Recoverable parts : stocking and repair : a literature analysis

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Recoverable Parts: Stocking and Repair
a literature analysis

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ABSTRACT

In order to do their work, service organizations need an inventory of spare parts. A subset of those parts is recoverable. Recoverable parts are waiting for repair, under repair, waiting for use or in use. In the older literature recoverable parts stocking is seen as an ordinary inventory control problem which can be solved with traditional inventory control systems. However, such control systems cannot tackle extreme uncertainty, which is an important feature of a repair environment. Subsequently, in later years recoverable parts stocking is seen not only as an *inventory control problem*, but as a *production control problem* as well. In this paper, literature on recoverable parts stocking is presented and analyzed. Relatively little attention has been directed to the following fields of interest: (i) decomposition of the control problem; (ii) short-term capacity planning; and (iii) integration of the maintenance policy. A comprehensive research of the subjects i and ii is proposed.

TUE/BDK/KBS/91-12, october 1991.

1. INTRODUCTION

This research proposal deals with production planning in workshops which encounter varying demand on short term. This planning situation usually can be seen in service organizations where repair shops perform maintenance of a turnaround of identical complex objects on a corrective and therefore an irregular basis. The objects to be maintained, so-called recoverable parts, change their states during the repair process, beginning in the failed and returning to the serviceable (or operational) state. The turnaround is a closed system which is characterized by the mix of objects in the failed and serviceable state. A turnaround planning model which accounts for short term demand variations has not been developed yet.

Before such a model can ever be developed, a good understanding of the service process itself is necessary. For this purpose, we present an example of a simple service process: the repair of a personal computer. PCs are modular in design and have a hierarchical but plain product structure. A PC is composed of a few subassemblies (e.g. printed circuit boards) which in turn are composed of several components (e.g. integrated circuits). This hierarchical product structure contains 3 levels; the PC, the subassemblies and the components. A PC failure is caused by one or more subassembly failures which are in turn caused by one or more component failures. When a failure occurs an engineer is sent to the customer with a kitstock of serviceable subassemblies. The engineer services the failed PC on the spot. After a concise diagnosis he or she replaces one or more failed subassemblies by their counterparts from the kitstock. If cost effective the failed subassemblies are sent on for repair in a workshop. There, after a brief diagnosis, failed components on a subassembly are exchanged by their serviceable counterparts from stock. Thus, the service process of a PC contains repair activities on 2 echelons; a repair activity (subassembly exchange activity) at the customer and a repair activity (component exchange activity) at the repair shop.

In some service industries, e.g. the aviation industry, the products have a more complex product structure and as a result the service process contains more intermediate repair echelons. Although they contain more intermediate repair echelons than simple service processes, complex processes essentially have the same service structure. The general structure of the service process is depicted in figure 1. Repair includes the activities disassembly, diagnosis, exchange and assembly. The parts that are needed for the assemble activity are obtained from the disassemble activity on the same repair echelon and the assemble activity on the next lower repair echelon.

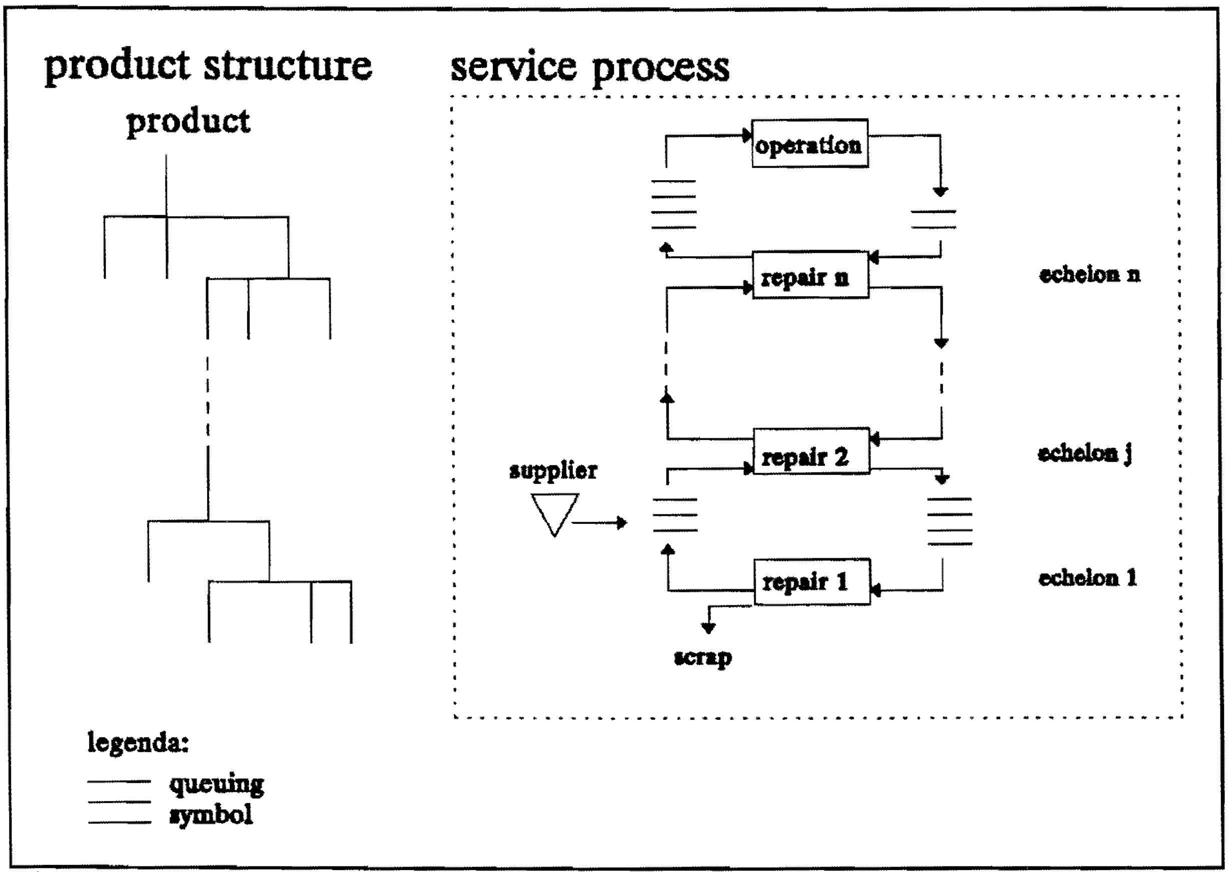

Figure 1: The general service structure.

To prevent confusion, we present definitions that are used throughout this paper and, sometimes, distinct from those used in other literature.

recoverable parts : failed or serviceable final and subassemblies which, as a rule, *cannot* be disposed of.

repairable parts : failed or serviceable parts which *can* be disposed of. Such subassemblies are to be encountered on the lowest level of repair.

multi-item : two or more part types on the same level of repair.

multi-echelon : a service structure with two or more hierarchical layers of repair. Each echelon represents one layer in the product structure. In some literature the hierarchical service structure is defined as multi-indenture.

Much literature on turnaround planning has been published. In the early literature the subject is treated as a pure *inventory control* problem, whereas the newer literature treats it as a combined *production and inventory* control problem. Section 2 provides an overview of the relevant literature. Section 3 gives a critical analysis of the same literature. Section 4 concludes with a brief discussion.

2. RELEVANT LITERATURE

The first inventory control analysis is based on a remarkable queuing theorem due to Palm (1938). Palm states that if demand (or breakdown) is Poisson distributed and repair capacity is infinite then regardless of the repair time distribution, the state probabilities depend only on the mean of the repair time. With the help of this theorem inventory control can be reduced to a simple cost analysis; holding costs vs. backorder costs. The resulting inventory control system is of the (S-1,S) type; when demand occurs an order is generated. In reality, some recoverable parts demand cannot be described as a Poisson process but as a compound Poisson process. Feeney et al. (1966) show that the theorem of Palm also can be applied to a compound Poisson process. They calculate the parameters for a (S-1,S) inventory control system under compound Poisson demand. Nowadays (S-1,S) systems are still in use for the control of recoverable parts.

The understanding gained on (S-1,S) inventory control systems resulted in the development of METRIC (Sherbrooke (1968)). METRIC is a multi-item multi-echelon inventory control system which was developed for the American Air Force. The model consists of a central warehouse (depot) and several parallel warehouses (bases). It minimizes total expected backorders (based on subassembly and component level) subject to a system investment constraint. METRIC is based on the following assumptions:

1. The demand process is described by a compound Poisson process.
2. Demand is stationary over the predicted period.
3. The decision on where repair is to be accomplished depends on the complexity of the repair only.
4. Lateral resupply between bases is ignored.
5. There are no condemnations.
6. The depot does not batch units for a recoverable item for repair.
7. Repair throughput times are independent.
8. Failures are statistically independent.
9. Items and warehouses may have different essentialities, but are considered equally essential.

Assumption 9 means that stockouts on each level in the product structure are equally important. Muckstadt (1973) poses that, in case of modular product design, only stockouts on subassembly level i.e. echelon n in figure 1 are important, because they directly prevent planes from flying. He develops his MOD-METRIC. MOD-METRIC only minimizes expected *subassembly* backorders subject to the same system investment constraint. Slay states that multi-echelon models like METRIC and MOD-METRIC underestimate the delay in repair time that has been caused by backorders on the next lower echelon (Slay

(1984)). To improve the accuracy of multi-echelon models, Slay develops his VARI-METRIC. Sherbrooke (1986) evaluates VARI-METRIC. He states that (i) VARI-METRIC is significantly better than METRIC, (ii) gives results which come close to simulation and (iii) is computationally only slightly more complicated than METRIC.

Simon develops a two-echelon inventory model (Simon (1969)). The model, called SIMON, obtains exact expressions for the stationary distributions of stock-on-hand and backorders at the various facilities. In comparison with METRIC, SIMON is more general because it permits condemnation (assumption 5), but less general because it assumes that all repair and transportation times are deterministic, and that demands are Poisson distributed.

Geraerds (1972) raises the possibility to reduce the varying character of aircraft breakdown by means of early preventive maintenance in order to save on turnaround. He develops a method to compare the actual arrival rate of airplanes to the average arrival rate. When the actual arrival rate is smaller than average, airplanes should be taken in earlier, in order to smooth the workload. It is interesting to investigate the possibilities of extending this method to lower echelons, thus to exchange airplane modules e.g. engines on a early preventive rather than corrective basis. Using this method, the METRIC assumptions 1 and 2 are challenged.

To reduce mathematical complexity METRIC supposes that the total number of servers (the repair capacity) is infinite and therefore repair throughput times are statistically independent, assumption 7. In reality, repair capacity is restricted and consequently workload will queue up in front of a repair capacity. As a result repair throughput times are correlated. Gross (1982) shows that the infinite capacity restriction is almost never true and that the error to be made can be quite large, especially when the amount of parallel servers (the repair capacity) is small.

Gross et al. (1983) develop a model that uses exponential repair times. They depict recoverable spares stocking as a steady state birth-death process with finite state space. The model is a single-item multi-echelon inventory and *production* control system. It is desired to find repair capacities and spare levels which together guarantee a specified system service level at minimum cost. In the same family of "Gross-models" we encounter a model of Ebeling (1991). His model too calculates repair capacities and spare levels subject to minimum cost and maximum availability constraints but addresses a *multi-item* multi-echelon situation. Balana et al. (1989) develop a model for a *transient* environment. They allow failure and repair rates to vary over time. Because of its complexity they describe a simple case with only one repair facility and one level of resupply. The model is solved using a randomization technique.

Hausman et al. (1982) describe a simulation model of a hypothetical repair shop with 3 echelons; (i) final assembly, (ii) sub-assembly and (iii) component repair. Like in METRIC, the model minimizes the stockout risk subject to a total budget constraint. As the spares budget decreases, the authors show that it is economical to remove the most expensive spares first. In other words, expensive spares are most likely to be in short supply and therefore should be scheduled into repair first. The authors describe a sequencing priority rule which schedules jobs in sequence of shortest runout times. With the help of the simulation model it is proved that the priority rule performs better than plain MOD-METRIC on all echelons. However, the authors advice to restrict the use of the sequencing rule to the lowest echelon alone.

Scudder (1984) extends the mentioned simulation model to a multiple failure case where more than one unit has failed in each item to be repaired. This is an improvement to METRIC's 8th assumption which implies that per final assembly only one sub-assembly is failed and per sub-assembly only one component is failed. The results show that procedures which perform well when only a single unit fails, also perform well when multiple failures occur. Finally, the simulation model is used for measuring the effect of overtime policies on all repair echelons (Scudder (1985)). The results indicate that overtime is most effective when *reactive* final assembly overtime is paired with *proactive* component overtime.

Graves (1985) provides an approximation model, similar to VARI-METRIC, for determining initial spares levels of recoverable items in a multi-echelon system. He compares the approximation model to METRIC. Graves shows that, assuming infinite capacity, the model is more accurate than METRIC in setting initial spares levels. Computationally, METRIC and the approximation model are equally complex. Graves assumes a lot-for-lot ordering policy. Lee at al. (1987^a) state that a batch ordering policy is more appropriate when setup costs, shipment costs or demand rates are relatively high. They relax Graves's assumption and fit his approximation model for a (S,Q) inventory control policy with batch size Q. The model performs well if capacity is assumed infinite, but poor if capacity is assumed finite. In the same article the authors introduce an approximation model which performs well in both cases. In another article, Lee et al. (1987^b) describe an approximation model where condemnation, METRIC's 5th assumption, is permitted. The model suggests an (S-Q,S) inventory control policy. The model performs well if infinite capacity is assumed.

Erkip et al. (1990) describe a multi-echelon inventory model with one supplier, one depot and several warehouses. In their model they allow parts demand to be (auto-) correlated both across warehouses and also in time. To overcome demand correlations, the authors state that the standard deviation must be increased with a significant multiplier in order to set optimal safety stocks. In their article, the authors derive such a multiplier. Although the article has not been written for a service environment, demand correlations most likely occur in some service environments, e.g. business electronics, as well. For instance computers tend to fail more often in hot summers. In that case, demand cannot be regarded as stationary, METRIC's 2^{th} assumption.

Panisset (1988) suggests to introduce MRP 2 in a repair environment. He encounters some characteristics which are typical for a repair environment but are not supported in MRP logic:

- A recoverable part should be repaired rather than purchased. This decision is not supported in MRP logic.
- Repair work implies disassembly: An activity which is not supported in MRP logic.
- Routings are known only after executing the disassemble activity. This makes it difficult to plan ahead.
- Repair routings embrace both the network (assembly) and the production (repair) type. Shopfloor control must be adjusted in order to handle both types at the same time.

Panisset succeeds in overcoming the problems mentioned above. In his article Panisset shows that MRP 2 performs slightly better than no planning at all.

The admission that the spare parts stocking problem is not so much an inventory control problem but rather a production control problem has directed attention to hierarchical planning models (Bertrand et al. (1985)). Hierarchical planning models, which have been developed lately for a production environment, decompose the planning problem in a goodsflow (GF) control problem and a production unit (PU) control problem. Whereas PU-control is responsible for the internal goodsflow in the PU, GF-control coordinates the goodsflow between PUs.

Schneeweiß (1991) describes a multi-item single-echelon production and inventory control problem which is encountered in the German aviation industry. The author not only deals with the mathematical, but also the organisational aspects of recoverable parts stocking. According to Schneeweiß, there is a major difference between recoverable parts stocking and ordinary production and inventory control problems. Whereas in ordinary production and inventory control problems the work in process and in stock can be adjusted by influencing the incoming raw materials; in recoverable parts stocking problems the spares levels must be determined well in advance. This time restriction allows the problem to be separated into a medium-term (planning) problem and a short-term (shopfloor) decision problem. On the medium-term planning-level the most economical initial spares vector is determined in two steps: (1) A spares vector is determined subject to an overall service level constraint, (2) The vector is adjusted using a marginal analysis on costs. Like in METRIC the result of the marginal analysis will be an expected shortage of high cost items. Therefore, on a short-term shopfloor-level individual service levels must be balanced, taking into account the actual state of the repair process. Items are scheduled in sequence of runout risk.

Bertrand et al. (1990) deal with the work-in-process and capacity aspect in a repair environment, both on a medium and short term. They describe a case in the repair shop of a Dutch steel manufacturing company. In the repair shop orders arrive irregularly and with a unknown work-content. As a result of various factors, actual progress on the shopfloor deviates from the planned progress. In order to agree upon throughput times the authors propose a buffer of repair orders. At a buffer overload, repair orders are subcontracted. The orders set apart for the repair shop are divided in suborders; one suborder for the disassembly work centre, several suborders for the repair work centre and one suborder for the assembly work centre. When disassembly is executed, the set of repair suborders, their routings and their work-contents become known. Throughput times of suborders are controlled with a technique called "workload control" (Plossl et al. (1979); Bertrand et al. (1981)). De Haas (1990) describes a similar case for a business electronics environment. In his case only few repair orders can be subcontracted. Therefore, at a buffer overload the possibility of temporarily expanding the workshop repair capacity is investigated.

Like Schneeweiß, Bertrand et al. (1991) acknowledge that in many practical situations it is desirable to give orders different flow rates. For example in a situation with 2 ordertypes; production vs. repair, where repair orders have priority. But a distinction in flow rates should not be allowed to cause a decline in overall performance. Therefore the average flow rates need to be controlled. This is done using workload control which set waiting time norms for every workcentre. Within the framework of workload control, flow rates are allowed to vary but only if for each workcentre the mix of waiting times is equal to the norm. This is achieved by the use of a due date sequencing rule with due dates which obey the waiting time norms. In their article the authors describe a simulation model for a pure job shop. In the model only 2 product categories are distinguished; products with a high flow rate and products with a low flow rate. The model is tested with different capacity utilization rates and product mixes. It turns out that waiting time reductions for the high flow rate product category can be obtained without affecting the overall performance.

3. LITERATURE ANALYSIS

In an excellent article Hausman et al. (1982) state that overall performance in a service environment is measured by how long it takes to replace a failed final assembly in the field. The authors regard performance as a function of 3 factors:

i. The initial spares inventory levels for final assemblies, subassemblies and components.
ii. The capacity to repair parts and to perform inspection, assembly, and testing of subassemblies and final assemblies.
iii. The priority scheduling system used in the repair shop.

A good understanding of all factors that can be influenced is important. The factors mentioned, can be influenced on different terms: factor i on a medium-term, factor ii both on a medium- and short-term and finally, factor iii on a short-term only. So, to support a control system, it is better to separate factor ii into "medium-term capacity" and "short-term capacity". Remarkably, the authors neglect the maintenance policy, e.g. preventive maintenance, which is also an important factor in adjusting the performance. Their model can be extended to a model with 5 factors:

1. The maintenance policy,
2. The initial spares vector,
3. The medium-term capacity,
4. The short-term capacity,
5. The priority scheduling system.

In this section these 5 factor are used to analyze the literature of the preceding section. Some articles are clustered and named after one of the authors. Other articles are clustered and named after the computer model they represent. The literature of section 2 is clustered as follows:

METRIC	Sherbrooke (1968, 1986); Muckstadt (1973); Slay (1984).
SIMON	Simon (1969).
Lee	Graves (1985); Lee et al. (1987^a, 1987^b).
Geraerds	Geraerds (1972).
Gross	Gross (1982); Gross et al. (1983); Balana et al. (1989); Ebeling (1991).
Hausman	Hausman et al. (1982).
Scudder	Scudder (1984, 1985).
Bertrand	Bertrand et al. (1981, 1985, 1990, 1991); De Haas (1990).
Schneeweiß	Schneeweiß (1991).

MRP 2 (Panisset 1988) is not included in the clustering. It is a control tool which is developed for stable assembly environments. A service environment is characterized by its uncertainty. Furthermore, some features which are characteristic for a service environment are not supported in standard MRP logic. After adjusting the MRP algorithm, it will be able to schedule unknown jobs with unknown routings in the

future. Because of its incapacity to deal with uncertainty, MRP 2 will not be taken into further considerations.

The models analyzed in this paragraph are all of an analytical nature. SIMON and the METRIC oriented models are directed to factor 2 "the initial spares vector" alone. The models implicitly state that, when the initial spares vector is set in a correct manner, the service process can be executed without any further control. However restrictive, these models are already very complex because they reflect a multi-item multi-echelon service process. The models of Lee account for factor 2 (in their first model) and the factors 2 and 3 (in their second model). The models are less restrictive than METRIC because they permit batching (and condemnation in the first model). The Gross queuing models account for the factors 2 and 3. These models too implicitly state that when the initial spares vector and the capacity levels are set no further control is necessary.

The model analyzed in this paragraph is a simulation model. Hausman takes into account the factors 2, 3 and 5; Scudder the factors 2, 3, 4 and 5. Short-term capacity adjustment is tested as a means to reduce the stockout risk. The effect of short-term capacity adjustment on the initial spares vector is recognized but has not been measured. The simulation model is very complete and can be a useful aid in developing a control system for a corrective maintenance environment.

The models analyzed in this paragraph are production control models. Geraerds recognizes the importance of factor 1 "the maintenance policy". The author mentions that other factors are important too. However, he does not elaborate on them. Bertrand's model account for the factors 3 and 4. The model is complete in not only showing which capacity to adjust but also when to adjust capacity. The model is restrictive in only considering subcontracting as a means to short-term capacity adjustment. The model of Schneeweiß considers the factors 2, 3 and 5. The model leaves opportunities for integrating the other factors but the author does not elaborate on them. The model is restrictive in considering only a single echelon.

The results are summarized in table 1.

Table I: Literature analysis.

ARTICLES	*FACTORS*				
	1	*2*	*3*	*4*	*5*
METRIC		X			
SIMON		X			
Lee		X	X		
Geraerds	X				
Gross		X	X		
Hausman		X	X		X
Scudder		X	X	X	X
Bertrand			X	X	
Schneeweiß		X	X		X

Table 1 shows that most literature has been directed to factor 2 "the setting of the initial spares vector". Even without considering the other factors the setting of the initial spares factor already appears to be rather complex. This is due to the interrelations which exist between different echelons. Furthermore, table 1 shows that little literature has been directed to the factors 1 "the maintenance policy" and 4 "short-term capacity adjustment".

4. DISCUSSION

At the Eindhoven University of Technology, a research project has been defined with the title: 'Production planning in situations with varying demand on short term'. Those unstable production situations are encountered in service environments where repair on recoverable parts is performed. The repair process of recoverable parts has an echelonized structure. Repair activities on different echelons are usually executed on different locations.

In this working paper we present an overview of the literature on recoverable parts. In the early literature, recoverable parts stocking is seen as a traditional inventory control problem. Methods are developed for the calculation of the initial spares vector. It is assumed that when the initial spares vector is calculated in a correct manner no further control is necessary. Although limited, the early literature is already very complex. In recent literature, recoverable parts stocking is seen as a combined production and inventory control problem. An increasing number of authors is directing attention to the production side of the control problem. Different aspects like: maintenance, capacity adjustment and priority scheduling rules are being investigated. However, a control system for a multi-echelonized service structure has not been developed yet. The research project aims to be a contribution to such a control system.

As we mentioned already, the early literature is rather complex. Complexity is caused by the interactions which exist between different echelons. However, from an organisational point of view, it is not advisable to treat the echelonized structure strictly as an integral system. Generally, echelons are situated at different locations; each echelon manager is responsible for the performance of a single echelon. This division of tasks results in an accessible service process on all echelons and therefore should not be changed. A control system should support this division of tasks and allow echelons to function fairly independently. Considering this organisational aspect and the five factors mentioned in table 1, in depth research is necessary on the following subjects.

1. Decomposition of a multi-echelon structure into multiple single-echelon structures,
2. Short-term capacity adjustment,
3. Integration of the maintenance policy.

Subject 1

Research must be engaged in finding conditions which must be satisfied before decomposition of a multi-echelon service structure is permitted. Among others, the following conditions must be investigated.

a. The interaction of different echelons. Only the failed subassemblies are shipped to lower echelons; Maintenance on serviceable subassemblies is executed on the same echelon. What implication has this interaction on the buffer of each echelon.

b. The stockout possibility on the lower echelons, what delay does a stockout on a low echelon cause for higher echelons;

c. The priority scheduling on lower echelons, priority scheduling rules on lower echelons must support the assemble activities on higher echelons

d. The implications of actions on a high echelon for lower echelons. For instance, what are the implications of overtime at an echelon for the next lower echelon.

When all conditions are investigated and satisfied, the following question needs to be answered: 'Is the solution of the decomposed control problem still close to optimal ?'

Subject 2

Consider a single repair echelon, e.g. an engine repair shop for aircraft industry. The repair shop recovers different engine types. Failed engines queue up in front of the repair capacity: Recovered engines queue up in front of the operation unit and wait for exchange in a similar airplane type. An arrival is initiated upon an engine failure and, in general, considered to be (compound) Poisson distributed in most literature. Repair times can have any distribution, but in the literature are usually assumed to be exponential. If demand occurs for an engine of an empty queue, a stockout is created and an airplane is grounded. It will be clear that a stockout is very expensive: The stockout risk must be restricted to a minimum. Most literature is directed to minimization of stock costs and the stockout risk. Using a marginal analysis, the result of an additional engine on the spares budget and the stockout risk is calculated. In case of a high capacity utilization, the stockout probability is likely to be described by a long tailed distribution. Due to the behaviour of such a distribution, a slight decrease in stockout risk can only be obtained at very high cost.

In reality, we see that the number of airplanes in operation is fixed. Somehow the repair shop is able to react on a temporary high input and to increase, temporarily, its throughput. So, in case of a temporary high input, queuing models do not reflect the 'real world' situation and are overly restrictive. In this particular situation, Repair time adjustment must be introduced as a parameter in the model as well. In the literature (Scudder (1985)) it is shown, that for high repair echelons, a temporary increase of the repair rate, by means of reactive overtime, is effective in reducing the stockout risk. Even so, *proactive* measures are more suitable as a control tool, but have not yet been shown to be effective. Within the scope of the research project, it is proposed to derive suitable means for proactive repair time adjustment as a control tool. The implications of proactive repair time adjustment must be measured not only on the stockout risk but also on the initial spares vector. Furthermore, implications for lower repair echelons must be determined.

Subject 3

Consider the same aircraft industry. Between two flights engines are checked against several norms. If the actual state of the engine has dropped below one of the norms, the engine is exchanged. However, higher warning norms can be set and an engine can already be exchanged when its actual state has dropped below such a warning norm. This maintenance policy can serve as a means to smooth the workload.

The research project has the aim to develop, incrementally, a control system for the service industry. The maintenance policy, however important, does not fit into such an incremental approach and therefore will not be taken into account within the scope of the research project.

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