate system downtime. Separate service level agreements are made for non-critical parts. Non-critical parts that have short lead times are not stocked but procured when needed, as they do not interrupt an efficient flow of system maintenance. Non-critical parts that are relatively expensive are not stocked either.

3.6.2   Select replenishment policy

A MLO is responsible for inventory replenishment of spare parts at all stocking points. For batching reasons the central warehouse replenishes the local stocking points only once during a fixed period (typically a couple of days or one week). This results in a (R, S)-policy for all parts at the local stocking locations. The length of the review period is set such that internal transport of parts is set up efficiently, i.e. regarding the transport load. In order to reduce system downtime costs, it may be beneficial to use emergency shipments from the central warehouse or lateral transshipments from other local stocking locations to deliver critical parts required at a local stocking point.

The MLO determines the timing and frequency of placing replenishment orders for the central stock based on supply characteristics. Spare parts for which framework contracts are set up are usually delivered only once during a fixed period. Hence the stock level needs to be reviewed only once during this period, which results in a (R, S)-policy for these parts. The stock level of other parts is reviewed daily, resulting in an (R, s, S) or (R, s, Q)-policy for these parts.

3.6.3   Determine replenishment policy parameters

The MLO uses different methods to determine replenishment policy parameters for non-critical parts and (partially) critical parts. For an overview of these methods we refer to Figure 10.

Non-critical parts that are relatively expensive have an order-up-to-level S equal to zero. For the other non-critical parts, the replenishment policy parameters are set such that a desired service level on item-level is achieved. Note that the size of the fixed order quantity is restricted by
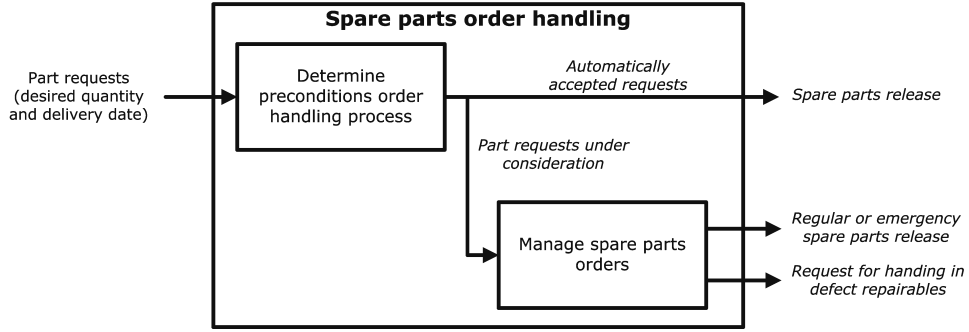
Figure 11: *Process of handling spare parts orders.*

supply source characteristics, such as minimum order quantities, multiples and quantity discounts, or technical information such as the shelf life of an item.

For (partially) critical parts one all encompassing model should be used to aim at a system (multi-item) service level. Optimizing policy parameters to satisfy a system service level is called the *system approach*. In maintenance logistics this is particularly useful, because MLO's are not interested in the service level of one part but in the multi-item service level instead. Note that if R is small compared to the lead-time, it is often appropriate to use models that assume continuous review.

The model should contain the following characteristics: (i) multiple-echelon, (ii) multiple-items, (iii) multi-indenture structure, (iv) emergency shipments from central depot, (v) lateral transshipments and (vi) multiple service level criteria. Input for this model is information on demand forecasting, supply structure management (supply lead times, parts prices), parts returns forecasting and information on the current inventory positions and replenishment policies of the spare parts. We note that some organizations also face budget constraints that need to be incorporated in the model as well.

3.7 Spare parts order handling

As discussed in section 2, system maintenance work order planning and release is done locally by the MO's. Each MO plans its work orders based on their available resource capacities. Resources that MO's share are spare parts, ordered at the MLO. Spare parts order handling is assigned centrally to the MLO and consists of the following steps: (i) accept, adjust or reject the order, (ii) release spare parts on the order and (iii) handle return order of failed repairable(s). For each of these steps, preconditions need to be defined as well as rules to manage these steps. A process overview of handling spare parts orders can be found in Figure 11.

3.7.1 Determine preconditions order handling process

The first decision in handling spare parts orders is to accept, adjust or reject the order. MLO's and MO's make agreements on realistic order quantities, order priority levels and order lead times. Advantage of checking spare parts orders is the fact that unrealistic or unusual orders can be

adjusted or, in case of incorrect orders, rejected. On the other hand, checking spare part orders is time consuming and increases the operational costs.

When checking spare part orders, the MLO obtains a trigger to contact the MO and adjust the order lead times and/or quantities. In this manner, MO's can reschedule certain tasks of their system maintenance work orders and adjust their spare parts orders based on the new system maintenance schedule. This might decrease system downtime (costs) caused by unavailability of spare parts.

A MLO needs to make a trade-off between the operational costs of checking spare parts orders and the costs of holding unnecessary inventory. Preconditions are set in such a way that the MLO obtains a trigger on spare parts orders that: (i) have unrealistic order quantities or lead times or (ii) cannot be met with the right quantity within the specified lead time even though the demand is realistic. Another condition to check spare parts orders is e.g. to check whether a part is requested for the first time. Demand forecasting information can be gained in consultation with the MO on the reason for requesting the part, e.g. it turns out to be a coincidence or it might give insight in the expected demand increase in the future.

Prioritization amongst spare parts orders while releasing spare parts is not easy in case the available stock is insufficient to meet all demand for that spare part. This is caused by the fact that the required spare parts are (i) part of a set of spare parts needed to start a maintenance task and (ii) are needed to start a different type of maintenance including different levels of criticality. Thus to fill orders spare parts order handling faces an allocation problem similar to that found in assemble-to-order systems. The optimal solution to this problem is not generally known.

Requested spare parts are released no earlier than the last transportation possibility to deliver the parts on or before the requested delivery date. Once spare parts are released on a work order, the return process for failed repairables starts. For this purpose, the MLO creates a return order to hand in the failed repairable by the MO within the agreed hand in time.

3.7.2 Manage spare parts orders

Incoming spare parts orders are either automatically accepted or not, based on the preconditions set in the previous section. There might be several good reasons for unusual or unrealistic orders, hence there are no standard rules for accepting, adjusting or rejecting spare parts orders. This task lies with the MLO, who needs to consult with the MO on this.

A spare parts order is closed when all part requests are fulfilled and all failed parts are handed in by the MO. MO's cancel spare parts orders by themselves as well. In these cases, the MLO needs to close the customer order, including the return order, and correct demand data if necessary.

3.8 Deployment

Deployment concerns the process of replenishing spare parts inventories. The deployment process consists of the following steps: (i) define preconditions order process and (ii) manage procurement and repair orders. A process overview of the deployment process can be found in Figure 12.
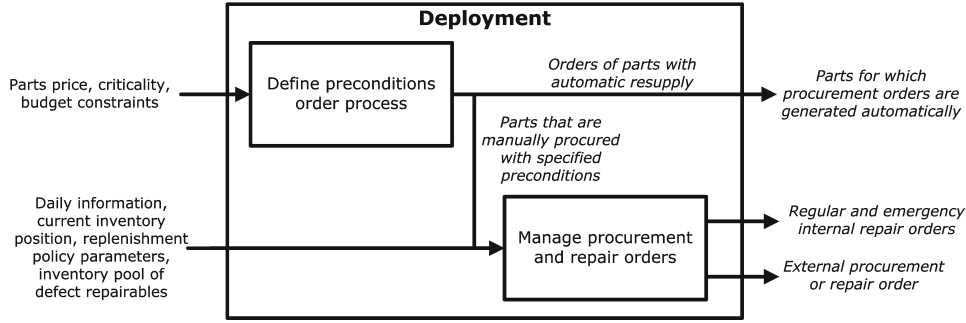
Figure 12: *Deployment process.*

3.8.1 Define preconditions order process

The replenishment policy parameters set by inventory control implicitly determine when to replenish spare parts inventories and what quantities to repair or procure. Deployment may deviate from this based on new (daily) information not known at the time the replenishment policy parameters were set, or when exceptional repair or procure orders arise from exceptional inventory levels. Deployment then starts a feedback loop to reconsider e.g. the demand forecast or supply lead times that lead to this exceptional inventory level. In this way deployment functions as an exception manager and setting rules for exception management is an important matter.

The MLO's should set a precondition on whether to replenish inventories with or without interference of deployment. Repair or procurement orders that are released without interference are not checked upon their necessity (regarding new information) and hence deployment might not order the right quantity. The MLO should automatically release orders for non-critical parts that are relatively cheap, that is, in case the decrease in operational costs (no deployment capacity needed) outweigh the obsolescence costs in case too much is ordered.

3.8.2 Manage procurement and repair orders

The process of managing procurement and repair orders consists of the following steps: (i) procure or repair parts with the right quantity and priority, (ii) check the quality of the received spare parts and (iii) monitor supply lead times. The MLO needs to determine which quantity of each part to order and with what priority, for parts for which the procurement or repair order is checked upon release. The quantity deployment actually orders may deviate from the order quantity set by inventory control, based on newly obtained information. When an order is received, the MLO needs to check the quality of the received parts, parts that do not meet the required quality standard on arrival cannot be used to meet customer demand for spare parts. When orders do not arrive within the agreed lead time, deployment takes necessary recourse actions.

4. Available literature and open research topics

In this section we provide available literature that provides support for making decisions in the framework. We do this per part in the framework and in the same order as in Section 3. When discussing the literature we also identify areas that require additional research. The intention is not to provide a comprehensive or exhaustive review of the literature. Though the references we provide are a good starting point to investigate specific areas of literature in more depth and find models to support decisions that need to be made.

4.1 Assortment management literature

The first decision in assortment management is whether or not to include a part in the assortment. Even when no inventory will be held for a part it may be beneficial to include it in the assortment so that technical information and supply contracts are taken care of in case of a failure. For this decision we have been unable to find any literature. We propose to use simple rules of thumb based on cost and failure rates.

Most of the information gathered on parts included in the assortment has a technical character. For example the criticality of a part can be determined through a *failure mode effect and criticality analysis* (Stamatis, 1995; Ebeling, 1997). We agree with Huiskonen (2001) that these type of analyses depend on technical and not logistical part behavior.

Parts technical information can be used to decrease stock levels or manage supply risks. We have been unable to find literature that supports the decision to gather parts technical information or not. We propose to use simple rules of thumb based on cost and failure rates.

Another decision that may occur in assortment management is the decision of whether or not to include parts that can be used to serve multiple asset types, but that may be more expensive than dedicated parts. Kranenburg and Van Houtum (2007) provide a model that can serve in making this decision. Note that in making this decision the quality of parts supplied by different suppliers (in terms of reliability) should also be accounted for. If this is an important issue the model of Öner et al. (2010) can be used.

4.2 Demand forecasting literature

To forecast demand for spare parts traditionally two families of techniques are used, namely (i) reliability based forecasting and (ii) time series based forecasting. We would like to add a third category which we shall label (iii) maintenance planning based forecasting.

Since demand for LRU's in many cases arises due to some kind of failure of equipment, forecasting demand is equivalent to forecasting failures. A recognition of this fact leads to reliability based forecasting. The techniques from reliability engineering can be used to deal with issues such as censoring and changing operating conditions. Furthermore the forecasts obtained are related to the installed base of equipment. Thus when the installed base changes the demand forecasts can easily be updated accordingly without the need for new data. Important references for these

techniques are Nelson (1982, 1990) and Ebeling (1997). More recently reliability literature has also addressed the real time forecasting of failures using some form of degradation data from sensors. We term this *prognostics* and refer the reader to Heng et al. (2009) for a recent survey.

Time series based forecasting is the traditional technique for demand forecasting in inventory control and also finds applicability in spare part inventory control. Its use is most suited when only historic demand data is available. Many common techniques such as exponential smoothing are part of standard textbook literature on inventory control (Silver et al., 1998; Hopp and Spearman, 2001). More sophisticated techniques such as autoregressive integrated moving averages (ARIMA) can be found in the seminal work of Box and Jenkins (1970). A somewhat separate stream of literature that is especially useful in forecasting demand for spare parts was started by Croston (1972). Croston observed that demand for certain items was intermittent and spare parts typically fall into this category. To increase forecast accuracy Croston proposes to forecast interarrival time and order quantities of demand separately. Based on this idea many contributions have been made. Teunter and Duncan (2009) benchmark many of these contributions and provide relevant references. Another technique in time series based forecasting is bootstrapping. Willemain et al. (2004) adapt this technique specifically to forecast spare part demand.

A third family of techniques that we advocate has received relatively little attention in the literature. This family of techniques bases the forecast of spare parts demand on maintenance planning information. In this manner some demand is known exactly ahead of time. Demand for other parts may occur as a result of planned inspections. When these inspections are part of the maintenance planning, they can be used to forecast demand more accurately. As Hua et al. (2007) put it: "demand of spare part at any time is a function of equipment maintenance operations and dependent on some explanatory variables". In particular maintenance planning can be used to accurately forecast demand for $x\%$-parts.

4.3   Parts returns forecasting literature

Parts return forecasting can be done using historic return rates. Here the methods from time series based forecasting as outlined in Section 4.2 can be used. The return rate of repairable parts that need to be scrapped can also be estimated using techniques from reliability engineering. Typically a part has several failure modes and a failure rate is associated with each failure mode. Some failure modes render the part no longer repairable while other types of failure can be repaired easily. Using models from reliability engineering (Nelson, 1982; Ebeling, 1997) these different failure rates can be estimated. From these estimates scrap rates can be determined as the fraction of non-repairable failure rates and total failure rate. In these techniques issues such as censoring and operating conditions can also be taken into account while this cannot be done by just using historic scrap rates.

4.4 Supply management literature

When a new capital good is taken into service, supply structure planning is primarily concerned with the question which parts to designate as repairables and when an item is designated as repairable whether or not we should outsource repair. These questions are answered by a level of repair analysis (Basten et al., 2009; Barros and Riley, 2001; Alfredsson, 1997; Basten et al., 2010).

An important part in supply structure planning is setting up and maintaining relations with outside suppliers and repair shops. These issues are addressed in purchasing literature, for example the book by Van Weele (2010) covers these topics.

Another important task concerns dealing with final orders when a supplier indicates that a part will become unavailable and a final order can be placed. In case the item under consideration is a repairable handled by our own repair shop Van Kooten and Tan (2009) provide a model for decision support. In case of consumables Teunter and Klein Haneveld (1998) and Teunter and Fortuin (1999) provide models for decision support.

4.5 Repair shop control literature

In our framework we decomposed inventory control from repair shop control. Consequently the only responsibility of the repair shop is to realize certain lead times, while inventory control is responsible to balance the workload offered to the repair shop. As such the repair shop functions much like a production unit in a conventional supply chain for which many models are available (Bertrand et al., 1990).

At the tactical level the capacity of the repair shop needs to be dimensioned. This is a machine repair problem from queueing theory (Iglehart, 1965). However it may be convenient to not directly consider the number of spare parts in the dimensioning decision in which case more general dimensioning methods may be used, e.g. from call center literature (Borst et al., 2004) or general manufacturing literature Hopp and Spearman (2001).

We note that making lead time and work load control agreements is not a simple matter. Repair capacity and inventory can both serve to buffer spare part demand variability. To find the most cost effective way to do this requires an integrated approach. To setup control and responsibilities in an organization integrating this control is not convenient. However results from models that integrate these decisions can be used to make judicious choices on lead-time agreements and workload control. An example is Adan et al. (2009) who show how static priorities can be used to reduce the lead times and required spare part investments for expensive parts. However much useful research on this interface can still be done.

For the daily scheduling of jobs many models are available (Pinedo, 2009). Also Caggiano et al. (2006) provide a model to allocate repair capacity in real time to different repair jobs based on current inventory levels. Priority schedules and use of flexible capacity in the form of overtime are discussed by Guide Jr et al. (2000) and Hausman and Scudder (1982).

4.6 Inventory control literature

For parts that are not critical, usually 'regular' inventory control models can be used as they are found in standard textbooks (Silver et al., 1998; Hopp and Spearman, 2001; Zipkin, 2000). Such models include classification of parts using ABC-analysis, lot-sizing using EOQ type models and statistical inventory control.

The unavailability of a critical part leads to system downtime. Control for these parts thus becomes a paramount task. The seminal contribution in (critical) spare parts inventory control is the Multi Echelon Technique for Recoverable Item Control (METRIC) model of Sherbrooke (1968). This model uses a multi-item approach and is valuable for controlling expensive critical parts that are replaced (mostly) correctively. The most noteworthy contributions since METRIC are the MOD-METRIC (Muckstadt, 1973) and VARI-METRIC (Sherbrooke, 1986) extensions, that find approximate means to relax the assumptions underlying the METRIC model. MOD-METRIC and VARI-METRIC have the attractive feature of including SRU's into the analysis. The most important models in spare parts inventory control have been consolidated in the books by Sherbrooke (2004) and Muckstadt (2005). Also Guide Jr. and Srivastava (1997) and Kennedy et al. (2002) provide a literature overview on spare part inventories and issues surrounding them such as emergency procedures (Alfredsson and Verrijdt, 1999; Song and Zipkin, 2009), lateral transshipments (Paterson et al., 2010), interaction with finite repair capacity (Sleptchenko et al., 2005), interaction with maintenance policies and obsolescence.

A new aspect in spare parts inventory control that literature has not yet addressed is advance demand information through prognostics, maintenance planning or a combination of these two. Most of the literature on spare parts inventory control assumes demand for parts arises from corrective maintenance, i.e. failures of parts. In the environment we consider most maintenance is performed either preventively or based on the condition of equipment. Thus advance demand information for parts is available in this context.

While advance demand information has been studied for regular supply chains, this knowledge is not immediately transferable to spare part supply chains. The main reason for this is that repairables have a closed loop supply chain such that the repair of a part cannot start before its replacement.

4.7 Spare parts order handling literature

When a spare part order has been accepted, i.e. the order is valid, the part may not be on stock locally. The priority that one may give to alternate sources such as other local stock-points or the central warehouse is an important issue. Current literature (Alfredsson and Verrijdt, 1999) usually assumes local transshipments are favored over emergency shipments from the central warehouse. In the present context this assumption is often violated, probably with good reason. Literature has yet to investigate this.

The second issue concerns allocation of spare parts to work orders. We already pointed out that this allocation problem is similar to the one found in *assemble-to-order* (ATO) systems. This

problem is known in general to be NP-hard (Akçay and Xu, 2004) even without the stochasticity involved in demand. Also in the present context the question of when, whether and how to hold back spare parts in order to fill complete work orders is still an open question for which only limited results are available (Lu et al., 2010). These limited results suggest that it can be beneficial to hold back inventory to fill complete work-orders. We note also that it has been pointed out that this allocation decision should be jointly optimized with the inventory control decision (Akçay and Xu, 2004).

4.8   Deployment literature

An important issue in deployment is the degree to which planners may deviate from replenishment order advices that follow from inventory policies. Empirical evidence from production scheduling suggest that planners disregard most such advices (Fransoo and Wiers, 2008). Thus aligning the autonomy of planners with the planning systems is an important issue that has been investigated in the production planning environment (Wiers, 2009). Empirically it has been observed that in more complex systems, planners tend to deploy more action variety (Fransoo and Wiers, 2006) and thus disregard planning advice more often. Whether or not this behavior is beneficial is still an open research question.

5.   Alternative design characteristics

The design of the presented framework has some characteristics that can be relaxed to accommodate closely related environments. First of all we characterize the supply process by using planned lead times. In some environments the stochasticity involved in external lead times is considerable. In these environments inventory control should account for the stochasticity in lead times. For example not all MLO's have enough buying power to set up lead time agreements with external suppliers. However for repairables repaired internally the lead time process is controlled within the framework through repair shop control. To the extent possible we advocate working with and carefully controlling planned lead times.

Furthermore we propose to integrate the inventory control of LRU's and SRU's, to exploit the the multi-indenture structure the assets and spare parts. A repair shop however is responsible for delivering within a planned lead time with high reliability. Thus the time a part spends in repair should exclude possible waiting time for SRU's since this waiting time is not in the scope of repair shop control. If the total time an item spends in repair is the responsibility of a repair shop, repair shop control should include SRU inventory control to align control with responsibilities.

6.   Concluding remarks and future research

In this paper we presented a framework for maintenance spare parts planning and control for organizations that use and maintain high-value capital assets. This framework can be used to

increase the efficiency, consistency and sustainability of decisions on how to plan and control a spare parts supply chain. We also provided literature to assist in decision making for different parts of the framework and identified open research topics. In future research case studies will be conducted to compare this framework to current processes and control functions at five different MLO's. We will investigate the importance of each decision on the performance of the MLO's and the human influence in making these decisions. These insights are starting point for formulating the best way to redesign maintenance logistics organizations.

Acknowledgements

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