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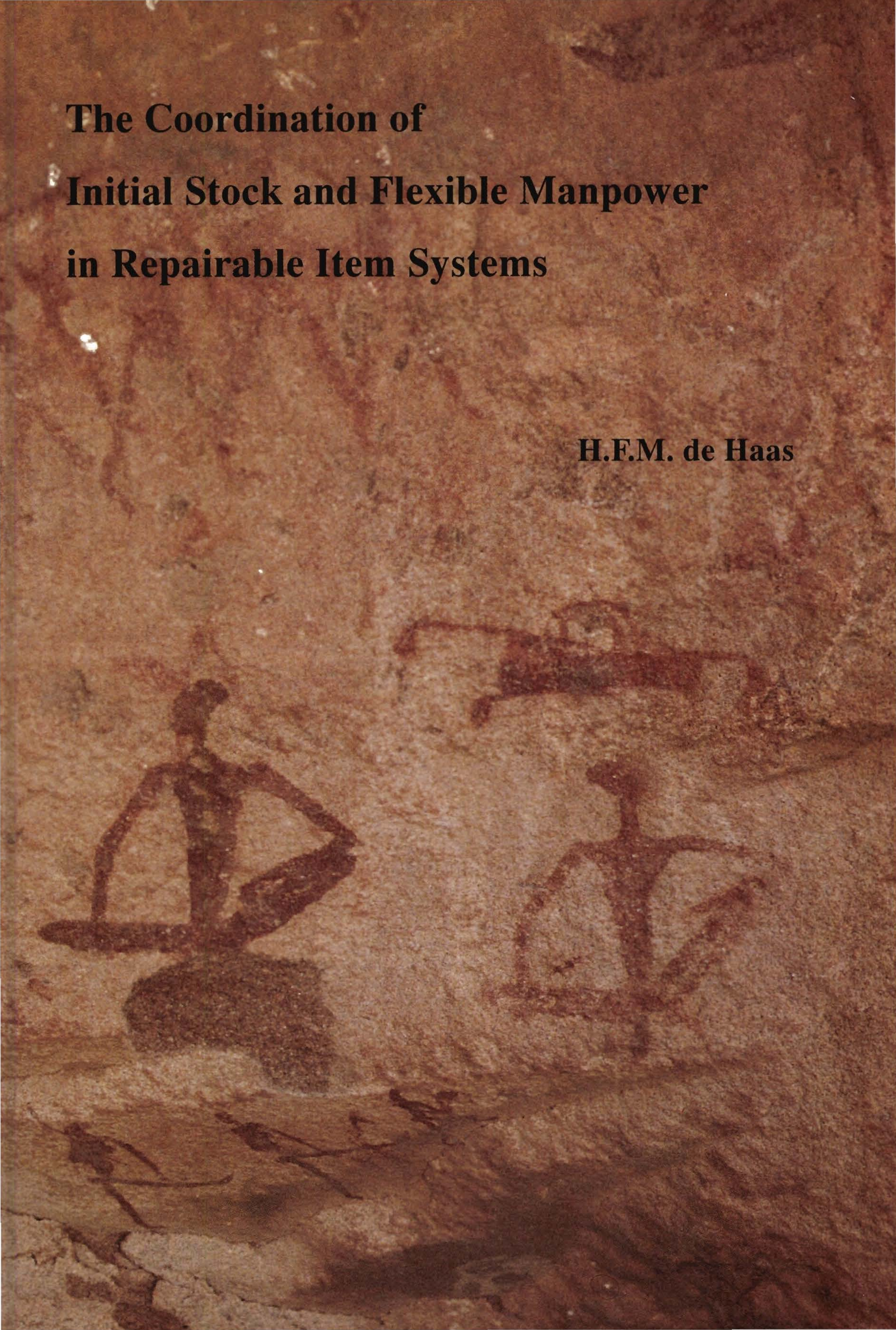
H.F.M. de Haas



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PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof.dr. J.H. van Lint, voor een commissie aangewezen door het College van Dekanen in het openbaar te verdedigen op woensdag 4 oktober 1995 om 16.00 uur

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Preface

I dedicate this dissertation to the memory of Hans Geurts who initiated this research project and persuaded me to undertake the research. It is with deep respect I remember his efforts to maintain control over the project, despite his fatal disease. Warmly I remind his everlasting sense of humour which he used as a powerful tool to make his point. He is sadly missed. For all of his support, when Hans died, and his contribution to the research I would like to express my gratitude to Bo Gits. Bo proved to be a critical but valuable discussion partner. These discussions have made an improvement to the quality and the content of this dissertation.

I acknowledge Will Bertrand and Tony Christer, the supervisors of this project, for their valuable input in the project. I especially appreciate the freedom that Will offers to Ph.D. students for developing their own ideas, even when this process may take quite some time. Tony, though he joined in fairly late, became heavily involved. His help also improved the english language in this dissertation a great deal. I thank Peter Sander and Frank van der Duyn Schouten, who completed the committee, for their valuable comments. Not being a mathematician I appreciate the help that I received in the formulation of the mathematical models. For this I acknowledge especially Ivo Adan and Jos verrijdt. Koos Huibers I acknowledge for the development of the simulation program used in this study.

In my research I worked together with the management of KLM's repair facility for the overhaul of jet-engines, CF6. I like to thank KLM for their interest in my research. On a part time basis I worked together with consultancy firm Rijnconsult. Together we developed a trade-off model to support management in the control of field service organizations. As a result of this cooperation I gained better understanding in the practical aspects of management problems. I thank Rijnconsult, and especially Maarten Swinkels, for the pleasant cooperation, the valuable working experience and, not unimportantly, the delicious meals.

Paul Stoop, my roommate, became a true friend. I admire him for his patience with unwilling personal computers. This quality helped me to turn my ideas into a nice document. Our departure from the Eindhoven University of Technology wil result in a dramatic drop in the sales for apple pastry. I thank family, friends and acquaintances for there continuous support. Finally I call the attention to my girlfriend Barbara. She is the living proof that the investment in my education in Mannheim was well spent.

Eindhoven, June 1995
Harrie de Haas

Table of Contents

1. Introduction

1.1. Preliminary Considerations

In the beginning of this century, organizations gave relatively little attention to the wishes of the customer with respect to the products they manufactured and sold. Products were manufactured in a small variety in large quantities on production equipment which by today's standards was uncomplicated. The organization of the production process had a functional orientation, the different process steps were decoupled by means of buffers. Products had long life cycles and were delivered to customers from stock.

Since those days the market is becoming more dynamic and demanding. Organizations must compete for the favours of the customer. To win the customer over, the organizations are producing and selling their products in more varieties, with short life cycles, at moderate prices and with a high quality. For many products, delivery from stock of a vast product variety is not economical anymore since it results in unacceptable stock costs. The broad variety as well the short product life cycles require advanced production equipment and techniques. In this changing environment a revolution from "production to stock" to "production on order" has taken place and the competitive measures of short and reliable leadtimes are becoming important. The organization of the production process has changed to a product oriented one with the process steps tightly coupled. The products may be manufactured in small batches, according to the principles of "just in time production". In this case the interruption of a process step can immediately result in a late delivery to the customer. In such an environment a sudden stoppage of the production process due to failing production equipment will be costly and the need for prevention of a sudden standstill of production is apparent.

An approach to deal with a sudden stoppage is avoidance (Geurts [1991]). Avoidance means either "elimination" or "making unplanned stoppage planned". Elimination, to some extent, is accomplished by means of modification. Making stoppage planned is more and more accomplished with the help of condition based maintenance concepts (Gits [1984]). Such concepts prescribe that inspection is carried out in planned time intervals. The necessary maintenance activities are generally only known after inspection and therefore they cannot always be executed in the planned time intervals.

Next to a reduction in the number of unplanned production standstills it is also important to minimize their duration. As a result of this we are noticing in some industries a development towards a component replacement strategy. This strategy requires a modular structure of the production equipment. During maintenance of the production equipment, the failed components are replaced by identical but serviceable components from stock. A failed component is either disposed off or repaired. In the latter case we term it a *repairable item*. The repairable items often represent a fair share of the investment in spare components. Studies of Sherbrooke [1968] and Geraerds [1991] show that they account for more than 50%, by value, of the total investment for spare components.

A repairable item that has failed is sent off for repair in a specialized repair facility. The capacity of such a repair facility is limited, which means that at certain points in time the demand for repair capacity can exceed the available repair capacity, causing the failed items to queue. Repair capacity consists of tools, machines and repair men. The repair capacity provided by repair men we term "manpower". Commonly the manpower is the most costly form of capacity and, therefore, the most limited. After repair the item is stocked to support future replacements. The system of limited capacity and stocks, through which there is a flow of repairable items, we term a *Repairable Item System (RIS)*. Typically, the flow of repairable items through a RIS has a circular character. Failures and repairs take turns, but the repairable item itself remains in the system. The number of items is, more or less, constant and purchased ahead. This constant number of repairable items we term the "initial stock". The management of a RIS can basically invest in manpower and in initial stock to meet the demand for repairable items. Clearly, the probability that demand can be filled immediately increases with the investment in initial stock and manpower. This probability we term the "fill probability". Both, decisions regarding the investment in initial stock and manpower should be coordinated, in order to obtain a required fill probability at minimum costs.

Due to tightening customer requirements, demand is becoming increasingly irregular. Repair men are confronted with rapid variations in the number of failed components. In reaction to these variations it would be convenient if the management of a RIS would have the means to vary the manpower level in time. The manpower variations that can be employed in reaction to the variations in the number of failed components we term the "manpower flexibility". Manpower flexibility, to some extent, can be imposed by the management of the RIS, for instance by actively adjusting the working day lengths of the repair men. In that case we talk of *Flexible Manpower Planning (FMP)*. The repair men become a flexible manpower. Due to loosening restrictions by both governments and unions the use of FMP has become a popular political issue in Europe. When the use of FMP is effective, it should be controlled together with the initial stock and the manpower.

The considerations regarding initial stock manpower and FMP should be part of a broader framework for the *Control of RISs*. It appears that, from a production and operations management point of view, the use of FMP in RISs and the framework for the control of RISs are little studied sofar. In this dissertation we address these topics.

1.2. Definitions

The most important terms in this study, printed in italics in the former section, are not included in the authorative dictionaries of the American Production and Inventory Control Association (APICS, Wallace [1984]) or the listing of the European Logistics Association (ELA [1991]). Definitions of closely related terms - such as service part instead of repairable item - are not a satisfactory expression of our requirements. We therefore introduce deviant terms and define them ourselves.

Repairable Item

A repairable item is:

> *"a subassembly, technically and economically repairable, that can fulfil its function in all production equipment of a specific kind."*

Examples of repairable items are widely available in practice i.e. power supplies, pumps, mounted printed circuit boards, weapon systems, jet engines, et cetera. From the examples it is clear that there are considerable differences in both the size and the complexity of a repairable item, e.g. compare a mounted printed circuit board to a jet engine. A jet engine corresponds with a major investment and for economical reasons it is considered important that not only the aircraft, but also the jet engine is restored as quickly as possible. Similar to the restoration of the aircraft, also the jet engine is restored by means of component replacement. Such a component, e.g. a turbine, again can be a repairable item. A repairable item containing other repairable items is termed a *multi-indenture repairable-item*. It is termed a *single-indenture repairable-item* otherwise (Muckstad [1973]).

Repairable Item System (RIS)

RISs have been studied under a variety of names. We mention "Technique for Recoverable Item Control" (Sherbrooke [1968]), "Reparable Item Inventory System" (Nahmias [1981]) and "Repairable Inventory System" (Hausman and Scudder [1982]). The aspect of "inventory (initial stock)" is emphasized in all these. We like to stress that next to the initial stock many other aspects of a RIS can be the subject of study. Therefore we introduce the more general term *Repairable Item System (RIS)* and define it as:

> *"A collection of one or more repair levels and one or more stock phases - each repair level with one or more repair departments with limited manpower, and each stock phase with one or more stock locations - through which there is a flow of a, more or less, constant number of repairable items, all in order to support one or more sets of identical machines".*

An example of a (complex) RIS, facilitating a set of machines, is depicted in Figure 1.1. The key words in the above definition are further explained.

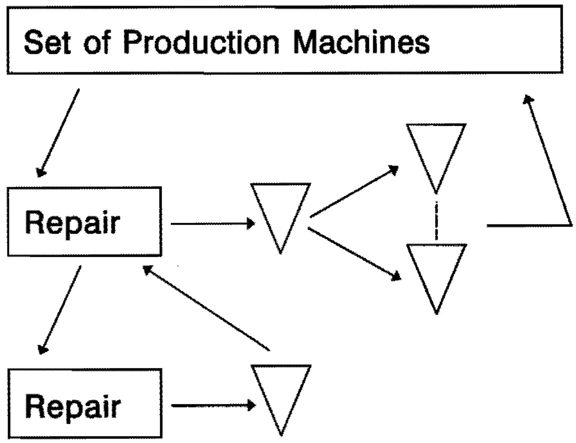

Figure 1.1: Repairable Item System

Set of Production Machines:
Each repairable item should facilitate a number of machines of the same kind. Such a group of identical machines we term a set. A set can be, for instance, a number of copiers or a number of aircraft. The set(s) of machines are supported by the RIS. They do not form part of the RIS.

Repair Levels and Departments:
After inspection of a multi-indenture repairable-item, the failed repairable parts are released from the item and sent off to a hierarchically lower repair facility for repair. Such repair facility we term a "lower repair level". The corresponding RIS we term a "RIS with multiple repair levels". A RIS for the repair of a single-indenture repairable-item is a "RIS with a single repair level". A repair level consists of one or more organizational units, each unit containing tools, machines and repair men. One such unit is responsible for the repair of one or more repairable items. We term such a unit a "repair department".

Limited Manpower:
The capacity of a RIS depends on the availability of tools, machines and repair men. All factors can be limited, that is the demand temporarily exceeds the availability. In our study we restrict ourselves to the RISs where the capacity of the repair men is the factor which is most limited. Such RIS we term a "RIS with limited manpower". We remark that all RISs, observed by us in practice, have limited manpower.

Stock Locations:
In order to accomplish a quick replacement of failed items, their serviceable counterparts are often stocked nearby the set(s) of production machines. If these sets are scattered, e.g. copiers, the stocks with serviceable items are also likely scattered. Such RIS we term a "RIS with multiple stock locations". If these stock locations are supplied by a common stock location we term it a "RIS with multiple stock phases and multiple stock locations". A RIS with a single stock location for the repairable items, for instance a RIS facilitating a blast - furnace, we term a "RIS with a single stock location".

Constant Number of Repairable Items (Initial Stock):
Except for some failed components that are disposed off during replacement or repair, the repairable items once purchased never leave a RIS. The disposal is generally very small, i.e. not more than 5% annually (Sherbrooke [1968]), and therefore is assumed negligible in our study.

Flexible Manpower Planning (FMP)

We define flexible manpower planning (FMP) as:

> *"The instrument that directs all measures to accomplish variations in the manpower on the short term. The instrument is under the authority of the manager and can be applied with a short leadtime".*

According to Schneeweiß [1992a], the attributes of FMP are leadtime and authority. "Leadtime" is the time between announcement and implementation of a measure and "authority" refers to the command that has the power to initiate a measure, the manager or the repair man. FMP in our study is used in response to an irregular demand pattern on the short term. Hence, we are interested in those measures with a short leadtime that can be initiated by the manager. There are four such measures (Faißt [1992a]): (1) subcontracting, (2) repair men leasing, (3) overtime and (4) variable working days.

Subcontracting is attended with some disadvantages. These are the long leadtimes, the high cost and sometimes the difficulty to find a suitable subcontractor. Leasing of repair men is a possibility if special skills are not required. Repair, however, usually requires skilled repair men, thus leasing is often not a suitable option for RISs. The use of overtime is probably initiated by the manager, but in practice nearly always accepted by the repair men because of the good financial compensation. It is, in general, an expensive measure of FMP. A variable working day means that the number of hours on a particular day is permitted to deviate, in either direction, from the number of working hours on a standard working day. This measure, yet little studied in RISs, is the subject of our research. In this dissertation we use FMP as a synonym for the application of variable working days.

Psychological effects associated with variations in the day length we assume negligible. In other words, we assume that FMP affects the output level of the repair men proportionally with the day length. Further research, outside the scope of this thesis, must show whether this assumption is valid.

FMP, when not properly controlled, could result in the use of extra manpower, i.e. structural overtime. To disentangle the use of "extra manpower" from the use of "variable manpower" in this study, we impose the requirement that the use of FMP may not result in extra manpower on the long term.

Control of a Repairable Item System

Control is generally defined for manufacturing systems as: "The coordination of supply and production activities in manufacturing systems to achieve a specific delivery flexibility and delivery reliability at minimum cost" (Bertrand, Wijngaard and Wortmann [1990]). Three aspects of control are emphasized in this definition: achievement, coordination of the activities and cost minimization. On the basis of these aspects we define the *Control of a Repairable Item System* as:

> *"The coordination of activities with the purpose to buffer against (the variations in) demand and repair throughput time in order to achieve a target at minimum cost."*

Control of RISs depends upon the demand for items, a target, the initial stock, the manpower, the priority rule to schedule failed components into repair and an FMP policy.

Demand:

In an important set of RISs, demand for a serviceable component is triggered by the perception of a component failure. Both practitioners and academics commonly assume that demand occurrences in these RISs appear according to a stationary state dependent Poisson distribution, the state depending on the number of machines currently in use in a set. This assumption is adopted in this dissertation. More likely, the demand distribution is not "stationary" but "time varying" on the long term. Establishing such in practice, however, is not easy due to the low demand level. In a RIS running into 200.000 items it appeared that demand for 85% of the items occurred not more than three times in one year (Geraerds [1991]). For these items it would be very difficult to determine a time varying demand pattern. In line with common practice we assume a stationary state dependent Poisson distribution in our study. Moreover, for reasons of simplicity, we assume that the demand for different items is mutually independent. For studies of systems with dependent demand we refer to Pijnenburg [1992].

Target:

The purpose of control is to contribute to the uptime of the machines in the set(s). Thus the targets that are set for, and the performance that is realized by, a RIS can be expressed in terms of contribution to uptime. This is however not a common measure in practice. The performance of a RIS is more often measured by service levels than by uptime. The service level definition most commonly used in practice, and therefore used in our study, is the "percentage of demands which is met from serviceable stock in a certain period" (Sherbrooke [1992]). We term this service level the "fill probability".

Cost Minimization:

The main costs in a RISs are due to the investment in stock, the employment of repair men and the investment in their flexibility. In this study it is advocated that, for full cost control, all these cost factors must be considered simultaneously subject to the fill probability target.

1.3. Research Questions and Outline

FMP, under the authority of a manager, has been the subject of negotiations between government, employers and employees in the last decennium. Recently the outcomes of these negotiations are showing more and more an acceptance of FMP. This also applies to RISs. Such developments, we suggest, justifies an in depth study. We put forward our first research question.

Q1: "How effective is the use of a flexible manpower planning in repairable item systems, measured in terms of a contribution to a service level ?"

Provided that FMP is effective, its introduction in practice should be considered. Then, FMP should be coordinated together with the other measures of control. The decision power for the different measures of control is, in practice, allotted to different management levels. To support these management levels in taking control decisions we would construct a framework for control. We concentrate on the coordination of FMP and initial stock in such a framework. We put forward our second research question.

Q2: "How can decisions regarding initial stock and flexible manpower be embedded in a framework for the control of repairable item systems ?"

Following an overview of the relevant literature on RISs in Chapter 2, it is shown that in spite of their relevance in practice, these research questions have received little attention by academics. The importance for further study of both research questions is evident. The first research question is addressed with the help of a simulation experiment in Chapter 3. The simulation results indicate that the effectiveness of FMP depends on a mixture of demand characteristics, on operational constraints for the RIS and on the characteristics of the applied FMP policy. For those RISs where FMP is potentially effective, it should be considered with the other measures of control. These measures are embedded in a framework for control. The framework is presented in Chapter 4. The relevance for practice of this framework is discussed in Chapter 5 with the management of a RIS associated with commercial aircraft overhaul in the Netherlands. Finally, conclusions are drawn and recommendations for further research are given in Chapter 6.

2. Relevant Literature

RISs regularly have been the subject of study, see the reviews of Nahmias [1981], Mabini and Gelders [1990] and Cho and Parlar [1991]. The review of Cho and Parlar is not restricted to RISs alone but addresses maintenance systems in general. All three reviews are structured along the "number of stock phases" (single phase versus multiple phases) and the "stock control" (periodic review versus continuous review). In this chapter we like to emphasize the manpower aspect and distinguish the classes "unlimited", "limited" and "variable" manpower. FMP, as defined in Chapter 1, is a subset of variable manpower.

2.1. Unlimited Manpower

In the early literature on RISs, the manpower constraint is assumed to be negligible. The literature primarily focuses on the determination of the stock levels in a RIS with two stock phases. The first contribution to the above problem hails from Sherbrooke [1968] with the introduction of METRIC, the abbreviation of "Multi-Echelon Technique for Recoverable Item Control". METRIC, developed for the US Air Force, models a RIS with a central stock location (depot) and a number of regional stock locations (bases). Repair of the failed items can be carried out both at the depot and the bases. The decision "where to repair" depends on the complexity of the repair. Resupply of the bases takes place according to a continuous review (S-1,S) replenishment policy, S-1 being the replenishment level. METRIC minimizes the total number of expected backorders at the bases, subject to a stock investment constraint. The model yields replenishment levels for the depot and the bases. The sum of all these levels together is the initial stock. The modelling assumptions are:

1. Demand is a stationary compound Poisson process.
2. Lateral resupply between bases is ignored.
3. All failed units are repaired.
4. Manpower is unlimited, batching for repair does not occur.
5. Failures are statistically independent.
6. All backorders at any base are equally important.

The computation of the replenishment levels is carried out with the help of a marginal procedure which increases the item stock levels subject to a budget constraint. In each iteration the procedure increases the initial stock level for that item with the lowest cost "per unit decrease in the expected number of back orders over all bases together". The procedure is inclined to give priority to low-cost items for admission in the initial stock.

Muckstadt [1973] states that for RISs with multiple repair levels only the number of expected back orders at the highest repair level should be considered. Specifically for these RISs he introduces MOD-METRIC, an extension on METRIC. Thus MOD-METRIC relaxes METRIC's 6th assumption. Slay [1980] states that both METRIC and MOD-METRIC underestimate the repair time due to manpower restrictions. He modifies METRIC to VARI-METRIC, an approximation which accounts for manpower. The model is evaluated by Sherbrooke [1986] who concludes that it produces better results than METRIC. Computationally the model is slightly more complicated than METRIC. Hillestad [1981] modifies METRIC to DYNA-METRIC, a model which accounts for a time-varying demand. The model is a relaxation of METRIC's 1st assumption. Graves [1985] introduces an approximative model for the determination of the stock levels in a RIS where, in contrast to METRIC, repair is only allowed at the depot. In a comparison, Graves shows that his model is more accurate than METRIC on a set of tests. Computationally, both models are equally complex.

Simon [1969, 1971] introduces a continuous review (S-1,S) model which permits disposal. It is in fact a relaxation of METRIC's 3rd assumption. The model obtains exact expressions for the stationary distributions of the serviceable stock-on-hand and backorders at the various bases. In comparison with METRIC Simon's model is more general in permitting the ability to write off items, but it is less general in assuming Poisson demand and deterministic throughput and transportation times.

Shanker [1981] studies a system, similar to Simon's model, namely with allowance of condemnation. Shanker however assumes an (s,S) ordering policy at the depot and consequently batch repair. The author derives exact expressions for the stock levels under the assumption of deterministic repair and lead times. (s,S) replenishment policies are typically studied in situations where demand rates are not particularly low. These situations are not of our specific interest. More studies in this field are carried out by Lee and Moinzadeh [1986, 1987a, 1987b]. A study of Lee [1987] is interesting in permitting lateral resupply between the bases which is a relaxation of METRIC's 2nd assumption.

Kaplan and Orr [1985] introduce the model OATMEAL. Unlike METRIC, their model does not maximize a service level subject to a stock investment budget constraint, but minimizes the budget with respect to a target service level. Moreover the location of the repair - which repair to carry out where - is included in the cost consideration. Singh, Shah and Prem Vrat [1980] carry out a case study in a RIS with multiple stock phases, where repair is allowed at the depot alone. The authors do not consider a service level but simultaneously minimize the cost for stock holding, back orders and transportation. They find that the size of the initial stock is quite insensitive to the estimation of the back order costs. Schaefer [1983] states that equipment can be in operation despite the fact that some of its components are failed. A maintenance job in such a situation consists of the replacement of a number of components. A job is completed only when all failed components are replaced. The probability that a job is completed instantaneously is defined the job completion rate. For a RIS with one repair level and one stock location the author shows that a target job completion rate can be obtained at minimum stock cost, or that a job completion rate can be maximized subject to a stock investment budget.

2.2. Limited Manpower

The most criticized assumption underlying METRIC is the 4th, unlimited manpower. This assumption enables Sherbrooke and others to apply Palm's theorem [1938]. This theorem states that if failures are generated by a stationary Poisson process and if repair throughput times are independent identically distributed random variables, then the steady-state number of units undergoing repair at any given time is also Poisson distributed with a mean equal to the product of the failure rate and the mean repair throughput time. Basically this means that manpower is unlimited. In practice, it is evident that the repair throughput time has a strong relation with the number of units awaiting repair. Gross [1982] shows that the unlimited manpower assumption can result in a serious overrating of the service level, especially in combination with a small number of repair men. Another shortcoming of the METRIC oriented models is the implicit assumption that the demand for serviceable units does not depend on the number of operational production machines in a set. This assumption could result in a significant overestimation of the failure rate when the required service level is not very high. Both shortcomings are met if the calculation of the inventory is treated in terms of finite source queuing models, i.e. derivations of the classical machine repair problem (e.g. Kleinrock [1975], Gross and Harris [1985], Taha [1987]).

Gross, Miller and Soland [1983] study a RIS with one depot and one base. The RIS contains only one item. Repair can be carried out both at the base and at the depot. Repair times are exponentially distributed. Demand is a function of the number of production machines currently in operation in a set, thus the demand function is state dependent. The model calculates the number of repair men and the stock levels which together guarantee a target service level at minimum cost. The RIS is modeled as a steady state birth-death process with a finite state space. The state space can get very large which results in computational problems. Approximate techniques have been developed to calculate the number of repair men and the stock levels in less computer time (Gross, Kioussis and Miller [1987a], Albright and Soni [1988], Albright [1989]). Faster algorithms enable Gupta and Albright [1992] to apply them to a RIS with multiple repair levels and multiple stock phases with a very large state space.

Gross and Miller [1984] remark that demand and repair characteristics in a RIS change from time to time, for example in a military context upon a shift from peace to war time. After such shift has taken place, it will take some time before a new steady state (if ever) is obtained. The behaviour of a RIS until the steady state is obtained is called the "transient behaviour". Such behaviour could be measured in a time-dependent service level. The authors obtain exact solutions for the measuring of a time-dependent fill probability in a RIS with two stock phases. In a comparison of their model with DYNA-METRIC the authors show that DYNA-METRIC overrates the fill probability. Gross, Kioussis and Miller [1987b] present a method which allows them to study transient behaviour in RISs with a very large state space. Their solution, though more accurate, is computationally much less tractable than DYNA-METRIC. Ahmed, Gross and Miller [1992] derive approximations to establish the difference between their more accurate solutions and DYNA-METRIC. Their approximations have two purposes. First, it can be determined in which situations DYNA-METRIC is a good approximation and thus should be used. Secondly, an alternative approximation which is computationally easy to implement is obtained when DYNA-METRIC alone is not a good approximation and consequently should not be used. Balana, Gross and Soland [1989] solve the problem of finding a least-cost mix of manpower and initial stock in a RIS with one stock location, satisfying a transient service level. Won [1993] remarks that the mean-time-between-failures in successive periods tends to increase due to reliability improvements, thus demand is time-varying. For a multi-phase RIS with a repair facility at the depot only, the author obtains time-dependent stock levels for the central depot under the assumption of a Poisson demand process and exponentially distributed repair times.

So far the queuing-type models obtain a least-cost mix of manpower and initial stock in *single-item* RISs. Ebeling [1991] addresses a *multi-item* RIS. Each item requires its own manpower. The model calculates manpower and stock levels subject to a maximum availability of the production equipment and a budget constraint. The problem is solved in two steps. In the first step the multi-item problem is decomposed in a number of single-item problems. For each single-item problem the optimum manpower and initial stock level in steady state is determined for different feasible budgets. In the second step the initial stock budget is distributed over the items with the help of a dynamic programming approach. Ebeling assumes that failed units are scheduled into repair in a first-come-first-served (FCFS) sequence. The distribution of the initial stock budget however results in an overrating of the low-cost items in stock at the expense of high-cost items. Such in combination with a FCFS rule would result in a shortage of high-cost items.

Shortage of high-cost items can be avoided when better priority rules are used for the scheduling of failed components. High-grade priority rules are studied in a number of articles. As a result of the need for detailed modelling in these articles we are noticing a shift from the development of analytical models towards the use of simulation models.

Schröder [1988] and Schneeweiß and Schröder [1992] state that the priority scheduling rule must be included in the determination of the initial stock. For the control of a multi-item RIS the authors present a hierarchical approach containing two control levels. On the top control level the initial stock is determined. For that purpose the steady state probability of a multi-item queue with failed units is determined. The units in the queue are arranged according to a static priority rule which considers the cost of purchasing and the repair throughput time. Next, with the help of a marginal analysis, the initial stock budget is minimized subject to an aggregate fill probability. On the bottom control level the failed units are scheduled into repair with the intent to balance individual fill probabilities. For that purpose a dynamic priority rule (more advanced than the rule that is considered on the top level) is used which encompasses information with respect to the work-in-process and the current serviceable stock. Both the cost minimization procedure that is used to determine the composition of the initial stock and the priority scheduling rule are improved in a study by Loinjak [1992]. In all these studies it is assumed that the demand level does not depend on the current number of production machines in operation.

Scudder and Hausman [1982] present a simulation model of a RIS with three repair levels. The object is to minimize the stockout risk at the highest repair level subject to a stock investment constraint. The authors introduce the index equalization technique. To each item they attach an index which is a weighing of demand, repair throughput time, stock purchasing cost and initial stock level. The authors show that an optimal composition of the initial stock is obtained when the index values for all items are approximately equal. In a comparison of the index equalization technique with MOD-METRIC the authors show that both methods provide similar results for the highest two repair levels. At the lowest repair level the index equalization technique produces (slightly) better results than MOD-METRIC. The authors show further that, when the stock budget decreases, it is economical to remove units from the most expensive items first. In other words, expensive units are most likely to be in short supply and therefore should be scheduled into repair first. Hausman and Scudder [1982] test a variety of sequencing rules at the lowest level of repair. They show, not surprisingly, that dynamic sequencing rules which make use of stock-status and work-in-process information from the lowest repair level outperform static sequencing rules. The performance of the rules is not improved if current information with respect to the current status of the higher repair levels is added. In addition Scudder [1984] studies a multiple failure case where more than one unit has failed in each machine to be repaired. The results show that procedures which perform well when only one unit fails also perform well when multiple failures occur. Chua, Scudder and Hill [1993] state that batching of (lowest-level) repairable-items may be necessary because of high setup cost. They compare several batching rules with respect to a service level. A batch is composed of the current number of failed units of a certain item awaiting repair. They show that a rule which selects batches on a shortest batch processing time weighted by the number of serviceable items in stock provides the best results.

2.3. Variable Manpower

Bertrand, Wijngaard and Wortmann [1990] address the operational control of a blast-furnace repair-shop. The management of the repair shop faces tight due dates, an irregular arrival of the repair orders, an unknown routing and an unknown job content until inspection and work preparation is carried out. Under the current control procedure the actual progress on the shop floor deviates from the planned progress which results in a poor performance. The authors propose a hierarchical decision structure consisting of three levels of control. At the top level a buffer containing repair orders is introduced. If the buffer exceeds a certain threshold, repair orders are subcontracted. A small number of rush orders is released to the repair shop. The remaining orders which are set apart for the repair shop are divided into suborders: one disassembly suborder, several repair suborders and one assembly suborder. At the middle level, the orders are released in accordance with the principles of workload control (Bertrand and Wortmann [1981]). The repair suborders are selected with the aim to maintain an equal average time slack. At the bottom level deviations from the actual progress are to some extent corrected by adjusting capacity, i.e. a reallocation of manpower, or by changing order progress priorities in the repair shop.

In a simulation study, Schröder [1988] addresses the use of FMP in a multi-item RIS with one stock location. He compares two cases on an aggregate fill probability. In the first case the repair rate is assumed fixed. In the second case the repair rate is tied to the number of failed units, the higher the number of failed units the higher the repair rate. In both cases the average repair rate, the composition of the initial stock and the priority rule to schedule units into repair are equal. The case with a fixed repair rate yields a slightly higher fill probability than the case with a variable repair rate.

Scudder [1985] carries out an explorative simulation study to the use of overtime in a RIS with three repair levels. Demand at the first repair level occurs according to a Poisson process. Under different conditions the effect of several overtime policies is studied on the mean number of delay days, a measure for the service level. All together six overtime policies are studied. The policies are either reactive or proactive and differ with respect to the repair levels where they are applied. Reactive overtime refers to a situation where no serviceable units are in stock on the first repair level when the decision is made to work in overtime. Proactive overtime refers to the situation where overtime is started when the first-level serviceable stock levels are insufficient to cover expected leadtime demand. The conditions in his experiment differ with respect to the applied priority rule to schedule failed items into repair, the initiation of proactive overtime and the characteristics of the repair time. All are varied on two levels. The priority rules are MSTREQ versus SPT. MSTREQ, an advanced rule, gives priority to that item which is currently most required on the higher levels of repair. SPT, a simple rule, gives priority to the item with the shortest processing time. Overtime is initiated when the number of units awaiting repair exceeds a certain threshold. The repair throughput times are chosen fixed versus variable and dependent on the complexity of the repair. Based on the results of a number of simulation experiments, the following conclusions are drawn: First, the use of overtime at any repair level improves the service level. At the lowest repair level the use of overtime is most effective. At the middle repair level the use of overtime does not appear to be very effective. Secondly, reactive overtime policies outperform proactive overtime policies. Thirdly, overtime is required much less frequently when a good priority scheduling rule is used. However overtime produces much better improvements in the service level when a simple priority rule is used.

In extension to the former study, Scudder and Chua [1987] examine proactive and reactive overtime in relation to different demand patterns and different initial stock budgets. The overtime policies are compared to a benchmark policy without overtime against the number of mean delay days. The two overtime policies are compared to each other on the basis of a benefit-cost ratio. The reduction in mean delay days, with regard to the benchmark policy (the benefit), is measured against the number of hours in overtime (the cost). The results show that the use of overtime is increasingly effective in combination with a reduction in the initial stock budget. The overtime policies are most effective in combination with a simple priority rule. In most instances the reactive policy yields the best cost-benefit ratio. Only in combination with a very regular demand pattern, the reactive overtime policy is outperformed by a proactive policy.

More studies to variable repair rates are carried out in a related area, a redundant system. Crabill [1974] represents a system with spare machines as a Markov network with one repair channel and state-dependent repair-rates. The repair rates increase with the number of failed machines. Variable costs are allotted to production losses and to the use of variable repair rates. The author obtains analytical solutions to balance both costs in steady state. He shows that, under certain conditions, the optimal repair rate is a non-decreasing function of the number of failed machines. Albright [1980] extends this result to a case with multiple repair channels. Van der Duyn Schouten and Wartenhorst [1993] study a maintenance system with one machine in operation, one spare machine and one repair channel. A failed machine can be repaired at two repair rates, a slow rate and a fast rate. It is decided which repair rate to apply at the beginning of a repair. When the second machine fails and the first machine is still in repair, the repair channel has an additional opportunity to changeover to the fast rate. Fixed and variable costs are allotted to a changeover. Only variable costs are allotted to a machine breakdown. The authors minimize the long run overall costs and show that the optimal change-over policy is of a control limit type: When exceeding a certain threshold, a changeover takes place. When fixed cost in respect of machine breakdowns are added, the optimal policy is not necessarily of a control limit type anymore.

2.4. Discussion

The overview of the literature shows that RISs have been extensively studied. The first publications already stem from the late sixties. In these publications the focus is on a mathematical description of the relation between the replenishment levels and a service level under the assumption of an irregular demand process. The replenishment levels have two functions in the control of a RIS. On the one hand they allow us to determine the investment in initial stock that is necessary to attain to a service level target. On the other hand, the replenishment levels support the operational control of the RIS. Upon a comparison of the current serviceable stock of an item with its replenishment level it can be decided if resupply is necessary. Resupply however is required lot-for-lot which means that demand is directly passed on to the repair shop. It is evident that such a policy inevitably results in varying requirements upon the manpower when the demand pattern is irregular. This in turn results in rapid variations in the repair throughput times. In case of limited manpower it is doubtful that the use of replenishment levels adequately supports the operational control of the repair facility of a RIS.

In the queuing type models, introduced in the eighties, it is recognized that service levels are affected by the initial stock and the manpower, thus both must be considered simultaneously subject to a target constraint. Unlike METRIC, the queuing models enable us to make such simultaneous consideration. These models, however, do not support the operational control of a RIS. Queuing models implicitly assume that failed units are scheduled into repair as long as manpower is available. They do not support the use of sophisticated priority rules to schedule failed units into repair. They commonly assume that repair is carried out in a FCFS sequence. More sophisticated rules are presented in the simulation studies. These studies have yielded priority rules which are able to support the operational control of a RIS. Simulation however can be time consuming and therefore it is not a particularly suitable tool for optimization.

Very few studies have been conducted into variable manpower in RISs. The most thorough is the overtime study of Scudder and Chua. From the study it is clear that a considerable benefit from overtime can result, though this benefit is affected by intervening conditions. The results of the (simulation) study by Scudder and Chua justifies a further (simulation) study into the potential effectiveness of FMP and the intervening conditions. Scudder and Chua hint that overtime, which is a form of manpower flexibility, should be included in a fundamental trade-off on costs between initial stock and manpower to attain to a target service level economically. In our view, this fundamental trade-off should be part of any framework for the control of RISs. Such framework is still absent in the literature and, therefore, requires further study.

3. Simulation Experiment

FMP will clearly influence the working hours of the repair men which in turn is expected to influence the performance of the RIS. Understanding this interaction is the objective of our first research question. In studying these interactions we pursue the following phases of an experimentally based research methodology:

"Select a number of RISs with different demand characteristics and operational constraints. Model these RISs with the help of a simulation model. Introduce in each RIS a policy in which all working days are equal in length and monitor the service level. The service level under this working day policy is used as a benchmark. Next, introduce in each RIS a number of FMP policies such that the working day on the long term is on average equal to the constant working day of the benchmark. Monitor again the service level in all RISs. Deviations in the service level with regard to the benchmark service level are a measure for the effectiveness of an FMP policy. Compare the effectiveness of different FMP policies in the RISs with different demand characteristics and operational constraints and formulate the conclusions."

In this chapter we introduce a simulation model of a RIS. In the model we introduce various demand characteristics and operational constraints by setting selected parameters to different values. For each setting of the parameters we introduce a number of FMP policies. The performance of these policies is measured in a service level. The deviation in the service levels with regard to some benchmark we term the response. The response is a measure for the effectiveness of an FMP policy. To predict how the response in each RIS is affected by the setting of the parameters, a number of hypotheses are put forward. These hypotheses are tested in the simulation experiment. The results of the experiment enable us to establish which parameters contribute to the potential effectiveness of FMP.

3.1. Model

The model of a RIS in the experiment is rather simple in comparison to the RISs in practice. On the one hand it can be argued that simple models do not accurately describe the full behaviour of the very complex systems which are prevalent in practice. On the other hand they are advocated for their transparency. In the RIS, introduced here, we strived for a compromise. That is we construct a RIS complex enough to reflect the main behaviour of the ones observed in practice, yet simple enough to maintain transparency in our study. This compromise has been achieved in discussion with the management of a RIS in practice.

Generic RIS:

The generic RIS, depicted in Figure 3.1, supports a number of machines used in production. We assume that the machines are continuously in operation. Each machine has one vulnerable component that can fail and is best repaired by component replacement. Several machines have the same vulnerable component in common. These machines form a set. No single machine is a member of more than one set. The component type concerned is called an item within the RIS. A specific component is a unit.

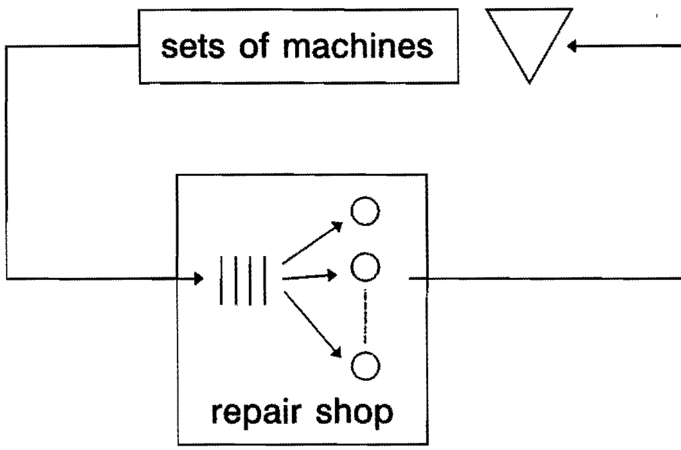

Figure 3.1: Generic Repairable Item System

In order to explain within this context the notions of set, production machine, item and unit we introduce an example. Consider a faculty at the university where all research workers have a personal computer (PC) at their disposal. Such PC we call a production machine. Assume that there are two kinds of PCs: One kind has a 3.86 processor, the other kind has a 4.86 processor. All PCs with a 3.86 processor compose one set, all PCs 4.86 compose the other set. The processor is attached to a printed circuit board (PCB). Assume that the PCB is the only vulnerable component in a PC. Then there are two kinds of PCBs: A PCB with a 3.86 processor and a PCB with a 4.86 processor. "PCB 3.86" we call an item. A specific PCB with a 3.86 processor we call a unit.

A unit ages and fails only in use. The mean rate of failure occurrences for a unit within a production machine depends upon the mean-time-between-failures (MTBF), which is assumed to be exponentially distributed with a same MTBF for all units of the same item. All items can have different MTBF. Their failures occur independently. Upon a failure, the failed unit is replaced with a serviceable unit from stock if available. If not available, the demand for a serviceable unit results in a back order. The time to replace a failed unit, in the case there is an identical and serviceable twin available in stock, is assumed negligible.

The failed unit is sent to a repair facility where it joins a single queue in front of a number of parallel repair channels. Each channel is occupied by one or more repair men. All repair men are identical and capable of repairing any unit. The number of working hours differs from day-to-day but is the same for all repair men. The length of a particular day is determined with the help of the FMP rule that will be presented in Section 3.4.

When a repair channel is idle, the unit with the highest priority is selected for repair according to a dynamic priority rule which is introduced by Hausman and Scudder (NTINV2-DBL; [1982]). This rule, shown by the authors to outperform others in a complex RIS, selects the item with the smallest level of net serviceable stock. That is the current on-hand stock minus the number of back orders for that item. When different items share the smallest level of net stock a tie-breaking procedure is used. When the number of serviceable units in stock is zero, it chooses the item with the shortest expected repair time. It selects the item with the earliest due date otherwise. The authors define the due date "the arrival time in the queue plus three times the expected repair time".

The selected unit is sent to a repair channel where it is repaired. All unit repair times of item j are identically distributed random variables with, therefore, an equal expected repair time. Variations in the repair times are neither very strong, nor very weak. Therefore, we model the repair times with an ERLANG-k distribution with shape parameter k=2. All units are ultimately repaired. Consequently, the sum of the units in use, waiting for or under repair or waiting serviceable in stock is constant. A repaired unit is sent into service when there exists a back order or otherwise transferred to a stock location where it remains in reserve of a future replacement. All transportation times are assumed negligible.

Simulation Program:

The behaviour of the generic RIS is simulated in Pascal language. The simulation program comprises five procedures. The first procedure, "set control", updates the number of production machines in use in a set. The second procedure, "stock control", updates the number of serviceable units in stock and the number of back orders. The third procedure, "manpower planning", determines the length of a working day on the basis of the current work in process (WIP) and an FMP policy. The fourth procedure, "priority scheduling", selects the next unit for repair. The fifth procedure, "reporting", generates a report after the expiration of a certain number of working days.

Simulations in Pascal are event driven. Three events can be distinguished: (i) the occurrence of a failure, (ii) the completion of a repair and (iii) the beginning of a working day. The failure and repair events are produced by means of sampling from a probability distribution. All events have a time label. The events are processed in order of their nearest point in time. The procedures "set control" and "stock control" are activated when the nearest event is the occurrence of a failure. The procedures "priority scheduling" and "stock control" are activated when the nearest event is the completion of a repair. If however a back order exists at this event, the procedure "set control" is also activated. The procedure "manpower planning" is activated at the beginning of each working day. The procedure "reporting" is activated after the expiration of a certain number of working days.

Verification:

Coding errors go easily unnoticed and simulation programs should therefore always be verified. Verification can be performed with the help of a product-form-network, an analytical model of a simple RIS (Baskett et al. [1975]). Both models are compared with respect to a fill probability. The fill probability is a measure for the percentage of demands in a certain period that will be met from serviceable stock at the time they are placed (fill rate; Sherbrooke [1992]). For the definition of the fill probability we reserve the subjoined variables. Fixed parameters are represented by upper case characters, stochastic variables are represented by lower case characters:

- The number of units j in initial stock is Y_j, $Y_j \geq 0$, $Y = \Sigma_j Y_j$, $1 \leq j \leq J$.
- The number of failed units j in the RIS at a decision epoch is s_j, $s_j \geq 0$, $1 \leq j \leq J$.
- The steady state probability of s failed units j is $p_j(s)$, $0 \leq p_j(s) \leq 1$, $\Sigma_j p_j(s) = 1$, $1 \leq j \leq J$.
- The fill probability for item j is f_j, $0 \leq f_j \leq 1$, $1 \leq j \leq J$.
- The average fill probability over all items is f, $0 \leq f \leq 1$, $1 \leq j \leq J$.
- The expected demand for item j per day is $E(d_j)$, $E(d_j) > 0$, $E(d) = \Sigma_j E(d_j)$, $1 \leq j \leq J$.

Clearly Y and I represent the number of stocked units and items respectively. In a technical note, enclosed in Appendix A, it is shown that the fill probability for item j can be defined as a probability of serviceable stock. In practice the fill probability is commonly expressed in percentage term. We now define f_j accordingly, that is

$$f_j = 100 \sum_{s_j=0}^{Y_j-1} p_j(s) \quad . \tag{3.1}$$

To deduce a measure of the fill probability over all items, we define this fill probability as a weighing of all item fill probabilities with respect to their expected demand rates, namely

$$f = \sum_{j=1}^{J} \frac{E(d_j)}{\Sigma_j E(d_j)} \cdot f_j \quad . \tag{3.2}$$

The product-form-network, as well as the embedding of the fill probability in this model, is explained in Appendix B, Section B.1. In a verification experiment in Section B.2, it is shown, under different parameter settings for a RIS with two items, that the fill probabilities produced by the simulation model are always within a narrow range of the fill probabilities produced by the analytical model. This fact, in conjunction with the extreme value tests, gives us confidence that the simulation model is accurate.

3.2. Demand Characteristics

In this study we deal with the application of FMP in relation to an irregular demand pattern. The variations in demand as well the composition of demand is affected by the demand for an item and the number of items within the RIS. To gain insight in the contribution of these factors to the effectiveness of FMP, they are included in our study. We term *factor A* "the daily demand rate over all items" and *factor B* "the number of items within the RIS". Both factors are varied on two levels in the experiment, a low level denoted by (-) and a high level denoted by (+). Four demand characteristics are defined: *A-B-* low demand, small number of items; *A+B-* high demand, small number of items; *A-B+* low demand, large number of items and *A+B+* high demand, large number of items. The corresponding parameter settings for the levels low and high for the factors A and B are taken from RISs in practice.

In an organization for the overhaul of jet-engines, we came across an example of a RIS which faces low demand. A jet-engine is replaced by a serviceable counterpart upon a normative failure and sent off for repair to a specialized repair facility. Consider two repair departments within the repair facility. In the first department *"A-B-"* an engine is inspected, dismantled, the failed modules are replaced and the engine is assembled and tested. The department repairs three items, i.e. engine types. The repair work is carried out in five parallel repair channels, all occupied by two or three repair men. In the second repair department *"A-B+"*, the failed modules, e.g. turbines and compressors, are cleaned, dismantled, the failed parts are replaced, the module is assembled and then tested. The department repairs ten items. Repair is carried out in eight parallel repair channels, each channel occupied by one or two repair men. Item daily demand rates vary between 0.3 and 0.4 for the engine repair department and between 0.05 and 0.20 for the module repair department. The item repair times vary in both departments from 60 to 80 hours.

In an organization for the repair of personal computers for the industrial market, we came across an example of a RIS which faces high demand. Right after the perception of a failure, a service engineer is sent to maintain the failed equipment. The engineer replaces, if appropriate, the failed component by a serviceable one. The failed component is transferred to a repair shop with several repair departments. The repair men in one department *"A+B+"* are responsible for the repair of ten types of mounted printed circuit boards (PCBs). PCBs are inspected, repaired and tested, all carried out by one repair man. The repair men are able to carry out any repair within their repair department. Another repair department *"A+B-"* is responsible for the mechanical repair of disc drives. Various types of PCs possess the same type of disc drive and, therefore, there exist only few types. We set the number of items visiting the department equal to three in the experiment. Item demand rates vary between 0.4 and 1.6 per day for the PCB repair department and between 3 and 4 for the disc drives repair department. Item repair times vary between 1.5 and 3 hours in both departments.

The options in the simulation experiment are compactly presented by the following set of parameters.

- The number of items in the RIS is J, $J \geq 1$.
- The average demand per day over all items is E(d).
- The weighed average item repair time in hours is E(r.), $E(r.)=\Sigma_j E(d_j).E(r_j)/E(d)$, $1 \leq j \leq J$.
- The number of parallel repair channels is C, $C \geq 1$.
- The number of repair men is R, $R \geq 1$.

Values of the parameters used in the experiment are given in Table 3.1. With regard to the item repair rates, only the average value E(r.) is included in this table. The values for parameter R in the table will be deduced in Section 3.3.

Table 3.1: Demand Characteristics.

A	B	E(d)	J	E(r.)	C
-	-	1	3	72.0	5
+	-	10	3	2.2	R
-	+	1	10	72.0	8
+	+	10	10	2.2	R

3.3. Operational Constraints

In this study we are concerned with a fundamental trade off between manpower and initial stock. It is accepted that the potential effectiveness of FMP could be affected by the results of such trade off. To gain insight in the effects of these factors, they are included in our study. We term *factor C* the "manpower" and *factor D* the "initial stock". On the basis of these factors we define four operational constraints for the RIS: *C-D-* low manpower, small stock; *C+D-* high manpower, small stock; *C-D+* low manpower, large stock and *C+D+* high manpower, large stock.

The number of repair men and the initial stock are relative notions. It is not clear, for instance whether 15 units represent a small or large initial stock unless it is related to some absolute measure. Absolute notions are "utilization rate" for manpower and "fill probability" for initial stock. The manpower utilization rate "ρ" is the demand in a period divided by the available manpower. Utilization rates of 0.70 (0.90) are considered moderate (high) in practice. We determine an integer number of repair men "R", in the simulation experiment, in accordance with these figures.

$$R = \left\lceil \frac{E(d).E(r.)}{\rho} \right\rceil \quad . \tag{3.3}$$

From equation (3.1) it appears that the fill probability for an item is a function of the initial stock level for that item. When one unit is added to the initial stock of item j, then the fill probability for item j, as well for all items, will increase. The idea is to add initial stock, and simulate, until the expected fill probability over all items is at least equal to some target fill probability. We seek to add units such that the total investment in stock is minimized subject to a constraint on the fill probability over all items. An allocation procedure to accomplish this in a RIS with similar characteristics is presented by Scudder and Hausman [1982] under the name "index equalization technique". For all items j they define an index, "$index_j$", which is a function of the unit cost C_j, the demand rate $E(d_j)$ and the initial stock level Y_j. The authors show that the highest service level per unit cost is obtained when the indices for all items are (more or less) equal.

$$index_j = Y_j . \frac{C_j}{E(d_j)} \quad . \tag{3.4}$$

With the index equalization technique, initial stock is added in each RIS until a fill probability over all items of respectively 0.50 and 0.95 is attained. These values are generally considered low and high. The values for the number of repair men "R" and the initial stock "Y" in the experiment are depicted in Table 3.2. In line with our expectations we see that R and Y increase when the factors C and D are set from a low to a high level.

Table 3.2: Operational Constraints

		A-B-		A+B-		A-B+		A+B+	
C	D	R	Y	R	Y	R	Y	R	Y
-	-	10	8	3	8	10	13	3	10
+	-	13	5	4	5	13	9	4	6
-	+	10	24	3	29	10	42	3	39
+	+	13	14	4	12	13	32	4	25

3.4. FMP Rule

The variations in the working day lengths are controlled by an FMP-rule. The rule adjusts the working days lengths at certain points in time, t^*, which appear every e days. At such a decision moment, the rule determines the working days in the interval $[t^*+\ell, t^*+\ell+e-1]$, conveniently denoted by $[\ell,e\rangle$. All working days within this interval are equal in length. Parameter "ℓ" is the minimum timespan between the announcement and the operation of a certain working day length. Parameter "e" is the operational duration of an altered working day length. To determine this length, a pivot value x is compared to the work in process (WIP) at t^*, "w_{t*}". If at t^* the WIP is greater (smaller) than the pivot value, the day lengths in the interval "$d_{[\ell,e\rangle}(w_{t*})$" will be longer (shorter) than the length of a standard working day, i.e. eight hours. The deviation of the WIP from the pivot is multiplied by parameter a. The greater the value of a, the greater the responsive change of the working days within the interval to the deviation, the greater the required manpower flexibility. This flexibility is bonded by two parameters D_{min} and D_{max}. That is the day lengths cannot be shorter (longer) than a prescribed minimum (maximum). The behaviour of the rule is illustrated in Figure 3.2. The minimum, standard and maximum working day in this figure are respectively six, eight and ten hours, x is set to 10 hours, a is set to 1/80.

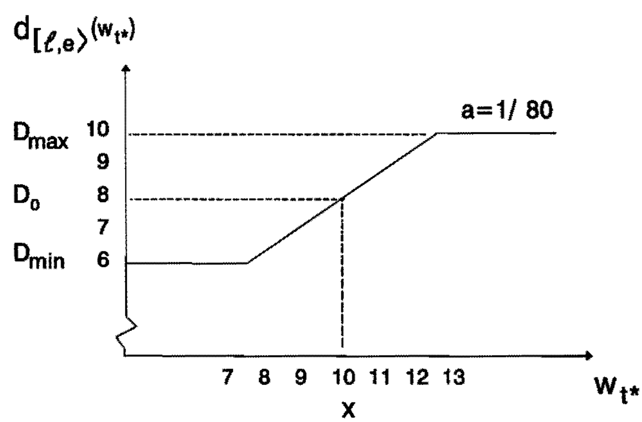

Figure 3.2: FMP - rule

Under FMP we require that the length of the average working day is in the long run equal to the length of a standard working day, i.e. eight hours. This requirement can be satisfied with an adequate choice of the pivot value. This value is in our simulation model determined in an iterative procedure. In the procedure, the pivot value is initially set to zero hours. Then it is raised in steps equal to a fraction of the mean-unit-repair-time. After each step we run a simulation, measure the deviation in length between the average working day and the standard working day. The procedure is stopped when this difference is minimal. Due to the increments in discrete steps, the average working day does not agree precisely with the standard working day. In the experiment we accept deviations within a range of ± 5 minutes.

In the description of the rule we recognize the following FMP parameters:

- The leadtime to announce a variation in the day length is ℓ days, $\ell \geq 0$.
- The operational duration of a variation in the day length is e days, $e > 0$.
- A multiplier for adjusting the impact of manpower flexibility is a, $a \geq 0$.
- The minimum length of a working day is D_{min} hours.
- The maximum length of a working day is D_{max} hours, $0 \leq D_{min} \leq D_{max} \leq 24$.

The remaining parameters are not FMP parameters.

- The points in time to decide upon changes in the working day length are t^*.
- The work in progress (WIP) at the beginning of a day t^* is w_{t*} hours, $w_{t*} \geq 0$.
- The pivot value is x working hours, $x > 0$.

The length of the days in interval $[\ell,e\rangle$ is $d_{[\ell,e\rangle}(w_{t*})$ with

$$d_{[l,e\rangle}(w_{t*}) = \begin{cases} \max(D_0 - a(x - w_{t*})D_0, D_{\min}) & w_{t*} \leq x \\ \min(D_0 + a(w_{t*} - x)D_0, D_{\max}) & w_{t*} \geq x \end{cases} \tag{3.5}$$

By assigning different values to the FMP control parameters ℓ, e, a, D_{min} and D_{max} we can study a great many *FMP policies*. Accounting for all these policies would result in an unacceptable run time for the experiment. To reduce the number of policies in the experiment, it would be convenient if a subset of these parameters could be fixed at sensible and realistic values. In the hope of gaining insight into the problem, we embedded (a simplified variant of) the FMP rule in the product-form-network that was used to verify the simulation model. A numerical analysis was undertaken with this model to obtain sensible settings for the parameters, a, D_{min} and D_{max} for use in the simulation experiment. Both the model and the numerical analysis are explained in Appendix C. The results are summarized below.

In the analysis we considered a RIS with two sets of machines (or items) Ia and Ib. Each set contains five identical machines, all with one vulnerable component. There is a unit failure once every two days, i.e. E(d)=0.5. One third of the failures arises within units "a" and two third within units "b". The units are repaired in a repair shop consisting of two parallel repair channels, i.e. C=2. Both channels are occupied by one repair man with occupation rate $\rho \approx 0.80$. The repair men have the skills to repair units a and b. The initial stock is set to seven units: two units a and five units b. For this RIS, we compare the use of a constant working day policy, the benchmark, with an FMP policy under different settings for the FMP parameters a, D_{min} and D_{max}. One of these three parameters is set to different values, while the two others are set to a reference value. The reference values are 0.5 for parameter a, 6 hours for parameter D_{min} and 10 hours for parameter D_{max}. The value 0.5 for parameter a corresponds with a half hour increase (decrease) in day length by every increase (decrease) in the WIP with one failed unit. The working day policies are compared with respect to the fill probability over all items, see equation (3.2). Their response is defined as "the fill probability under FMP minus the fill probability under the benchmark", that is the percentage increase in fill probability attributable to FMP. The responses for the different parameter settings in the analysis are summarized in Figure 3.3. The response of parameter a corresponds with the parameter settings on the first line underneath the x-axis of the graph. The response of D_{min} (D_{max}) correspond with the parameter settings on the second (third) line underneath the x-axis.

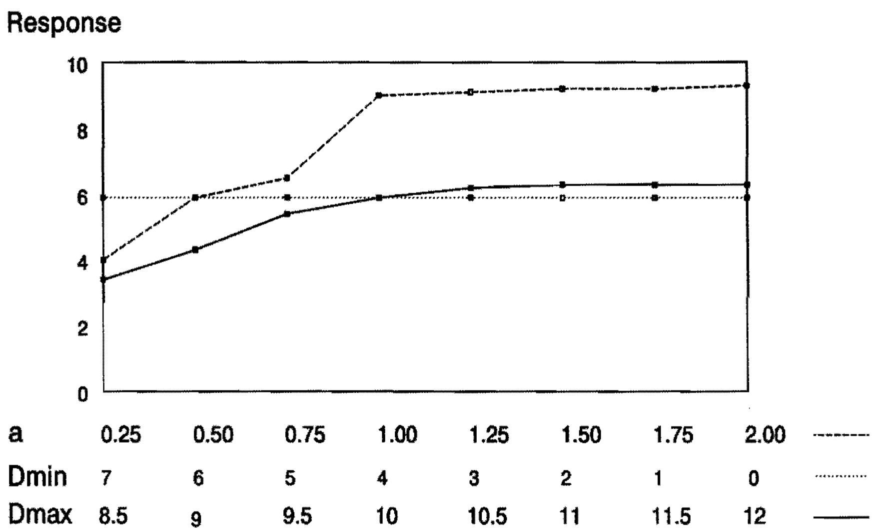

Figure 3.3: Responses for the FMP parameters

The curve for parameter *a* shows a sudden climb with *a* set to one hour. This sudden climb corresponds with a resetting of the pivot value from three to two failed units. The change is necessary to minimize the deviation between the average day length and standard day length. Because the pivot is raised in discrete steps there is a minor deviation between both values. While resetting the pivot, a little manpower is added or withdrawn. This phenomenon causes a sudden increase or decrease in the response.

The analysis indicates that the potential effectiveness attributable to FMP increases with higher maximum day lengths and higher FMP multiplier values. It appears that a fair share of the potential benefit is already obtained at a moderate increase in the setting of these two parameters. The response is rather insensitive to the setting of the minimum day length. In the experiment we set the FMP multiplier value to 0.5, which corresponds with half an hour increase in the day length at every increase of the WIP by one unit. The minimum day length is set to 6 hours, the maximum day length to 10 hours. The standard day length, finally, is set to 8 hours.

Realistic settings for the leadtime and the duration of employment are not easily derived. We make them form part of our study. We term *factor E* the "leadtime of announcement" and *factor F* the "operational duration". The leadtime we set to 0 and 5 days, the operational duration to 1 and 5 days. Outcomes of future deliberations among employers and employees should reveal how realistic these settings for the parameters really are. On the basis of the factors E and F, we consider four FMP policies in the experiment: *E-F-* short leadtime, short duration; *E+F-* long leadtime, short duration; *E-F+* short leadtime, long duration and *E+F+* long leadtime, long duration. Next to these four FMP policies we define a benchmark in which the repair men are available eight hours on every working day. The policies are compactly represented in Table 3.3.

Table 3.3: FMP Policies

E	F	ℓ (days)	e (days)	a (hrs)	Dmin (hrs)	Dmax (hrs)
-	-	0	1	0.5	6	10
+	-	5	1	0.5	6	10
-	+	0	5	0.5	6	10
+	+	5	5	0.5	6	10
benchmark		-	-	0	8	8

3.5. Response

The effectiveness of FMP is expressed in terms of a contribution to the fill probability over all items. An improvement in this fill probability due to the use of FMP we term the "response (r)". Note that the fill probability is bounded to 100%. Consequently there is little scope for improvement when a high fill probability is already obtained under the application of the benchmark policy. In our definition of the response we relate the improvement in the fill probability to the maximum improvement that can be obtained.

$$r = 100 \, . \, \frac{f_{FMP} - f_{benchmark}}{100 - f_{benchmark}} \tag{3.6}$$

The potential effectiveness of the FMP policies will now be established in the experiment under different demand characteristics and operational constraints for the RIS and in combination with different characteristics for the FMP policies.

3.6. Hypotheses

In order to predict the results of the experiment we put forward seven hypotheses. The intuitive considerations underlying these hypotheses are discussed following the formulations.

H1: "The effectiveness of FMP decreases with an increase in the demand rate."
H2: "The effectiveness of FMP decreases with an increase in the number of items."

The hypotheses with regard to the demand characteristics can be explained as follows. H1: The demand for all items is the sum of the demand for each item within in the RIS. The demand for all items, like the demand for each item, is a Poisson process. A measure for the demand fluctuations is the coefficient of variation. Typically in a Poisson process the squared coefficient of variation is the reciprocity of the average demand level. Thus an increase in the average demand level results in a decrease in the coefficient of variation and, consequently, in a decrease in the demand fluctuations. We expect that FMP is a powerful tool in reaction to demand fluctuations. Thus with a decrease in these fluctuations FMP would become less effective. H2: The failed units are scheduled into repair with the help of a highgrade priority rule. Scudder [1985] shows that, in combination with such a rule, there is little effectiveness proceeding from flexibility (overtime). We expect a decrease in the potential benefit of FMP when the priority rule will show to its full advantage, i.e. in a RIS with many items.

H3: "The effectiveness of FMP decreases with an increase in the manpower."
H4: "The effectiveness of FMP increases with an increase in the initial stock level."

The hypotheses with regard to the operational constraints of the RIS can be explained as follows. H3: Under tight manpower, there is little flexibility in reaction to the variations in the demand process. We assume that, especially in this situation, there will be a need for the flexibility provided by FMP. H4: When the stock level increases, not only the number of stock outs, but also their duration will decrease. We assume that a fraction of the stock outs - those with the shortest duration - can be prevented by the use of FMP. At an increase in the size of the initial stock, there are more stock outs with a short duration and, therefore, there are more stock-outs that potentially will be prevented by using FMP.

H5: "The effectiveness of FMP decreases with an increase in the leadtime of announcement of variations in the day length."
H6: "The effectiveness of FMP decreases with an increase in the operational duration of a certain day length."
H7: "All FMP policies are more effective than the benchmark in all situations."

The hypotheses regarding the characteristics of the FMP policies can be explained as follows. H5 and H6: In combination with an extensive leadtime or operational duration, there is a delayed reaction on the current WIP and, consequently, there exist a greater probability of an improper adjustment of the day length. We expect that the effectiveness of FMP decreases with an increasing number of improper day length adjustments. This intuition is substantiated by a simulation study of Fryer [1974] on the effectiveness of manpower transfers between different departments in a jobshop. It appears that, as might be expected, transfers are most effective when they are initiated with a short leadtime. We assume that such manpower transfers have some contextual resemblance with FMP. H7: The purpose of all FMP policies is to better tune the manpower level of the repair shop with the variations in the WIP. We expect such to be effective in all situations.

3.7. Results

In the experiment we test whether the hypotheses can be accepted. A hypothesis is accepted when the corresponding main factor A, B, C, D, E or F has a statistical significant contribution to the response and when this contribution can be considered relevant for practice. Any substantial increase in the fill probability resulting from the use of FMP we consider relevant for practice.

The contribution to the response is commonly measured in terms of a linear regression effect. These effects could be determined, in principle, in an experiment with a *fractional* factorial design (Kleijnen [1987]). In such an experiment, estimates for the main effects are obtained in a study of a fraction of the situations that can be formed by all combinations of the factors A, B, C, D, E and F and their levels (-) and (+). These estimates, however, are corrupted because the effects of the main factors are confounded with the effects of factor interactions. Also these factor interactions can be significant. Therefore, when these interactions are unknown, it is recommendable to choose a *full* factorial design, see for instance Law and Kelton [1991]. This design, though more time consuming, yields pure estimates for the effects of the main factors.

A full factorial experiment of six factors on two levels requires a study of 2^6 or 64 situations. For each situation we simulate one run, partitioned into five independent subruns, each subrun with an observation of a response. With this procedure, we increase the number of degrees of freedom in our experiment and so improve the discernment potential of the statistical test. Independence between the subruns, requires a sufficient number of simulation days per subrun. In Appendix D it is established that subruns consisting of 1,000 (10,000) simulated days for a RIS facing high (low) demand may be considered independent. The results of the experiment are enclosed in Appendix E.

A striking feature of the results is the considerable number of negative responses. The use of FMP is clearly not effective in all situations. It appears that FMP is especially ineffective in situations with a combination of a high demand level and short repair times (A+) and a low manpower (C-) and a long leadtime of announcement (E+). To verify this, we include the effect for the factor interaction "AE" in our study.

The statistical significance of the main factor effects and interaction AE is examined with an "analysis of variance (ANOVA)" in Appendix E. In this analysis the mean square of the responses, due to the resetting of a factor from a low to a high level, is related to the error mean square over all observations. When there is no significant effect, the quotient of both squares is "F distributed". Effects are significant (with a significance level of 0.95) when F-value > 3.84. The results of the ANOVA test are summarized in Table 3.4.

Table 3.4: Statistical Test

Factor	Effect	F - Value	> 3.84
A	-11.69	35.10	significant
B	-1.67	0.72	
C	-5.34	7.34	significant
D	7.04	12.72	significant
E	-11.67	34.97	significant
F	-5.95	9.08	significant
AE	-9.55	23.41	significant

According to the results all effects are significant, except for effect B. The sign of the effect tells us whether the effect yields an increase or decrease in the response. Taking these signs into consideration we conclude that all hypotheses can be accepted, except for H2 and H7. Factor B, hypotheses H2, has a negative effect, thus the potential effectiveness of FMP tends to decrease a little with an increase in the number of items. The effect, however, is not statistically significant. Therefore, we suspect that the effectiveness of FMP is rather invariant to the choice of the priority rule which is used to schedule failed units into repair. We exclude factor B and set it to a low level in the further analysis.

The statistical significant effects are not necessarily also relevant from a practical point of view. Effects are relevant when they result in a substantial improvement in the fill probability. The increments and decrements in the fill probability are depicted in Table 3.5. In this table we have included for each RIS - that is for each combination of the factors A, C and D - the average simulated fill probability under the application of the benchmark policy f_{bm} and the increment or decrement of the other policies Δf with regard to this fill probability. Δf_{-+}, for instance, represents the fill probability for the RIS under the application of FMP policy E-F+ minus f_{bm}. Increments or decrements smaller than 1% we do not consider substantial and are, therefore, deliberately not included in the table.

Table 3.5: Practical Relevance

A	B	C	D	f_{bm}	Δf_{--}	Δf_{+-}	Δf_{-+}	Δf_{++}
-	-	-	-	54.0	5.6	4.4	5.1	1.7
+	-	-	-	57.8	4.9	-4.5	-2.9	-5.5
-	-	+	-	51.2				
+	-	+	-	60.5				
-	-	-	+	95.6	4.0	3.7	3.9	3.6
+	-	-	+	97.0	2.9	-1.6	1.4	-6.3
-	-	+	+	95.7	1.0			
+	-	+	+	95.4				

Table 3.5 shows that in quite a number of RISs no substantial improvements can be obtained by using FMP. For those RISs where FMP is effective, the maximum increments amount to some 5% under the given settings for the parameters. In numerous RISs the use of FMP is ineffective. Decrements in the fill probability, due to the use of FMP, can also amount to some 5%. Apparently it is important to consider the characteristics of the RIS previously to introducing FMP.

The relevance of the main factors A, C and D can be established by a mutual comparison of the values in column Δf_{--}. The relevance of factor A, the demand level, can be determined by a comparison of the increment in the fill probability of the first and second RIS. The results show nearly the same improvement, thus the scope for improvement is very similar in both RISs. It appears that factor A is not relevant. The most powerful effect stems from factor C, the utilization of the manpower. Noticeable is the fact that, for all RISs with ample manpower, the use of FMP results in hardly any effect. Accordingly, the use of FMP should only be considered in RISs which operate under tight manpower constraints. The effectiveness of FMP seems to be rather invariant to the setting of the target fill probability, i.e. factor D. A comparison of the improvement for the first and fifth RIS hints that an increment from 50% to 55% requires a similar level of manpower flexibility as an increment from 95% to 100%. This is a very important result. It is well-known that the fill probability increases less than proportional with the initial stock level. See for instance Table 3.2, where a doubling of the fill probability requires more than a doubling of the initial stock level. Thus FMP is especially an appropriate substitute for initial stock for RISs which operate under high service level targets.

The relevance of factor E, the leadtime to announce a change in day length, can be determined upon a comparison of the values in column Δf_{--} with the values in column Δf_{+-}. All values in column Δf_{+-} are worse than the values in Δf_{--}, thus an increase in the leadtime has a negative effect on the fill probability. It can even result in an important decrease in the fill probability. The relevance of factor F, the operational duration of a changed day length, can be determined upon a comparison of the values in column Δf_{--}

with the values in column Δf_{-+}. The conclusions for the factors E and F are the same, though the effect caused by factor F is not as strong. The factors E and F reinforce one another, especially in a negative sense. Important decrements in the fill probability can be obtained when both factors are set to a high level.

For low-demand RISs, the success of FMP depends merely on the operational constraints for the RIS. In these RISs FMP should only be considered in combination with a high manpower utilization and a high service level target. For high-demand RISs not only the operational constraints but also the characteristics of the FMP policy are important. FMP policies in high-demand RISs must be very adaptable. With this we mean that day lengths can be reset quickly.

The use of rigid FMP policies is to be avoided in RISs with high demand levels and short repair times which operate under tight manpower. This can be explained as follows. In combination with high demand the status of the WIP changes rapidly. Apparently the current WIP status is not a graduator for the WIP status next week. In determining the length of the working days next week on the basis of the current WIP status two errors may be made. Next week's working days are set too long or too short. The first type of error will hardly result in any effect on the fill probability. The second error, however, will result in a considerable drop in the fill probability, especially when the RIS is operating under tight manpower. Apparently, in RISs with high demand and short repair times and ample manpower and rigid FMP policies (AE and AEF) this drop in the fill probability cannot be compensated by proper day length adjustments.

From the results it is evident that the potential benefit of FMP in RISs depends on a mixture of the demand characteristics, the operational constraints of the RIS and the characteristics of the applied FMP policy. Only in situations where on the basis of the results in this chapter a positive contribution may be expected, the introduction of FMP should be considered in practice. In that case the FMP factors must be coordinated together with other factors responsible for the control of a RIS as well with cost factors. In practice, the responsibility for control is allotted to different management levels. To support these management levels in taking their decisions, we introduce a framework for the control of a RIS in Chapter 4. The use of FMP is embedded in that framework.

4. Framework for Control

In Chapter 1 we defined control as: "The coordination of activities that have the purpose to buffer against (the variations in) demand and repair throughput time in order to achieve a target at minimum cost." The coordination of the activities is accomplished by a set of decisions, made by managers at different hierarchically ordered levels in an organization. The relation between these decisions is visualized in a framework for control.

In the early literature on planning and control theory, it is assumed that a management decision can be assigned to a level in the framework on the basis of its impact and its repetition frequency (e.g. Anthony [1965]; Bitran and Hax [1977]). Three types of decisions are commonly distinguished in this approach. The strategic decisions at the highest level, the tactical decisions at an intermediate level and the operational decisions at the lowest level of control. Clearly, as we descend in the framework, the higher is the repetition frequency of the decisions and the smaller is their impact.

In our definition of control we explicitly mention the minimization of costs. Cost minimization requires the simultaneous consideration of all decisions bearing an important cost aspect. Such decisions, however, can be strategic, tactical or operational. If we would follow the traditional train of thought, the decisions with an important cost aspect would be scattered over different control levels in the framework and, as a consequence, a joint cost consideration is impractical. It is advocated, therefore, in the more recent literature that important cost factors should be considered at one decision level in the framework, irrespective of their repetition frequency and operational duration (Bertrand et al. [1990]; Schneeweiß [1995]). At this level, the cost are simultaneously minimized subject to a target constraint, formulated by the management on a higher level in the organization. The cost minimization yields directives that are handed over to the next lower level where the operational control is executed.

The directives for the operational control could in principle be determined with the help of a detailed monolithic mathematical model. Such an approach, however, has two disadvantages. First, from a mathematical point of view the construction of a detailed model which accounts for the main characteristics of an entire RIS would be an extremely complex task. Rather we would construct a number of simple loosely connected models. Secondly, the responsibility for decision-making within organizations is spread over a number of organizational departments. If all managers of these departments would be supported with only one model, then they would be jointly responsible for the realized performance for the entire RIS. When deviations between the realized and target performance occur, it is not difficult to imagine that they would be easily inclined to seek for explanations in one another's department. In other words, the derivation of directives with the help of a single monolithic model would not fit the organizational structure of the RIS. Rather we construct a model, define a target and measure a service level for each organizational department. These targets are not mutually independent. They can be deduced from a management goal with the help of a rough mathematical model.

In our view, the framework for the control of a RIS should contain three hierarchically ordered decision levels, see Figure 4.1: target coordination, structural control and operational control. In the *target coordination*, manpower and initial stock are roughly balanced for the entire RIS. In addition, targets for each organisational department are derived from a management goal. The targets form the input for the *structural control* of each separate organizational department within the RIS. In the structural control, the (combination of) means to achieve the target are evaluated on costs and practical motives for each department individually. Directives are determined for the *operational control* of the individual organisational departments. With the help of these directives the working day lengths are determined and the progress of the work within the departments is controlled.

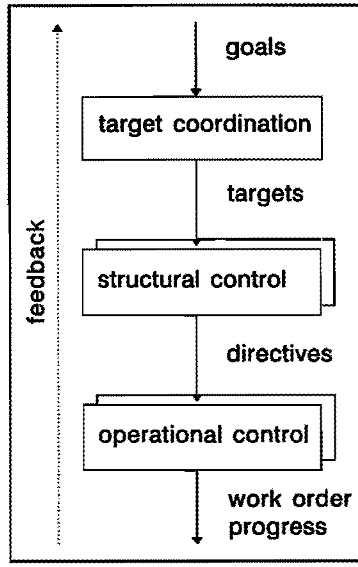

Figure 4.1: Framework

Regular feedback of information is important to improve the process of control. Information with respect to the realized performance by the organisational departments must be fed back to the management that is responsible for the target coordination of the entire RIS. Information regarding the realized service levels, the stock levels, the manpower levels and the manpower flexibility, i.e. the day lengths must be fed back to the managers that are responsible for the structural control of the departments. Finally, information regarding the speed and quality of the repairs must be fed back to the management that is responsible for the operational control of the departments.

When feedback information regarding the realized performance is compared with the anticipated performance there can exist a discrepancy. This discrepancy can be caused by: (i) deviant conditions, (ii) deviant behaviour of the repair men, (iii) a poor model or (iv) poor input data used at the outset. In the first case, an analysis of the discrepancy can be used to better anticipate the conditions in the following period. In the second case, an analysis of the deviations can be used for the reeducation of the repair men. In the third case, an analysis of the discrepancy can result in an improvement of the models. In the fourth case, an analysis of discrepancies can result in a better data collection.

4.1. Target Coordination

Management goals at a high level in the organization are generally formulated in rough terms, e.g. "Our organization must realize a 95% service level to the customer". In case of a complex RIS, see for instance Figure 1.1 in Chapter 1, this goal refers to the required performance for the downstream stock locations. It is by no means a performance measure for the management of the repair departments. The notions for "customer" and "organization" are different on distinct levels in the RIS. In our view a RIS is a collection of organizational departments, each department with own customers and run by a management with a need for own targets. Two kinds of organizational departments can be distinguished in a RIS: (1) Stock locations under the responsibility of store managers and (2) Repair departments under the responsibility of foremen, see Figure 4.2. Only the locations for the stocking of serviceable end-items we regard as organizational departments. Stocks for the lower-indenture items we consider work in progress and consequently they are the responsibility of the management of a repair department.

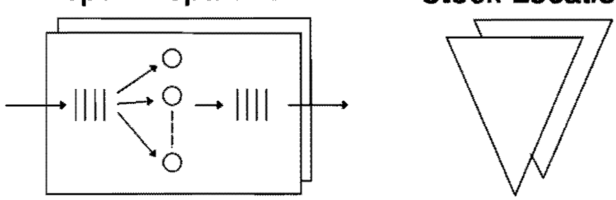

Figure 4.2: Organisational Departments

In the target coordination, targets for each organizational unit within the RIS are deduced from the roughly formulated goal statement. The deduction can be supported by a mathematical model which represents the behaviour of the entire RIS. It is clear that the construction of a detailed mathematical model for a RIS with multiple stock phases and repair levels is a complex task. Rather we put up with rough models, for instance the METRIC type models (Sherbrooke [1992]). These models are particularly rough in assuming uncorrelated repair times and a FCFS priority rule to schedule failed units into repair. Other less critical assumptions underlying these models are explained in Chapter 2, Section 2.1. The assumptions result in a slight over estimation of the performance measures, especially when the utilization of the manpower is high (Gross [1984]). In many cases, however, the METRIC models are quite an accurate representation of the processes in a RIS, see for instance the studies of Scudder and Hausman [1982] and Sherbrooke [1984] who compare METRIC models to detailed simulations. Other more complex models are available for those cases where METRIC is not an adequate representation (Ahmed et al. [1992]).

Hence we illustrate how targets can be deduced from a goal with the help of METRIC and MOD-METRIC. METRIC, for the calculation of stock levels in a RIS with multiple stock phases, and MOD-METRIC, for the calculation of stock levels in a RIS with multiple repair levels. These models were developed in the seventies at the RAND corporation and implemented at the US Air Force. In determining the initial stock for each stock location, these models minimize the number of expected back orders at the downstream stock locations subject to a budget constraint. When these stock levels are filled in in equation (3.1) in Chapter 3, fill probabilities are obtained for the stock locations (METRIC) and the repair departments (MOD-METRIC). These fill probabilities serve as targets. A combination of METRIC and MOD-METRIC can be used to derive stock levels in a RIS with multiple stock phases and multiple repair levels (De Haas and Verrijdt [1994]). We obtain the targets for this RIS in a two-step routine.

STEP 1: Targets for the Stock Locations

The METRIC model is initialized with data concerning demand rates, stock replenishment times, and with a goal, i.e. a desired fill probability over all downstream stock locations. The size of the initial stock is increased in a number of iterations. In each iteration METRIC allocates the initial stock to the various stock locations. On the basis of the stocks in each location, the expected fill probability for each stock location is determined using equation (3.1) in Chapter 3. In addition, the fill probability over all downstream stock locations together is determined using equation (3.2). The iterations stop when the fill probability over all downstream stock locations attains the goal. The fill probability for an individual stock location serves as a local target for the store manager of that location. The initial stock levels at each individual stock location have the function of replenishment levels. The serviceable stock for an item can be operationally controlled by means of a (S,S-1) stock replenishment policy. If the METRIC model, though rough, is a robust representation of the RIS, the proposed stock control procedure must result in the attainment of the targets in reality. Besides target, the fill probability for the central stock location is also used as an input parameter for the MOD-METRIC model.

STEP 2: Targets for the Repair Departments

The MOD-METRIC model is initialized with data concerning demand rates, repair throughput times and with the target fill probability for the central stock location. In an iterative procedure, similar to the one described in step 1, MOD-METRIC calculates the initial stock levels for the lower-indenture repairable-items such that the fill probability for the central stock location can be achieved. On the basis of the stock levels, the fill probabilities for each indenture of the repairable-item are deduced, using again equation (3.1). The fill probabilities of all repairable-items, processed within the same repair department, are averaged using equation (3.2). The averaged fill probabilities serve as targets for the repair departments.

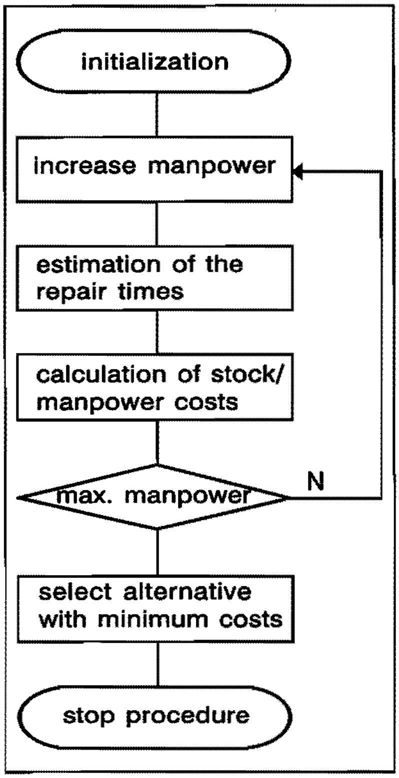

Figure 4.3: Target Coordination

The model can be used in an evaluation procedure for the determination of cost effective alternatives, see Figure 4.3. Initially, the repair men operate under a high utilization. When the number of repair men increases their utilization decreases and, as a consequence, also the repair throughput times decrease. This relation between manpower and repair throughput time can be estimated empirically or with one of the models available in the Operations Research literature, e.g. Graves et al. [1993]. After estimation of the repair throughput times, the stock levels and targets can be calculated with the forementioned two-step routine. When the number of repair men and the initial stock levels are filled in in a cost function, an estimation for the costs is obtained. This procedure can be repeated a number of times. After some stop criterion is met, for instance on the maximum manpower, the alternative with the lowest costs is selected. The targets associated with this alternative are imposed upon to the management of the repair departments.

4.2. Structural Control

A target for a repair department, resulting from the target coordination can be obtained with (a combination of) four means. These are: (i) the investment in initial stock, (ii) the employment of manpower (iii) the use of an FMP policy and (iv) the use of a priority rule to schedule failed units into repair. All four means must be considered simultaneously on cost and practical motives for each repair department individually.

To support this consideration we propose to construct a detailed simulation model for each repair department. The models are initialized with the characteristics of the repair departments, a set of priority rules and a constant working day policy. The set of priority rules can contain complex dynamic priority rules or simple static rules that proved robust in practice. For each priority rule the initial stock is determined with the help of the simulation model. This is not necessarily time-consuming for there are ample analytical techniques available in the literature which are able to quickly determine a rough estimate for the initial stock level subject to a target constraint, see for instance Schneeweiß and Schröder [1992]. In fact, the simulation model is only used for fine tuning.

After a suitable priority rule is selected, a number of manageable FMP policies are evaluated on a cost basis with the help of the procedure in Figure 4.4. In this procedure, the repair men initially operate under a high utilization. When the number of repair men increases, their utilization decreases and, consequently, the service level will improve. We are however not interested in a better service level but rather in obtaining the target service level at lower cost. Therefore the initial stock is reduced in a number of iterations until the target service level is just attained. Now the total cost for the initial stock and the employment of the repair men are calculated. Then an FMP policy is introduced and a number of simulation runs is required to find the FMP parameters. A suitable policy will force up the fill probability needlessly. To prevent this the initial stock is again reduced in a number of simulation runs until the target is just attained. Now the total cost can be calculated under the condition that an FMP policy is applied. This procedure is repeated for a number of FMP policies and manpower levels until some stop criterion is met. The procedure yields a number of feasible options, with and without FMP, along with an estimate of their costs. From these, a manageable option with reasonable costs is selected. The required initial stock and manpower levels are fed back to the target coordination for approval. Note that at the target coordination estimates for both factors are available from the rough balancing for the entire RIS. The selected priority rule and FMP policy are placed at the disposal of the foreman who is responsible for the operational control of the repair department.

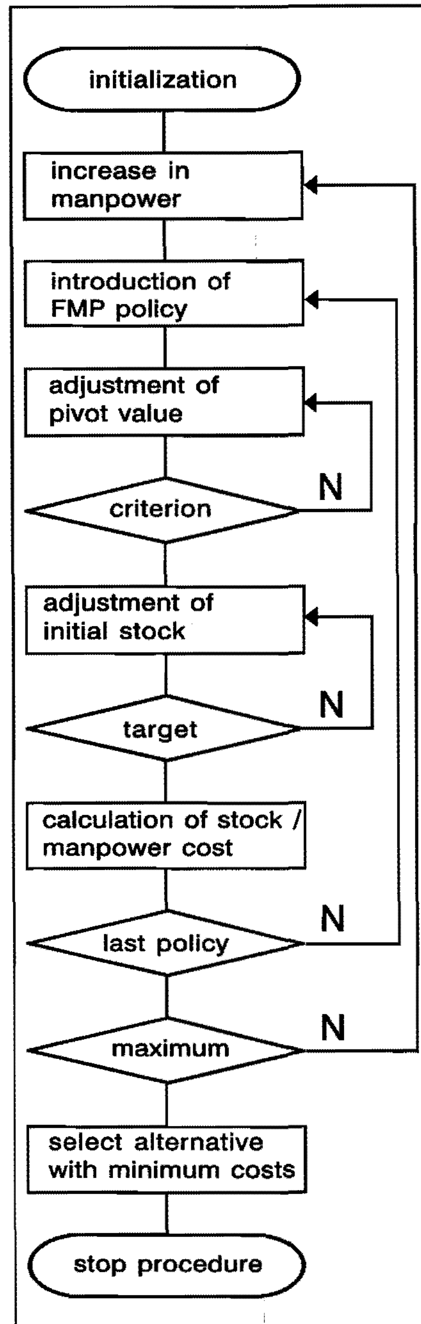

Figure 4.4: Structural Control

The quality of the procedure increases with the number of evaluated options, however so also does the simulation time. More options can be evaluated in the same time if analytical models become available. Such could be the field of further research for mathematicians.

Critical in the selection of an attractive option is the cost valuation of initial stock and flexible manpower over a certain horizon. Cost valuation is not trivial as it is often difficult to establish which costs are affected by the considered control decisions. The cost evaluation must also suit "ongoing" RISs. Manpower (flexibility) and initial stock in ongoing RISs is available from an investment in the past. With the loosening restrictions in respect of the use of FMP, the main trade-off in RISs today concerns the exchange of initial stock for manpower flexibility. In our discussion we restrict ourselves to this trade-off and base it on cash flow considerations over some horizon. The length of the horizon is determined by the factor with the longest financial commitments, i.e. manpower or initial stock.

The intermediate sale of initial stock would result in a positive cash flow at time zero, equal to the sales value. The negative cash flow, attended with the introduction of FMP is quite arduous. In a discussion with representatives from employer's organizations and unions it became clear that the valuation will depend on the branch of industry and, within the branch, on the particular organization. The representatives shared the view that the introduction of FMP, if rewarded at all, will result in a higher salary for the repair men rather then in all sorts of allowances. They expect that the compensation will depend on the time between announcement and implementation of day length variations "ℓ" and on the maximum permitted deviation from the standard day length "ΔD". Other factors they considered of minor importance. To determine the impact of the use of FMP on the cash flow more accurately, further research is required by economists.

For a formal presentation of the cash flows, attended with the sale of initial stock and an investment in manpower (flexibility) we identify the following variables:

- The cash flow attended with resale of salvage of the initial stock at time 0 is c_0.
- The cash flow attended with FMP in year k is c_k.
- The time span of the financial commitments is T years.
- The earning power per annum of the RIS is i.
- Some function of the FMP costs is $f(\ell, \Delta D)$.
- The net present value of the trade-off is V.

The net present value of the trade-off is

$$c_k = -f(\ell, \Delta D) \qquad \wedge \qquad k \geq 1$$

$$V = \sum_{k=0}^{T} \frac{c_k}{(1+i)^k} \quad . \tag{4.1}$$

An exchange of initial stock for FMP is attractive when $V > 0$.

4.3. Operational Control

Operational control refers to the problem of coordinating the progress of the repair orders through the departments of the repair shop. The operational control in a complex repair shop with one repair level is addressed in a case study by Bertrand, Wortmann and Wijngaard (BWW) [1990]. In this section we incorporate the main ideas for the control of a single department and refashion these into an approach for the operational control of a repair department within a RIS.

For the operational control of a single repair department, BWW introduce the following procedure. Regularly and depending on a comparison of the current status of the WIP in the department with a workload norm for that department (stated in terms of manpower) it is decided how much work to release in the department. On the basis of a comparison of the status of the serviceable stock for the department with a priority rule it is decided which work orders to release. In the decision function *dispatch* both types of information are linked and the work orders are released to the repair department. A work order includes a number of process steps which must be carried out before a certain due date. The progress of the work order through the process steps is controlled by *internal due dates*, set by the foreman of the repair department. Due to the uncertain character of repair work there still remain some variations in the WIP. In reaction to these unexpected variations BWW propose the use of *manpower flexibility*. It pertains to the use of overtime and the allocation of repair men within the repair department.

The use of overtime, like FMP, causes changes in the lengths of the working days. We assume that these deliberately pursued changes can be incurred with substantial costs and therefore we rather account for them already at the structural control level. For the (re)allocation of repair men to the repair work, on the other hand, we assume that costs are not incurred. On the basis of these cost considerations we decompose the decision function "capacity adjustment" into two separate functions: *Flexible Manpower Planning* and *allocation of repair men within the department to the repair work*. The FMP function determines the length of the working days on the basis of a comparison of the FMP parameters resulting from the trade-off at the structural control and from the status of the WIP(t^*-ℓ) in the repair department. The working day length, in turn, influences the manpower. Note that the manpower level affects the workload norm which is used in the dispatch function. Thus the number of dispatched work orders increases (decreases) with an increasing (decreasing) manpower level available. In another decision function, the repair men are allocated to the repair work on the basis of considerations other than economical, e.g. the skills and the experience of a repair man or his ability to work a certain number of working hours on a particular working day. Parallel to the BWW study the progress of the work orders is controlled by internal due dates which are set in accordance with the current status of the WIP, see Figure 4.5.

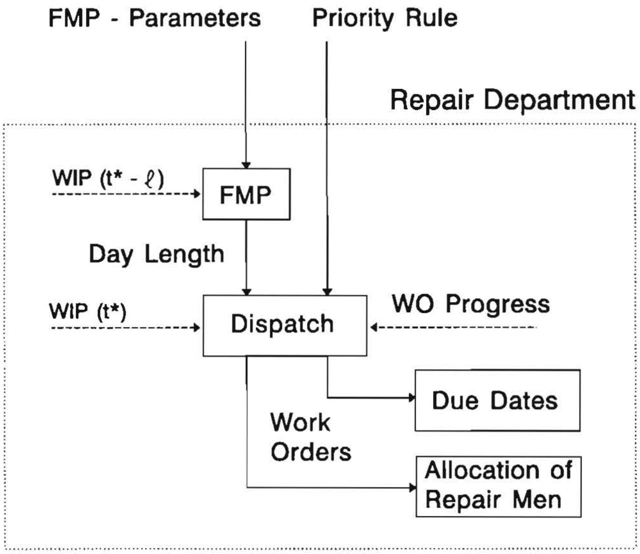

Figure 4.5: Operational Control

A noticeable difference, in comparison with the BWW study, is the situation of the dispatch function in the repair department. Dispatch, in their study, is used to coordinate the progress of the work orders over the repair departments and therefore the responsibility for this function is outside the scope of the foremen. RISs, however, can do without this coordination function due to a remarkable result of Hausman and Scudder [1982]. In their simulation study of a RIS with multiple repair levels and departments they show that the performance of priority rules, not accounting for status information in other repair departments, are as good as the performance of the priority rules that do include such information. Thus the need for operational coordination between the departments disappears. In that case the responsibility for the dispatch function can be allotted to the foremen of the repair departments.

Sofar, we developed a decision structure for a RIS in which repair men do not possess the skills to work in other repair departments. If FMP would be applied in this situation it can happen, on a particular working day, that the repair men in one department are working less hours than standard whereas at the same time the repair men in another department are doing overtime. If repair men would be multi-skilled and able to perform work in other departments they could be transferred in order to equalize the day lengths over the departments. This transfer of repair men may not affect the required manpower level in the departments. We illustrate this with a simple example. Consider a RIS with two repair departments, each usually occupied by five repair men. The required manpower for department one on a particular day is 30 hours. The requirement for department two is 45 hours. Consequently the five repair men in department one have a working day of 6 hours and the repair men in department two have a working day of 9.5 hours. If one repair man could be transferred from department one to department two than all men would have a working day of 7.5 hours. The manpower in repair department one is still 30 hours. The manpower in department two is still 45 hours.

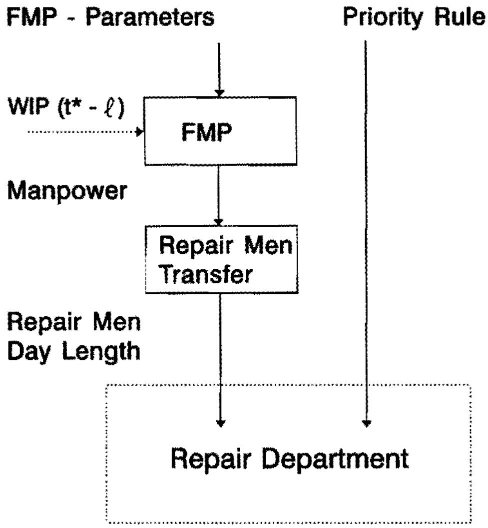

Figure 4.6: Repair Men Transfer

For the exchange of repair men between departments we introduce a new decision function "repair men transfer", see Figure 4.6. The decision function clearly is a coordinating function over the departments, thus the responsibility for this function must be situated outside the scope of the foremen. While the input for this decision function is provided solely by the decision function "FMP", also the responsibility for FMP must be raised to a higher level and, consequently, is put outside the scope of the foremen. The input for the repair men transfer function is comprised of the required manpower level, the proposed day length and the proposed number of repair men for each repair department. In this decision function the differences between the working days per department are minimized subject to the manpower constraint for each repair department. The minimization procedure yields a new proposal for the number of repair men per department and their working day length. The proposal can result in the transfer of repair men between the repair departments.

5. Case Study

In Chapter 4 we introduced a framework for the control of a RIS with multiple repair levels and multiple stock phases. With the help of this framework we assess a current decision structure used in practice for the control of a RIS with these characteristics. The assessment enables us to formulate recommendations for improvement of the current decision structure. These recommendations, which are the conclusions of the author, have been discussed with the management of the RIS. On the basis of this discussion we establish whether the use of the framework offers scope for improvement of the control of RISs in practice and, in this manner, we establish the practical relevance of our study.

5.1. Jet-Engine Overhaul

KLM, the Dutch national airline, operates a fleet of aircraft for the transport of passengers and cargo. During aircraft maintenance, the condition of the jet-engines is compared to a set of norms. When the condition is not in accordance with the norms a jet-engine is termed failed. Failed engines are replaced from stock by serviceable ones. Failed engines are sent off for repair to CF6, a specialized repair facility at Schiphol Airport in Amsterdam. When a repair is completed the then serviceable engine is stored at one of the main airports in support of a future engine replacement.

In this case study we concentrate on the repair facility CF6. The facility employs 600 workers, 450 of them are repair men, working in two shifts five days a week. The repair men overhaul approximately 200 engines annually, which enter CF6 irregularly and often unexpectedly. The layout of CF6 corresponds with the product structure of a jet-engine. A jet-engine is a complex multi-indenture item. It consists of a number of modules which in turn consist of a number of parts. For the repair of the engines, the modules and the parts, CF6 comprises of ten repair departments. In one department the engines are inspected, dismantled, assembled and tested. The failed modules are transferred, depending on the kind of module, to one of the three module repair departments. There the modules are dismantled into parts, assembled and tested. The failed parts are transferred to a "common" department where they are cleaned and examined for the existence of cracks. After that the repair requirements can be determined. On the basis of these requirements it is decided whether the repair of the parts must be subcontracted (40%) or carried out in one of the six internal part repair departments (60%). The repaired parts are returned to the module repair department where they originated. The repaired modules are returned to the engine repair department. The structure of the RIS is depicted in Figure 5.1. The downstream stock locations in this figure are not under the control of CF6.

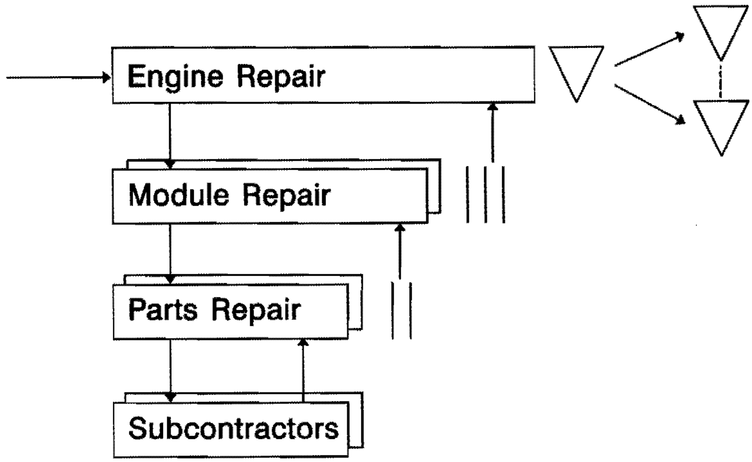

Figure 5.1: RIS for the Overhaul of Jet-Engines.

For the repair of a jet-engine there are two options: (1) A quick *pool repair* in which the failed modules and parts of an engine are replaced by serviceable ones. The failed modules and parts are repaired at a later stage and can be subsequently used for the pool repair of another engine of the same kind. This repair procedure requires the existence of a pool of modules and parts. The pool consists of about 35 kinds of modules and about 1500 kinds of repairable parts. (2) A lengthy *Time & Material (TM) repair* in which the failed modules and parts are repaired and put back in the original engine. A pool repair requires an investment in the pool. The depreciation of this investment is accounted for by CF6 in the price for a repair. A pool repair is therefore more expensive than a TM repair. A TM repair, on the other hand, requires a longer repair throughput time than a pool repair and, consequently, a higher investment in spare engines for the customer. Pool customers commit themselves with lengthy contracts because of the investment in the pool. For TM customers shorter contracts, i.e. three years, are more common. CF6 considers concluding even shorter TM contracts in the future. In this case study we limit our attention to the control of pool repairs alone. Currently, they account for 85% of the repairs.

Engine repair is characterized by a great level of uncertainty. First, there is uncertainty in demand on the short term. Failures occur irregularly and cannot accurately predicted. Secondly, there is uncertainty in the work content of a repair. Detailed information becomes available only after parts have been cleaned and inspected. Thirdly, there is uncertainty in the routing of a repair. Accurate information for the establishment of the routing becomes available after an engine is dismantled and repair requirements become known. As a result of the great uncertainty control is a difficult issue. For a number of years the control issue has been receiving attention from the management of CF6.

5.2. Current Decision Structure

In former years, the purpose of engine overhaul was strictly the provision of support to the fleet of aircraft of the KSSU partners. KSSU was until recently a consortium which consisted of four partners including KLM. In the latest decennium the competition increased. KLM promoted itself as a reliable airline, operating its schedules on time. An unplanned "aircraft on ground" could blemish this image and, therefore, sharp goals where formulated for all maintenance departments, and thus also for the engine overhaul shop. Currently, the market for jet-engine overhaul is characterized by excessive capacity. To cover the surplus, CF6 is promoting jet-engine overhaul to third parties. As a result of all this, CF6 is facing increasingly tight customer requirements and a more professional control approach is required. Within the frame of this professional approach, the management of CF6 started with the establishment of ten self-empowered repair departments. The operational control for each repair department was put under the supervision of a foreman. Two years ago CF6 developed a new decision structure for the control of pool repairs. Currently, a new structure for the control of TM repairs is being developed. In this section we focus on the decision structure for pool repairs. Within this structure we distinguish three hierarchically ordered decision levels. In line with the jargon in this dissertation, we term these levels: target coordination, structural control and operational control, see Figure 5.2.

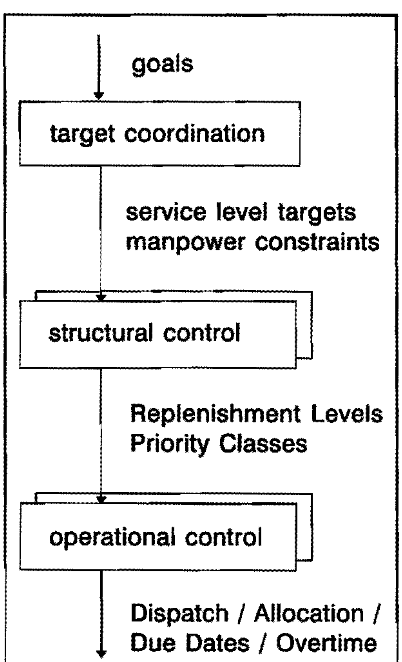

Figure 5.2: Decision Structure CF6.

Target Coordination:

At the highest management level in the CF6 organization, service level targets are formulated for the repair departments: 90% for the engine repair department, 80% for the module repair departments and 70% for the part repair departments. The targets were formulated long ago and are not clearly defined. It is for instance not clear to the middle management of CF6 whether they are defined per repairable item or a weighing over all items.

As a result of the poor economic situation in recent years, the middle management of CF6 were advised to be parsimonious in the employment of extra repair men. So, in addition to the targets, manpower constraints are also imposed upon the management responsible for the structural control of the repair departments.

Structural Control:

The structural control is carried out for each repair department individually. At this decision level the target service level and the manpower constraints, coming from the target coordination, are translated into parameters for the operational control of the departments. The decisions regarding the structural control are mainly concerned with the determination of the initial stock (pool). The formulae to determine the initial stock per item are incorporated in the software and are not easily accessible today. We have the impression that the formulae are deduced from the classical (S-1,S) formula (Feeney and Sherbrooke [1966]). S, in this formula, represents the initial stock per repairable item. The items are divided among two classes by CF6. A class of items, the more expensive ones, receive priority in the repair process which results in a shorter average repair throughput time and a lower initial stock for these items. As a consequence the other, less expensive, items have an otherwise longer throughput time and larger initial stock. It appears evident that the mix over all items is more economic than it would be when the priority classes have not been taken into account.

Operational Control:

This decision level is concerned with the dispatching of work orders to the departments and the control of the progress of these work orders within the departments. The dispatching of work orders is supported with replenishment levels. According to the classical (S-1,S) stock replenishment policy, a work order is created when the number of serviceable units drops below the initial stock S. At CF6 the replenishment level is set equal to a lower level than S for cost accounting reasons. Repair is added value, increasing the value of the stock and, therefore, the stock costs for CF6. From a cost accounting point of view it is more economical to stockpile failed than serviceable units. A share of failed stock is maintained when replenishment levels are deliberately set to lower values.

Work orders are passed on to the foremen of the repair departments. In principle they must determine the repair sequence of the work orders with the help of the two priority classes. According to these classes, all units of the expensive priority class must be processed first. Sequencing in line with these "static" classes, however, would frequently result in a stock out of the inexpensive items. To prevent this, the foremen deviate regularly from the principle and base priorities on current demand and shop information. They process the most urgent work orders first, independent of their priority class.

At the beginning of each shift the foremen allocate the repair men to the released work orders. The process of allocation is rather straight forward because the vast body of repair men is multi-skilled and able to carry out various tasks within the repair department. The foremen set due dates for the completion of the work orders and verify their progress.

Due to the uncertainty in demand, work content and routing, the repair departments are periodically confronted with unforeseen temporarily high peeks in the WIP. These peaks result in arrears of the work orders. To make up arrears, the foremen appeal to the willingness of the repair men to work in overtime. Overtime is worked on average two hours per shift per day approximately. Working overtime is accepted by the repair men because of the attractive financial compensation. When severe arrears arise the use of overtime is authorized by the middle management of CF6 and, when necessary, repair men are temporarily transferred from or to other departments.

5.3. Assessment

A comparison of the current decision structure for the control of CF6 with the ideas that are put forward in Chapter 4 of this dissertation highlights some similarities. In both approaches there is a three-tired decision structure and the highest decision level yields the targets for the repair departments. Also, in both cases the middle decision level is for the derivation of the control parameters for a department. With the help of these parameters, the progress of the work orders is coordinated through the repair departments. With regard to the enactment of the decision levels, there are some notable differences.

Target coordination:

Similar to current practice at CF6 we propose to set target service levels for each repair department individually. In contrast to CF6 we deduce these targets from the management goals with the help of a mathematical model. We showed that well-known models in the literature, such as METRIC and MOD-METRIC, can be used to derive these targets. Using these models we constructed a routine for the deduction of targets for each repair department in a RIS with three repair levels and two stock phases (De Haas and Verrijdt [1994]). In a numerical analysis, the management goal was set to "greater than 95% service" and targets for the repair departments where deduced under a wide range of settings for demand and repair throughput times. In general we calculated service level targets for the repair departments varying from 50% to 70% which were approximately 20% lower than the current targets. Based on this numerical analysis we have the impression that the current service levels targets are set unnecessary high. These targets form the input for the determination of the initial stock. Initial stock levels generally increase more than proportionally with the service level target. Setting the targets for the repair departments to lower values will therefore result in considerable savings in the initial stock costs (> 20%) without necessarily affecting the service to the customers. What does change are the initial stock levels.

Structural Control:

The attainment to a service level target requires an investment in initial stock and manpower. Both are related. Imagine an increase in the number of repair men. This would result in a lower manpower utilization and, consequently, a reduction in the repair throughput times. A decrease in the repair times, in turn, would allow a decrease in the initial stock to attain to the same target. To obtain a minimum investment in initial stock and manpower, both investments must be balanced. The balancing issue can be refined and improved by including advanced priority rules and manpower flexibility. Priority rules are either static or dynamic. Dynamic rules, unlike static ones, account for current demand and shop information and generally result in a better performance, i.e. up to 20% (Hausman and Scudder [1982]). These substantial savings could make the use of a dynamic rule worthwhile for CF6, in spite of the increased control complexity. On the basis of the results in Chapter 3 we assume that the use of overtime is only effective in those departments which operate under high service level targets. Consequently, the use of overtime is not effective, except maybe, for the engine repair department.

Currently, the decision power at CF6 for the initial stock, the manpower, the priority rule and overtime is allotted to three different decision levels. Manpower investments are restricted at the target coordination level, initial stock investments and the priority rule are simultaneously considered at the structural control level and overtime costs are considered at the operational control level. The allotment of different cost factors to different decision levels hampers a simultaneous cost consideration and results in suboptimization. We recommend to allot the responsibility for all cost factors to the structural control level.

It is difficult to determine the savings that would have been obtained by a more coordinated balancing of the costs without having had access to detailed information and without having detailed models at our disposal which apply to CF6. On the basis of interviews with foremen, however, we have the impression that in some departments (crack control and engine repair) the repair men are fully occupied. It is likely that the savings on manpower in these departments in recent years have been offset by the expenditure on a costly initial stock. With respect to the overtime costs, about one million USD annually, we doubt, on the basis of the results in Chapter 3, whether these have contributed to an increased service to the customers.

Operational Control:

Work orders are released to the repair departments following a comparison of the current number of serviceable units with the replenishment levels. This approach is ambiguous. Initial stock is purchased in reaction to demand variations. Thus the number of serviceable units should be allowed to fluctuate in time. As a result of the use of replenishment levels, however, CF6 tries to maintain a constant level of serviceable stock. Instead, the repair men are having to deal with demand variations, which creates pressures and results in overtime. We recommend to release work orders when manpower is available rather than upon a comparison with replenishment levels. For a single item we analyzed the setting to lower replenishment levels within CF6 than would generally be suggested in the literature. The analysis was supported with the product-form-network, introduced in Appendix B. Repair rates ensuing from states greater than the replenishment level were set to zero in the model. It appeared that the realized service level decreased with a decrease in the replenishment levels. Probably the artificial savings in the cost accounting are offset by real costs for the additional means to compensate for the loss in service level. If CF6 proceeds dispatching work orders with the help of replenishment levels, we suggest that these levels are set equal to the initial stock for each item.

The sequencing of the work orders is supported by static priority classes. Through experience, however, the foremen have learned that including the latest demand and shop information results in a better sequencing. On the basis of this information they often deviate from the priorities, determined in accordance with the static priority classes. In our view, better results and better support in the sequencing would be obtained with a dynamic priority rule. The use of overtime is not constrained by a higher decision level. For the foremen it is therefore difficult to establish if and when there is a need for overtime. We suggest that KLM continues to be reserved in the use of overtime until better directives from the structural control level become available.

5.4. Discussion

In a number of aspects the current decision structure can be considered for improvement. We recommend action with respect to the following issues.

1. Setting the targets for the different repair departments to lower values.
2. Reducing the initial stock levels in accordance with the lower target values.
3. Reallocating the decision power such that the responsibility for the cost of initial stock, manpower and overtime will be concentrated in one decision level.
4. Eliminating the stock replenishment level as a condition for the release of work orders to the repair departments. Instead work orders should be released when manpower is available.
5. Supporting the foremen with dynamic priority rules.
6. Restricting the use of overtime.

These recommendations were discussed with representatives of CF6 including foremen, middle management and consultants. Though some of the recommendations may seem quite radical, all were frankly discussed and judged upon their merits.

The first recommendation initially turned out to be counter-intuitive to those present, especially to the foremen. This can be explained by the fact that the foremen have another perspective of the "customer". Their customers are other repair departments. The recommendation was accepted after the results were put in the perspective of the entire RIS. The second recommendation was recognized by all. In recent years, units have been removed from stock without customers having complained. Moreover the repair throughput time decreased and, consequently, the initial stock could be further reduced. Recently, a further notable reduction in the initial stock is studied by consultants with the help of simulation models. Their results support our findings. The third recommendation was approved. In recent years, more and more decision power has been delegated to lower decision levels. Traditionally, the responsibility for the employment of manpower and especially the purchase of initial stock is allotted to a high decision level because of the investment that is involved. A possible reallocation of the decision power with respect to these factors has been discussed in the past and will be subject of discussion in the future. Our recommendation will fuel this discussion. Also the fourth recommendation was approved. The replenishment levels have been introduced only two years ago. Not satisfied with the setting of the levels, the topic has been discussed over and over by the middle management of CF6. At the moment the elimination of replenishment levels for dispatching purposes is being considered. The fifth recommendation was not approved. To maintain transparency in the sequencing, it was felt, especially by the consultants, that simple (static) priority rules are to be preferred. The sixth recommendation was approved but not approached with great enthusiasm. Currently, the use of overtime is employed in reaction to uncontrolled repair throughput times. The savings in initial stock resulting from a better controlled throughput time are, provisionally, considered more important than potential savings in overtime costs.

All participants agreed that the assessment of the current decision structure with the framework for control has resulted in interesting recommendations and a better understanding of the control problems. The recommendations, presented in this case study, will be included in future considerations for the improvement of the current decision structure. The fact that the recommendations are considered valuable by practitioners sustains the practical relevance of the framework for control that is presented in this dissertation.

6. Final Remarks

6.1. Conclusions

In this dissertation we addressed two research questions. The first question deals with the effectiveness of FMP in RISs. The second research question addresses the coordination of initial stock and flexible manpower in a framework for the control of RISs. Though both questions are relevant in practice, it appeared that they were little studied by academics.

On the First Research Question:

On the basis of a literature study it seemed plausible that the potential effectiveness of FMP is not only determined by FMP itself but also by the characteristics of the RIS. This assumption was the motive for our study on the effectiveness of FMP in RISs. In a simulation experiment we have studied several FMP policies in various RISs. The FMP policies differed with respect to (1) the measure of responsive change in day length, (2) the minimum day length, (3) the maximum day length, (4) the leadtime between announcement and implementation of a change in day length and (5) the operational duration of a changed day length. The RISs differed with respect to (6) the demand levels, (7) the number of items, (8) the manpower utilization and (9) the required service levels.

The effectiveness of FMP was measured in terms of a contribution to a service level. The results show that the conditions of the RIS have a stronger impact on the effectiveness of FMP than the characteristics of the FMP policy. With respect to the characteristics of FMP, it appeared that an increase in the measure of responsive change and an increase in the maximum day length contribute positively to the effectiveness of FMP. With just a little extra responsive change or just a little extra day length already a fair share of the maximum effect can be obtained. The effectiveness of FMP seems rather insensitive to the minimum day length. Lengthening the leadtime of announcement or the operational duration of a change in day length reduces the flexibility and, not surprisingly, reduces the effectiveness of FMP.

With respect to the characteristics of the RIS it appeared that, in combination with ample manpower, no significant contribution will emerge from the use of FMP. In RISs, facing tight manpower and high service level targets, the use of FMP is effective. Under the same conditions, however, the RIS is also the most sensitive to a worsening in the service level due to the use of FMP. This is the case for RISs where demand is relatively high, repair times are short, and the FMP policies rather rigid, i.e. with long leadtimes. Apparently, the introduction of FMP in practice should be approached with great care.

On the Second Research Question:

RISs in practice can be very complex in having various related stock locations and repair departments. In our control approach we decompose such complex RIS into a number of loosely connected self-empowered stock locations and repair departments. The control of these self-empowered units requires an involvement of different managers. To support these managers we have presented a framework for control. It comprises of three hierarchically ordered decision levels: At the highest level target coordination, at the middle level structural control and at the lowest level operational control.

At the *target coordination level*, manpower and initial stock are roughly balanced for the entire RIS. Targets for each stock location and each repair department are deduced from a management goal with the help of a mathematical model. Together with the targets, (serviceable) stock replenishment levels are deduced for the individual stock locations. On the basis of these replenishment levels the stocks can be operationally controlled. The targets form the input for the structural control of each separate repair department within the RIS.

At the *structural control level* the (combination of) means to achieve at the target are evaluated on costs and practical motives for each repair department individually. The evaluated means are the acquisition and control of the initial stock, the employment of repair men, the selection of the FMP-rule to schedule failed units into repair and the FMP policy to determine the length of the working days. The selected priority rule and FMP policy are passed on to the management that is responsible for the operational control of the repair department.

At the *operational control level* work orders are dispatched with the help of the priority rule and their progress within the repair department is controlled by due dates. In addition, the lengths of the working days are controlled by a decision function "Flexible Manpower Planning". In the proposed framework the working day lengths can be different for distinct repair departments at the same day. If this is considered undesirable and when the repair men are able to carry out repair work in other departments, an additional decision function "manpower transfer" can be added. The function balances the day lengths over the repair departments.

The framework was used to evaluate the decision structure of a repair shop in the Netherlands. The evaluation highlighted some weaknesses in the decision structure currently employed. These weaknesses were discussed with the management responsible for the structural and operational control of the shop. On the basis of the evaluation, adjustments in the current decision structure are being considered. Evidently, the framework for control proved to be a useful evaluation tool for practitioners.

6.2. Further Research

In this dissertation we commenced our research with a study of a very simple RIS. The simplicity enabled us to model the RIS and, with this model, we gained insight in the dynamics of the system under the application of FMP. We used this insight in the development of a framework for the control of more complex RISs. Important issues in this framework are the division of the RIS into self-empowered organisational departments and subsequently the structural and operational control of each individual organisational department. Underlying this study we have made many assumptions. Relaxing some of those would result in interesting topics for further research.

FMP in Practice:

In this dissertation, we have to a great extent ignored the human and the legal aspects of FMP. When introducing FMP it was assumed that the working behaviour of the repair men would not be affected. Clearly the introduction of FMP could be coupled with notable changes in the working conditions. The effect of these changing conditions on the working behaviour of the repair men would be an interesting topic for research within the behavioural sciences.

Legally the use of FMP is restricted, though these restrictions are liable to changes. At the moment the discussions between governments, employer's organizations and unions concentrate on legislation regarding the "time between announcement and effectuation of a change in the working day length", the "duration of a changed day length" and on the "maximum day length". The results in Chapter 3 of this dissertation show that all three notably affect the potential benefit of FMP in RISs. New legislation relating perhaps to health and safety issues as well as employment conditions is always possible. Legislation with a constraining influence upon, say, the leadtime of announcement, could annul the potential benefit which is ensuing from the use of FMP. Before revising legislation it is required that many more FMP policies are studied in many more situations.

Mathematical Approximations:

In the structural control of a repair department the costs for initial stock, manpower, priority rules and manpower flexibility are evaluated, subject to a target constraint. In Chapter 4 of this dissertation we have demonstrated how such evaluation can be carried out with the help of a simulation model. Simulation models, however, can be slow and are therefore not particularly suitable for evaluation purposes. A preferred option, if available, would be to fit mathematical approximations. This, however, requires a firm mathematical basis. We encourage mathematicians to develop these mathematical approximations.

Economic Considerations:

In this dissertation it is advocated that the costs for initial stock, manpower and manpower flexibility should be jointly considered. Pitfall in this joint consideration, however, is the valuation of costs. The acquisition of initial stock, on the one hand, is typically considered a finance problem. The storage of initial stock and the processing of failed stock is incurred with demonstrable expenses and, therefore, considered a typical money-flow problem. The employment of manpower is, likewise, a finance problem whereas the use of manpower flexibility is also a money-flow problem. Finance issues are traditionally considered the field of research for finance experts whereas money-flow issues are considered the field of research for money-flow analysts. The balancing of initial stock and flexible manpower would require an integration of knowledge from both disciplines. We encourage economists to conduct further research to an integration of both cost approaches.

Demand Information:

In our study we have restricted ourselves to a class of RISs in which demand information is not available on the short term. In another class of RISs, however, some demand is known as a result of an adequate warning of the failures. There is an adequate warning when a failure is detected and the maintenance requirements are known. The actual repair, however, can be postponed because the safety conditions are not in jeopardy. In combination with use-based maintenance-concepts, the maintenance interval and also the maintenance requirements are known. In combination with condition-based maintenance-concepts only the timing of the maintenance intervals is known. In this case one can try to predict the maintenance requirements in these time intervals. When the maintenance requirements are known or can be predicted fairly well, demand information becomes available for the RIS. An interesting research topic for industrial engineers would be the incorporation of this demand information in the control of RISs.

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Appendices

A. Expected Fill Probability.

The determination of the expected fill probability in a periodic-review (R,S) stock-replenishment system is more transparent than the determination of the fill probability in a continuous-review (S-1,S) stock-replenishment system, such as the RIS. In this Appendix it is shown that the fill probability in a (S-1,S) system can be derived from the fill probability in a (R,S) system. The derivation is due to Ton de Kok and Jos Verrijdt.

For the derivation of the fill probability in a RIS we define the following variables.
- The stock level is S.
- The fill probability is f(S).
- The Poisson demand rate is λ.
- The repair time is L.
- The review period is R.
- The demand during the repair throughput time is D_L.
- The demand during the review period is D_R.
- The steady state Poisson probability of k units in resupply is $p(k \mid \lambda L)$.

The fill probability in a (R,S) system is

$$f(S) = 1 - \frac{E[(D_{L+R}-S)^+] - E[(D_L-S)^+]}{E[D_R]} \quad . \tag{A.1}$$

Each demand triggers a replenishment in a (S-1,S) system, i.e. $D_R = 1$. On the basis of this property and equation (A.1), the fill probability can be reformulated as follows:

$$\begin{aligned} f(S) &= 1 - \frac{E[(D_{L+R}-S)^+] - E[(D_L-S)^+]}{E[D_R]} \\ &= 1 - \frac{E[(D_L+D_R-S)^+] - E[(D_L-S)^+]}{E[D_R]} \\ &= 1 - \frac{E[(D_L+1-S)^+] - E[(D_L-S)^+]}{1} \\ &= 1 - E[(D_L-(S-1))^+] + E[(D_L-S)^+] \quad . \end{aligned} \tag{A.2}$$

The demand in a RIS is assumed to be a Poisson process, with a demand rate during the repair throughput time equal to λL. We have therefore from equation (A.2) that

$$
\begin{aligned}
f(S) &= 1 - \sum_{k=S}^{\infty} (k-(S-1)) . p(k \mid \lambda . L) + \sum_{k=S+1}^{\infty} (k-S) . p(k \mid \lambda . L) \\
&= 1 - \sum_{k=S}^{\infty} (k-S+1) . p(k \mid \lambda . L) + \sum_{k=S+1}^{\infty} (k-S) . p(k \mid \lambda . L) \\
&= 1 - \sum_{k=S}^{\infty} p(k \mid \lambda . L) \\
&= \sum_{k=0}^{S-1} p(k \mid \lambda . L) \quad .
\end{aligned}
\tag{A.3}
$$

B. Verification

In a verification test we examine for a simple RIS whether the fill probabilities, produced by the simulation model of Section 3.1, do agree with the results of an analytical model under a number of parameter settings. The analytical fill probabilities are produced by a product-form-network. This model is explained in Section B.1. We thank Ivo Adan for his valuable suggestions in the formulation of this model. The fill probabilities, produced by the analytical model, are compared with the fill capabilities that are produced by the simulation model. The comparison is discussed in Section B.2.

B.1. Product-Form-Network

In the formulation of the analytical model for the generic RIS of Section 3.1 we add the following simplifying assumptions:

- All units have equal expected repair times.
- The repair times are exponentially distributed.
- The failed units are repaired in a FCFS sequence.

Under these assumptions the RIS can be formulated in terms of a "product-form-network", a special class of Markov closed-loop queuing-networks. For a comprehensive reference on the exact analysis of product-form-networks see the paper of Baskett et al. [1975]. We formulate the model for a RIS with only two items, "a" and "b". For the definition of the model we reserve upper case characters for fixed parameters, lower case characters for variables and greek lower case characters for rates.

- There are M_j machines containing item j, $M_j \geq 1$, $j \in \{a,b\}$.
- The total number of units j within the RIS is K_j, $K_j = M_j+Y_j$, $j \in \{a,b\}$.
- There is a function of the number of machines at any time in use $v_j(i)$, $v_j(i) = \min(i,M_j)$, $j \in \{a,b\}$.
- The number of repair men within the RIS is R, $R \geq 1$.
- There is a function of the number of repair men at any time in use $v_r(i)$, $v_r(i) = \min(i,R)$.
- The number of failed units in the RIS at any time is k_j, $0 \leq k_j \leq K_j$, $j \in \{a,b\}$.
- The steady state probability of i units in queue j is $P_j(i)$, $j \in \{a,b,r\}$.
- The steady state probability of k_a and k_b failed units in the RIS is $P(k_a,k_b)$, $0 \leq P(k_a,k_b) \leq 1$.
- The normalization constant is c, $0 < c < 1$.
- The failure rate of an operating unit j is γ_j, $\gamma_j > 0$, $j \in \{a,b\}$.
- The standard repair rate of a unit is μ_0, $\mu_0 > 0$.

In the model, the RIS is dealt with as a network of three queues a, b and r. The queues "a" and "b" comprise all units a and b in operation in a machine or serviceable in stock. Queue "r" comprises all failed units a and b. As a consequence of the assumption that both the failure and repair times are exponentially distributed the queues satisfy the Markov property. Due to this property two events cannot coincide. Then an event is always the occurrence of a failure or the occurrence of a repair. A failure j results in an increase in the number of failed units j, "k_j", by one. A repair j results in a decrease in the failed number of units j by one. We could also say that a failure j (repair j) results in a decrease (increase) of the number of the serviceable units j "K_j-k_j" by one. The number of serviceable units in queue j, "K_j-k_j" with $j \varepsilon \{a,b\}$, is a measure for the state of queue j. If the repair rate exceeds the failure rate, the transitions in time from and to state "K_j-k_j" reach an equilibrium. The system is in steady state. The steady state probability of K_j-k_j serviceable units in queue j, "$P_j(K_j-k_j)$", is a function of the steady state probability of the previous state $P_j(K_j-k_j-1)$, the characteristics of that state and the item failure rate γ_j. The characteristics of the states differ with respect to the number of machines in operation. This is expressed with function $v_j(i)$. Due to the relationship with the previous state, the state probabilities of all states can be derived from state probability $P_j(0)$, when this state probability is initially set to one. The steady state probability of K_j-k_j serviceable units in queue j is

$$P_j(K_j-k_j) = \prod_{i=1}^{K_j-k_j} \frac{1}{v_j(i).\gamma_j} \quad . \tag{B.1}$$

In a similar way the individual state probabilities for queue r can be derived. The derivation depends on the state probability $P_r(0)$, the number of repair men in use $v_r(i)$ and the standard repair rate μ_0. This time however there are a number of options to enter a state. Consider a queue with two failed units a and one failed unit b. This queue can be due to a following failure occurrences "baa", "aba" or "aab". The probability of each state must be multiplied by the number of options to enter the state. The number of options is compactly represented by the binomial coefficient. The steady state probability of k_a+k_b failed units in queue r can be derived from the probability of state $P_r(0)$, when this state is initially set to one. The steady state probability of k_a+k_b failed units in queue r is

$$P_r(k_a+k_b) = \begin{bmatrix} k_a+k_b \\ k_a \, , \, k_b \end{bmatrix} \prod_{i=1}^{k_a+k_b} \frac{1}{v_r(i).\mu_0} \quad . \tag{B.2}$$

In a product-form-network, the state probabilities of the RIS are the product of the individual state probabilities and a normalization constant "c". The normalization constant is added to accomplish a sum over all state probabilities equal to one. In determining its value, the constant is first set to one. After that the state probabilities are calculated and summed. The reciprocity of the sum of the state probabilities is the normalization constant. The steady state probability of k_a and k_b failed unit in the RIS is

$$P(k_a,k_b) = c \,.\, P_r(k_a,k_b) \,.\, \sum_{j\in\{a,b\}} P_j(K_j-k_j) \quad . \tag{B.3}$$

Note that the states of the different queues are related. In case queue r contains k_j units j, than queue j must contain the remaining $(K_j\text{-}k_j)$ units j. The probability that precisely s units a are failed is $P_j(s)$ with j is a. $P_j(s)$ is equal to the sum of all probabilities $P(k_a,k_b)$ where k_a is s_j with j is a. If we substitute $P(s_j)$ in function (3.1) we have derived an analytical solution for the fill probability of item j in the RIS.

B.2. Verification Test

In the verification test we consider a RIS with two items a and b. The parameters that characterize the RIS, (M_a, M_b, λ_a, λ_b, Y_a, Y_b, R), are set to (10, 10, 0.06, 0.04, 4, 2, 2) respectively. Different conditions for the RIS are created as a result of the setting of the repair rates to different values, such that the manpower utilization "ρ" corresponds with the levels (0.50, 0.70, 0.90). For the RIS under these utilization rates we compare the fill probabilities, produced by the analytical model, with the fill probabilities that are produced by the simulation model. The simulated fill probabilities are not exact values and, therefore, they are presented along with a (95%) confidence interval. The determination of this interval is explained in many statistical handbooks, e.g. Law and Kelton [1991], and repeated here.

For the definition of the confidence interval we reserve the following variables:

- The number of simulation subruns is n.
- The average simulated fill probability is $\bar{f}$.
- The standard deviation of the subrun fill probabilities is s.
- The upper critical point of a student-t variable is $t_{n-1}^{\alpha\backslash 2}$.

The simulated fill probability, along with the confidence interval is determined as follows:

$$\bar{f} \pm \frac{s}{\sqrt{n}} \cdot t_{n-1}^{\alpha/2} \quad . \tag{B.4}$$

The simulation results, that is the average value along with the confidence interval, are obtained in 20 subruns. Each subrun contains 10,000 simulation days. Both the simulation and analytical results are compared in Table B.1.

Table B.1: Comparison of Analytical and Simulation Results.

Utilization ρ	Fill Probability Analytical	Simulation
0.50	94.2	94.2 ± 0.2
0.70	82.9	82.8 ± 0.4
0.90	60.6	60.8 ± 0.8

All analytical results in the validation experiment are within the confidence intervals of the simulated results. The results gives us confidence that the simulation program is accurate.

C. FMP Parameters

FMP can be embedded in a product-form-network under the assumption that changes in the length of a working day commence upon a change in the status of the WIP. The operational duration of the change in the working day length is equal to the time between two changes in the WIP. Clearly this assumption does not fit in with common practice. It does however not affect the parameters that make up the intrinsic behaviour of the FMP rule, i.e. a, D_{min} and D_{max}. The effect of different settings for these parameters can be analyzed quickly with such model. The model is explained in Section C.1, the numerical analysis in Section C.2.

C.1. Embedding of FMP in the Product-Form-Network

Under FMP the repair men work a different number of hours on distinct working days. An adjustment in the length of a working day proportionally affects the repair rate of a repair man that day. This can be illustrated with an example. Consider a repair man on a daily basis. The man is employed eight hours on a standard working day and able to finish on average one repair every hour. His standard daily repair rate is, accordingly, eight. If, as a result of the available flexibility, the repair channel is employed nine hours on a particular day than the repair rate increases to nine that day. The change in the daily repair rate is due to the change in the day length only. Thus the FMP rule, by definition a rule that directs changes in the day length, can be defined as a rule that directs changes in the repair rate.

For the definition of the FMP rule in such terms we reserve the following variables:
- The minimum repair rate is μ_{min}.
- The maximum repair rate is μ_{max}.
- The standard repair rate is μ_0 with $\mu_{min} \le \mu_0 \le \mu_{max}$.
- The repair rate when s units are failed is $\mu(s)$ with $\mu_{min} \le \mu(s) \le \mu_{max}$.

To express the FMP rule in a state-dependent repair-rate, we ignore the "announcement leadtime" and the "operational duration" and substitute w, D_0, D_{min} and D_{max} in function (3.5) by s, μ_0, μ_{min} and μ_{max} respectively. Finally we substitute d(w) by $\mu(s)$ with

$$\mu(s) = \begin{cases} \max(\mu_0 - a(x-s)\mu_0 , \mu_{min}) & s \le x \\ \min(\mu_0 + a(s-x)\mu_0 , \mu_{max}) & s \ge x \end{cases} \quad . \tag{C.1}$$

The ratio between the minimum (maximum) and the standard repair rate is equal to the ratio between the minimum (maximum) and standard day length

$$\mu_{min} = \frac{T_{min}}{T_0} \cdot \mu_0 \qquad and \qquad \mu_{max} = \frac{T_{max}}{T_0} \cdot \mu_0 \quad . \tag{C.2}$$

The rule is embedded in the product-form-network when the standard repair rate μ_0 is substituted by the state dependent repair rate $\mu(s)$ in equation (B.2). This substitution is not detrimental to the product-form of the network for its definition was already state dependent.

The iterative procedure in the analytical model for the determination of the pivot value such that the average repair rate approaches to the standard repair rate is very similar to the iterative procedure that is used in the simulation model, see Section 3.4. In the procedure the pivot value is initially set to zero failed units. After that the value is systematically raised by one failed unit. After each iteration the state probabilities are calculated and the deviation between the average and the standard repair rate is determined. This deviation decreases monotonously with an increase in the pivot value. The procedure stops when the absolute minimum deviation is obtained.

C.2. Numerical Analysis

In a numerical analysis the parameters that are believed characteristic for a RIS, i.e. (M_a, M_b, γ_a, γ_b, Y_a, Y_b, R, ρ) see Appendix A, are set to the values (5, 5, 0.33, 0.66, 2, 5, 2, 0.80) respectively. Two working day policies are introduced in the RIS: a constant working day policy versus an FMP policy. The FMP policy can be described with three parameters:

- A multiplier a for adjusting the impact of flexibility.
- The minimum repair rate (or day length) μ_{min}.
- The maximum repair rate (or day length) μ_{max}.

One of these three parameters is set to different values in the analysis whereas the other two parameters are set to a reference value. The reference value are set: parameter a to 0.0625, μ_{min} (0.5 hours) to $0.75\mu_0$ (6 hours) and μ_{max} to $1.25\mu_0$ (10 hours). Value 0.0625 for parameter a corresponds with half an hour increase (decrease) in day length upon every unit failure (repair). The FMP policy is compared to a constant working day policy, the benchmark, with respect to an average fill probability over both items a and b. The fill probabilities are averaged using equation (3.2). The results are recorded in the Tables C.1., C.2 and C.3.

Table C.1: Parameter a

Parameter a	Pivot Value	Fill Probability Benchmark	FMP
0.03125	2	80.5	84.5
0.06250	2	80.5	86.4
0.09375	2	80.5	87.0
0.12500	3	80.5	89.5
0.15625	3	80.5	89.6
0.18750	3	80.5	89.7
0.21875	3	80.5	89.7
0.25000	3	80.5	89.8

Table C.2: Minimum Repair Rate μ_{min}

Parameter μ_{min}	Pivot Value	Fill Probability Benchmark	FMP
$0.0000 \times \mu_0$	3	80.5	86.4
$0.1250 \times \mu_0$	3	80.5	86.4
$0.2500 \times \mu_0$	3	80.5	86.4
$0.3750 \times \mu_0$	3	80.5	86.4
$0.5000 \times \mu_0$	3	80.5	86.4
$0.6250 \times \mu_0$	3	80.5	86.4
$0.8750 \times \mu_0$	3	80.5	86.4

Table C.3: Maximum Repair Rate μ_{max}

Parameter μ_{max}	Pivot Value	Fill Probability Benchmark	FMP
$0.0625 \times \mu_0$	2	80.5	83.9
$0.1250 \times \mu_0$	3	80.5	84.8
$0.8750 \times \mu_0$	3	80.5	85.9
$1.2500 \times \mu_0$	3	80.5	86.4
$1.3125 \times \mu_0$	3	80.5	86.7
$1.3750 \times \mu_0$	3	80.5	86.8
$1.4375 \times \mu_0$	3	80.5	86.8
$1.5000 \times \mu_0$	3	80.5	86.8

The fill probability appeared not to be effective for different settings of μ_{min}. This may be due to the rather moderate setting for the pivot value in the analysis, i.e. x=3. In combination with this pivot value, the length of a working day is hardly affected by the setting of μ_{min}. A more accurate analysis, regarding the effect on the fill probability due to a resetting of parameter μ_{min}, requires a higher value for the pivot. To obtain this higher value, the numerical analysis of μ_{min} is repeated with different values for the parameters (Y_a, Y_b, ρ). These are set to the values (7, 14, 0.95) respectively. In this situation, the pivot value increases to 7 units, see Table C.4. Again, however, we notice that a resetting of parameter μ_{min} resorts very little effect.

Table C.4: Minimum Repair Rate μ_{min}

Parameter μ_{min}	Pivot Value	Fill Probability Benchmark	FMP
0.0000 x μ_0	7	89.7	98.2
0.1250 x μ_0	7	89.7	98.2
0.2500 x μ_0	7	89.7	98.2
0.3750 x μ_0	7	89.7	98.2
0.5000 x μ_0	7	89.7	98.2
0.6250 x μ_0	7	89.7	98.3
0.8750 x μ_0	7	89.7	98.4

D. Simulation Parameters

A simulation run usually consists of a transient phase and a number of independent subruns. The transient phase continues until the steady state is obtained, that is when the averaged output variables do not substantially change anymore. The subruns must contain sufficient events to assume that their averaged output variables can be assumed to be independent variables.

D.1. Transient Phase

The length of the transient phase can be determined graphically according to Welch, as described by Law and Kelton [1991]. The transient phase is affected by the manpower utilization of the RIS. A transient phase which is appropriate for a RIS under a high utilization, also suits the RIS under a low utilization. We derive an appropriate transient phase for a RIS with manpower utilization rate 0.90, i.e. data set A+B+C-D-E-F-.

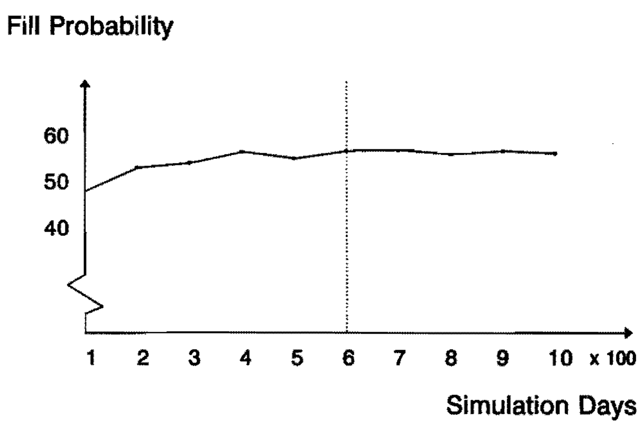

Figure D.1: Transient Phase

In Figure D.1, the average fill probability is related to transient stages of different lengths. Note that after 600 days the measured fill probability does not change substantially anymore. We assume that after this many days the steady state is obtained. For safety, we set the length of the transient phase to 1,000 days for RISs with A+ and to 10,000 days for RISs with A-.

D.2. Subrun Length

Right after completion of the transient phase, all output variables are reset to zero. After that the simulation is continued in order to determine a number of independent fill probabilities. It is unlikely that the fill probability on two successive simulation days may be considered independent. Two averaged values over a number of simulation days, however, are considered mutually independent when this number of simulation days is sufficiently large. The number of simulation days, required for one measurement of the fill probability, is called a subrun. Independence between subruns can be assumed when the first order auto correlation between the averaged output variables is negligible. This is tested with the "Von Neumann ratio", as explained in Kleijnen and Van Groenendaal [1992]. We reserve the following variables for the definition of the ratio:

- The Von Neumann ratio is q.
- The number of test runs is n.
- The average fill probability in subrun k is f_k.
- The average fill probability over all subruns is $\bar{f}$.
- The expected value of a standard normal variable is μ.
- The standard deviation of a standard normal variable is σ_q.
- The upper critical point of a standard normal random variable is $z_{\alpha/2}$.

$$q = \frac{\sum_{k=1}^{n-1} (f_k - f_{k+1})^2}{\sum_{k=1}^{n} (f_k - \bar{f})^2} \quad . \tag{D.1}$$

The Von Neumann ratio approximately follows a $N(\mu,\sigma_q^2)$ distribution with μ=2 and

$$\sigma_q^2 = \frac{4(n-2)}{n^2-1} \quad . \tag{D.2}$$

The subruns are assumed independent when

$$| q-2 | < z_{\alpha/2} \cdot \sigma_q \quad . \tag{D.3}$$

This criterium is usually tested with 100 subruns. In a series of test runs for the set of parameters we found that subruns should consist of about 300 simulation days before they can be considered independent with a significance level of 0.95. To be assured of independence we set the number of simulation days in a subrun to 1,000 days for the RISs with characteristic A+ and to 10,000 days for the RISs with characteristic A-.

E. Statistical Analysis of the Results

In this appendix we present the results of a full factorial 2^k design with k=6. In this design, six factors (A, B, C, D, E, F) are varied on two levels (-) and (+). The results for each situation are obtained in one run, containing five subruns. The results, depicted in Table E.1, are analyzed with the help of an ANOVA test. In this test the mean square for each effect is related to the mean error square. We introduce:

I	The number of simulation runs, $1 \leq i \leq I$.
J	The number of subruns in each simulation run, $1 \leq j \leq J$.
r_{ij}	The response of subrun j in run i.
eff_a, eff_{ae}	The effect of factor A (interaction AE).
MS_a, SS_a	The mean square and sum of squares for factor A.
MS_{ae}, SS_{ae}	The mean square and sum of squares for interaction AE.
MS_e, SS_e	The error mean square and the error sum of squares.
SS_t	The total sum of squares.
v	The degrees of freedom.

The sum of squares for each factor (interaction) can be derived from the linear regression effects. To determine the effect for a main factor, for instance A "eff_a", the level sign of factor A in run i, A_i, is multiplied by the sum of the subrun responses in run i, $\Sigma_j r_{ij}$. The total response over all subruns "I" is divided by the number of observations "$2^k.J$". The effects for the other main factors and interaction AE are determined in the same way.

$$eff_a = \frac{\Sigma_i A_i \cdot \Sigma_j r_{ij}}{2^k.J} \qquad eff_{ae} = \frac{\Sigma_i A_i.E_i \cdot \Sigma_j r_{ij}}{2^k.J} \tag{E.1}$$

The mean square for each factor is derived from its effect. The degrees of freedom for each effect is k-1, i.e. v=1, thus the mean is equal to the sum of squares in this experiment. The mean error square is derived from the total sum of squares and the sum of squares of all estimated effects. The degrees of freedom is equal to the number of observations minus the number of estimated effects minus one, i.e v=312. The "F-value" for each factor is the quotient of the factor mean square and the mean error square.

$$SS_a = eff_a^2 . 2^k . J \qquad SS_e = SS_t - \Sigma_k SS_k \qquad SS_t = \Sigma_i \Sigma_j r_{ij} - \frac{r_{..}^2}{I.J}$$

$$MS_a = \frac{SS_a}{v} \qquad MS_e = \frac{SS_e}{v} \qquad F = \frac{MS_a}{MS_e} \tag{E.2}$$

A factor has a significant contribution when $F > F^1_{312}(0.95)$.

Table E.1: Simulation Results (Run: 1 - 32)

Run	Factor						Response per Subrun				
	A	B	C	D	E	F					
1	-	-	-	-	-	-	13.7	12.6	10.0	11.8	11.9
2	+	-	-	-	-	-	12.4	11.6	11.4	12.3	10.3
3	-	+	-	-	-	-	8.0	13.2	7.9	10.2	9.0
4	+	+	-	-	-	-	14.6	14.1	13.7	11.1	14.0
5	-	-	+	-	-	-	1.3	0.4	0.5	1.0	0.7
6	+	-	+	-	-	-	1.9	1.2	1.0	1.7	1.3
7	-	+	+	-	-	-	0.3	0.3	0.3	0.5	0.3
8	+	+	+	-	-	-	2.2	1.7	1.6	1.4	2.0
9	-	-	-	+	-	-	95.1	87.3	94.2	84.2	92.4
10	+	-	-	+	-	-	95.7	98.7	95.4	97.2	97.7
11	-	+	-	+	-	-	27.8	53.6	45.6	46.2	39.6
12	+	+	-	+	-	-	61.8	62.8	59.7	50.3	62.2
13	-	-	+	+	-	-	26.3	19.8	21.2	24.0	22.9
14	+	-	+	+	-	-	20.3	20.4	22.7	19.2	14.6
15	-	+	+	+	-	-	-0.1	4.2	4.8	1.8	1.2
16	+	+	+	+	-	-	4.1	6.6	2.5	4.8	4.8
17	-	-	-	-	+	-	12.7	10.5	6.2	9.5	8.0
18	+	-	-	-	+	-	-8.3	-10.5	-12.7	-9.4	-12.7
19	-	+	-	-	+	-	6.6	12.5	6.5	9.0	7.8
20	+	+	-	-	+	-	-11.8	-10.8	-12.4	-16.8	-11.3
21	-	-	+	-	+	-	0.6	-0.0	-0.1	0.6	-0.3
22	+	-	+	-	+	-	-0.2	0.1	-0.3	-0.3	-1.0
23	-	+	+	-	+	-	-0.2	0.1	-0.3	-0.3	-1.0
24	+	+	+	-	+	-	0.5	0.7	0.0	-0.0	0.6
25	-	-	-	+	+	-	90.2	75.9	87.7	75.4	84.6
26	+	-	-	+	+	-	-30.5	-47.8	-62.0	-58.7	-78.7
27	-	+	-	+	+	-	22.8	49.3	40.2	41.9	34.7
28	+	+	-	+	+	-	-0.4	-9.4	-5.7	-17.4	0.5
29	-	-	+	+	+	-	13.8	6.9	8.6	5.6	9.5
30	+	-	+	+	+	-	2.1	0.4	1.0	-0.6	-3.3
31	-	+	+	+	+	-	-1.3	1.8	2.2	0.3	-0.4
32	+	+	+	+	+	-	1.2	-0.5	-0.8	0.1	-0.1

Table E.1: Simulation Results (Run: 33 - 64)

Run	Factor						Response per Subrun				
	A	B	C	D	E	F					
33	-	-	-	-	-	+	13.6	11.6	8.5	9.8	11.0
34	+	-	-	-	-	+	-3.9	-7.1	-8.7	-8.1	-7.4
35	-	+	-	-	-	+	7.5	13.1	7.9	10.5	8.7
36	+	+	-	-	-	+	-1.9	-3.5	-3.8	-7.9	-3.2
37	-	-	+	-	-	+	1.2	-0.0	0.4	0.7	0.4
38	+	-	+	-	-	+	0.7	-0.6	-1.1	-0.2	-1.6
39	-	+	+	-	-	+	0.1	0.2	0.1	0.4	0.2
40	+	+	+	-	-	+	0.6	0.8	0.8	-0.0	1.4
41	-	-	-	+	-	+	93.8	85.2	91.9	81.3	90.5
42	+	-	-	+	-	+	26.3	42.8	53.3	61.6	57.2
43	-	+	-	+	-	+	27.7	52.5	43.9	45.4	38.7
44	+	+	-	+	-	+	36.4	40.8	37.6	19.2	36.7
45	-	-	+	+	-	+	21.0	13.9	14.1	20.7	18.9
46	+	-	+	+	-	+	3.4	0.4	1.8	2.8	0.9
47	-	+	+	+	-	+	0.0	3.5	3.9	0.9	-0.1
48	+	+	+	+	-	+	1.5	2.0	-0.1	1.5	2.6
49	-	-	-	-	+	+	6.2	4.8	0.8	2.1	3.4
50	+	-	-	-	+	+	-10.2	-14.0	-13.1	-11.7	-16.2
51	-	+	-	-	+	+	6.6	12.0	5.8	9.2	7.0
52	+	+	-	-	+	+	-14.2	-15.9	-14.8	-20.5	-17.1
53	-	-	+	-	+	+	-0.0	-0.5	-0.4	0.0	-0.5
54	+	-	+	-	+	+	-0.9	-0.1	-1.7	-0.4	-1.3
55	-	+	+	-	+	+	-0.1	-0.2	-0.1	0.0	-0.4
56	+	+	+	-	+	+	0.0	0.4	-0.6	0.2	1.1
57	-	-	-	+	+	+	88.7	70.4	85.4	73.4	79.1
58	+	-	-	+	+	+	-215.1	-199.9	-242.5	-163.8	-222.7
59	-	+	-	+	+	+	22.7	49.0	39.4	41.4	33.9
60	+	+	-	+	+	+	-81.0	-70.0	-52.8	-80.3	-56.2
61	-	-	+	+	+	+	12.7	5.1	6.5	9.0	7.6
62	+	-	+	+	+	+	-1.8	-0.3	0.4	-6.3	-6.5
63	-	+	+	+	+	+	-1.5	2.0	1.7	-0.3	-0.9
64	+	+	+	+	+	+	0.0	0.3	-2.1	0.3	1.6

Summary

Unplanned machine failures could result in loss of production and, consequently, can be incurred with high cost. To minimize the duration of machine standstills spare components are used in the maintenance process. During maintenance of a production machine, it is quickly restored by replacing its failed components by identical but serviceable counterparts from stock. A subset of the failed components is technically and economically repairable. We term them *repairable items*. A repairable item that has failed is sent off for repair in a specialized repair facility. After repair the item is stocked to support future replacements. The system of repair capacity and stock locations, through which there is a flow of repairable items, we term a *Repairable Item System (RIS)*. RISs can be very complex systems especially when they contain a number of repair departments and a number of stock locations.

The repair capacity in a RIS consists of machines and repair men. This capacity is limited, which causes failed units to queue. We have restricted our study to RISs in which the capacity of repair men is more limited than the capacity of machines. The capacity of the repair men we term *manpower*. The number of repairable units flowing through a RIS is more or less constant. These units we term the *initial stock*. The performance of a RIS is in practice commonly measured in terms of a *fill probability*. This measure is defined as the percentage of demands that can be supplied from stock in a certain period. In general, the greater the manpower and / or initial stock, the better the fill probability that can be attained. It is self evident that the higher the initial stock and / or manpower the higher their costs. Within structural control, the cost for the manpower and initial stock should be jointly considered, subject to a required fill probability.

The studied RISs are characterized by an irregular and unpredictable demand pattern for serviceable components in the short term. In reaction to these demand variations, it would be convenient when the management of a RIS would have the means to vary the manpower in time. The manpower variations that can be employed in reaction to the variations in the number of failed components we term the "manpower flexibility". Manpower flexibility, to some extent, can be imposed by the management of the RIS, for instance by actively adjusting the working day lengths of the repair men. In that case we talk of "Flexible Manpower Planning (FMP)". The repair men, working under FMP, become a *flexible manpower*. Due to loosening restrictions on the part of both governments and unions, the use of FMP has recently become a popular political issue within Europe.

Following a review of the relevant literature on RISs it appears that the use of FMP in these systems has been little studied sofar. From "related" overtime studies it seemed plausible that the potential effectiveness, resulting from the use of FMP, depends on the characteristics of the FMP policy as well the characteristics for the RIS. This assumption is the motive for our first research question.

Q1: "How effective is the use of a flexible manpower planning in repairable item systems, measured in terms of a contribution to a service level ?"

In studying this research question we modeled a RIS with the help of a simulation model and gave this RIS different characteristics by setting distinct parameters to different levels. The RISs differed with respect to (1) the demand levels, (2) the number of items, (3) the manpower utilization and (4) the target fill probability. In a simulation experiment we introduced in each RIS a policy in which all working days were equal in length and monitored the fill probability. This fill probability is used as a benchmark for the RIS under the given conditions. After that we introduced in each RIS a number of FMP policies such that the working day on the long term is on average equal to the average working day of the benchmark. The FMP policies differed with respect to (5) the measure of responsive change in day length, (6) the minimum day length, (7) the maximum day length, (8) the leadtime between announcement and implementation of a change in day length and (9) the operational duration of a changed day length. For all these FMP policies we monitored the fill probability in all RISs. Deviations in the service level with regard to the benchmark service level are a measure for the effectiveness of an FMP policy in the RIS under the given conditions.

The results show that the characteristics of the RIS have a stronger impact on the effectiveness of FMP than the characteristics of the FMP policy. With respect to the characteristics of FMP, it appeared that an increase in the responsive change in day length and in the maximum day length contribute positively to the effectiveness of FMP. With just a little extra responsive change or extra day length already a fair share of the maximum effect can be obtained. The effectiveness of FMP seems rather insensitive to the minimum day length. Lengthening the leadtime of announcement or the operational duration of a change in day length reduces the flexibility and, not surprisingly, reduces the effectiveness of FMP. With respect to the characteristics of the RIS, it appeared that in combination with ample manpower no significant contribution will emerge from the use of FMP. In RISs, facing tight manpower and high service level targets, the use of FMP is effective. Under the same conditions, however, the RIS is also the most sensitive for a worsening in the service level due to the use of FMP. This is the case for RISs where demand is relatively high, repair times are relatively short, and where the FMP policies are rather rigid, i.e. have long leadtimes. Apparently, the introduction of FMP in RISs in practice should be approached with great care.

In those RISs where FMP is effective, its introduction in practice should be considered. Then, FMP should be coordinated together with the other measures of control. These other measures are the acquisition and control of the initial stock, the employment and allocation of manpower and the use of the priority rule to schedule failed units into repair. The decision power for the control of these measures is, in practice, allotted to different management levels. To support these management levels in taking control decisions we would help them with the construction of a framework for control. In this framework we focus on the coordination of the initial stock and the flexible manpower. We put forward our second research question.

Q2: "How can decisions regarding initial stock and flexible manpower be embedded in a framework for the control of repairable items systems ?"

RISs in practice are sometimes very complex due to the existence of many related stock locations and repair departments. In our control approach we decompose such complex RIS into a number of loosely connected self-empowered stock locations and repair departments. The control decisions for these stock locations and repair departments are recorded in the framework for control. It comprises of three hierarchically ordered decision levels: At the highest level target coordination, at the middle level structural control and at the lowest level operational control.

At the *target coordination level,* targets for the individual stock locations and repair departments are determined. These targets are deduced from a management goal with the help of a mathematical model. In addition to the targets, (serviceable) stock replenishment levels are deduced for the individual stock locations. On the basis of these replenishment levels the stocks with serviceable units can be operationally controlled. The targets form the input for the structural control of each distinct repair department within the RIS.

At the *structural control level* the (combination of) means to achieve at the target are evaluated on costs and practical motives for each repair department individually. The evaluated means are the seize and the composition of the initial stock, the manpower level, the priority rule to schedule failed units into repair and the FMP policy to determine the length of the working days. The proposed initial stock and manpower levels are fed back for approval to the management responsible for the target coordination level. The selected priority rule and FMP policy are passed on to the management responsible for the operational control of the repair department.

At the *operational control level* work orders are dispatched to the repair department with the help of the priority rule. The progress of the work orders within the repair department is controlled by internal due dates. The repair men are allocated to the repair work. The lengths of the working days are controlled by the decision function "Flexible Manpower

Planning". The lengths of the working days are determined upon a comparison of the FMP rule with the actual work in process. In the proposed framework the working day lengths can be different for distinct repair departments at the same day. If this is considered undesirable, and when the repair men are able to carry out repair work in other departments, an additional decision function "manpower transfer" can be added. The function balances the day lengths over the repair departments.

Control is a continuous process. To improve the results of the process the feedback of information is important. Information with respect to the realized fill probabilities at the stock locations and repair departments must be fed back to the management responsible for the target coordination of the entire RIS. Information regarding the realized fill probability for the individual repairable items, the initial stock levels, the manpower levels and the working day lengths must be fed back to the managers responsible for the structural control of the departments. Finally, information regarding the speed and quality of the repairs must be fed back to the management responsible for the operational control of the departments.

The framework was used for the evaluation of the decision structure currently employed for the control of a repair shop in the Netherlands. The evaluation highlighted some weaknesses in the current decision structure. These weaknesses were discussed with the management that is responsible for the structural and operational control of the repair shop. On the basis of the evaluation, adjustments of the current decision structure are being considered. Evidently, the framework for control has proven to be a useful evaluation tool for practitioners.

Samenvatting

Ongeplande stilstand van machines kan gepaard gaan met produktieverliezen en als gevolg daarvan hoge kosten. Om de stilstand snel te verhelpen, en daarmee de kosten van stilstand te beperken, worden reservedelen gebruikt in het onderhoudsproces. Tijdens het onderhoud van de produktiemachine worden defekte modules vervangen door identieke reservedelen uit voorraad. Een deel van de defekte modules is technisch en economisch repareerbaar en, na reparatie, weer te gebruiken als reservedeel. Deze categorie onderdelen duiden we aan met de term "wisseldeel". Het geheel van voorraad en reparatiecapaciteit waardoor een aantal wisseldelen stroomt duiden we aan met de Engelse term *Repairable Item System (RIS)*. RISs kunnen zeer complexe systemen zijn, met name wanneer ze zijn opgebouwd uit verschillende reparatiecapaciteiten en voorraadlokaties.

De som van alle wisseldelen - defekt, in reparatie of gerepareerd - in een RIS is min of meer constant. We noemen dit aantal de *initiële voorraad*. De reparatiecapaciteit in een RIS is samengesteld uit menscapaciteit en machinecapaciteit. In dit proefschrift beperken we ons tot RISs waarvoor geldt dat de capaciteitssoort *menscapaciteit* beperkt is. Een beperkte capaciteitssoort heeft tot gevolg dat defekte wisseldelen moeten wachten alvorens ze kunnen worden gerepareerd. De prestatie van een RIS wordt doorgaans gemeten in een servicegraad. Deze is gedefinieerd als: "Het percentage van de vraag naar gerepareerde wisseldelen dat direkt uit voorraad kan worden voldaan in een bepaalde periode". In het algemeen geldt, hoe groter de menscapaciteit en / of de initiële voorraad, des te hoger de servicegraad die kan worden behaald. Natuurlijk geldt ook, hoe groter de capaciteit en / of de initiële voorraad, des te hoger de gemaakte kosten. Bij de logistieke beheersing van een RIS gaan we uit van het principe dat de kosten van menscapaciteit en initiële voorraad door één instantie worden afgewogen met inachtneming van een gewenste servicegraad.

De bestudeerde RISs worden gekarakteriseerd door een onregelmatig en onvoorspelbaar vraagpatroon op de korte termijn. In reaktie op de variaties in de vraag zou men graag de beschikking hebben over een "flexibele menscapaciteit", d.w.z. meer capaciteit dan gebruikelijk bij een relatief hoge vraag en minder capaciteit dan gebruikelijk bij een relatief lage vraag. Deze flexibiliteit kan gecreëerd worden door het management van een RIS door het introduceren van werkdagen met een variabele lengte. De lengte van de werkdagen wordt vastgesteld met behulp van een "flexibele werkdagregel". De introduktie van variabele werkdagen in de industrie, en ook in RISs, is momenteel inzet van onderhandelingen tussen werkgevers- en werknemersorganisaties in diverse landen binnen Europa. Als gevolg van die onderhandelingen wordt het gebruik van flexibele werkdagregels steeds meer geaccepteerd als een middel in de logistieke besturing.

Ondanks de aktualiteit van het onderwerp blijkt uit een literatuurstudie dat de introduktie van variabele werkdagen in RISs weinig is bestudeerd door wetenschappers. Wel zijn er aanverwante studies verricht naar het gebruik van overwerkregels in dit soort systemen. Op basis van deze studies lijkt het aannemelijk dat de effektiviteit van het gebruik van variabele werkdagen bepaald wordt door zowel de condities van het RIS als het type flexibele werkdagregel. Dit vermoeden vormt het uitgangspunt voor een eerste onderzoeksvraag.

V1: "Hoe effektief is het gebruik van flexibele werkdagregels in RISs, gemeten in een bijdrage in de servicegraad ?"

Tijdens de studie van deze onderzoeksvraag hebben we het gedrag van een eenvoudig RIS nagebootst met een simulatiemodel. In het simulatiemodel hebben we het RIS verschillende condities aangemeten door bepaalde parameters op twee nivo's in te stellen, een laag en een hoog nivo. De condities van het RIS varieerden we met betrekking tot: (1) het totale vraagnivo, (2) het aantal soorten wisseldelen, (3) de werkdruk en (4) de opgelegde servicegraaddoelstelling. Door het variëren van vier parameters op twee nivo's hebben we een RIS met 16 condities gecreëerd. We spreken van 16 RISs. In elk RIS hebben we een werkdagregel ingevoerd die voorschrijft dat elke werkdag precies acht werkuren telt. Vervolgens is de gemiddelde servicegraad gemeten na afloop van een groot aantal gesimuleerde dagen. Deze servicegraad funktioneert als uitgangsmaat. Vervolgens hebben we in elk RIS een groot aantal flexibele werkdagregels ingevoerd. In deze werkdagregels kan een bepaalde werkdag meer of minder dan acht uren bedragen. Echter, alle regels hebben met elkaar gemeen dat een werkdag *gemiddeld* acht werkuren telt. De flexibele werkdagregels varieerden we met betrekking tot: (5) de aanpassingsintensiteit ten opzichte van de hoeveelheid onderhanden werk, (6) de minimale daglengte, (7) de maximale daglengte, (8) de tijdsduur tussen aankondiging en implementatie van een wijziging in de werkdaglengte en (9) de aanwendingsduur, dit is de periode die gewerkt dient te worden met een bepaalde daglengte. Voor elke flexibele werkdagregel in elk RIS hebben we de servicegraad gemeten en vergeleken met de uitgangsmaat. De grootte van de verschillen tussen de servicegraad en de uitgangsmaat geeft inzicht in de mate van effektiviteit van een flexibele werkdagregel in een bepaald RIS.

De resultaten laten zien dat de condities van het RIS een grotere invloed hebben op de effektiviteit dan de karakteristieken van de flexibele werkdagregels. Ten aanzien van de karakteristieken van de werkdagregels merken we op dat een verhoogde aanpassingsintensiteit en een toenemende maximale daglengte een positieve invloed hebben op de effektiviteit van flexibele werkdagregels. Echter, een groot deel van het maximaal te bereiken effekt, wordt al gerealiseerd bij een kleine toename van de aanpassingsintensiteit of van de maximale daglengte. De effektiviteit van flexibele werkdagregels is niet gevoelig voor veranderingen in de minimale werkdaglengte. Een verlenging van de aankondigingsof aanwendingsduur betekent vermindering van flexibiliteit en heeft, niet verassend, een negatieve invloed op de effektiviteit van flexibele werkdagregels. Ten aanzien van de condities van het RIS merken we op dat bij lage werkdruk geen noemenswaardig effekt uitgaat van welke flexibele werkdagregel dan ook. Blijkbaar bestaat er alleen bij hoge werkdruk behoefte aan extra flexibiliteit. Het gebruik van flexibele werkdagregels is potentieel het meest effektief in RISs met een hoge werkdruk en een hoge doelstelling voor de servicegraad. Echter, onder dezelfde condities is een RIS ook gevoelig voor een negatief effekt. Introduktie van een flexibele werdagregel leidt dan tot een daling van de servicegraad. Dit is het geval als flexibele werkdagregels met een lange aankondigings-duur, en in mindere mate een lange aanwendingsduur, worden geïntroduceerd in RISs die naast genoemde condities ook nog een hoge vraag en korte reparatietijden hebben. Daarom verdient het aanbeveling om de condities van het RIS zorgvuldig in ogenschouw te nemen alvorens men overweegt over te gaan tot het introduceren van flexibele werkdagregels in de praktijk.

In die RISs waar op grond van de gepresenteerde simulatieresultaten een positief effekt verwacht mag worden van flexibele werkdagregels, kan introduktie ervan in de praktijk worden overwogen. In dat geval dienen deze regels te worden gecoördineerd tezamen met andere aspekten die van invloed zijn op de logistieke besturing. Dit zijn: (i) de aanschaf en besturing van de initiële voorraad, (ii) het in dienst nemen en toewijzen van personeel en (iii) de keuze en het gebruik van een prioriteitsregel in de reparatie van defekte wisseldelen. De beslissingbevoegdheid in organisaties over deze aspekten is gealIokeerd aan verschillende instanties. We ondersteunen deze instanties in het nemen van hun beslissingen met een besturingsraamwerk. In dit raamwerk richten we ons specifiek op de afstemming van initiële voorraad en flexibele capaciteit. We introduceren een tweede onderzoeksvraag.

V2: "Op welke wijze dienen beslissingen ten aanzien van (de afstemming) van initiële voorraad en flexibele capaciteit ingebed te worden in een raamwerk voor de logistieke besturing van RISs ?"

RISs in de praktijk zijn doorgaans zeer complex van aard door de aanwezigheid van tal van reparatieafdelingen en voorraadlokaties. In de door ons ontworpen besturingsaanpak decomponeren we een complex RIS in een aantal reparatieafdelingen en voorraadlokaties die (nagenoeg) onafhankelijk van elkaar kunnen worden worden bestuurd. De besturingsbeslissingen voor deze reparatieafdelingen en voorraadlokaties zijn opgenomen in het raamwerk voor besturing. Het raamwerk bestaat uit drie hiërarchisch geordende beslissingsnivo's. Op het hoogste nivo "strukturele afstemming", op het middelste nivo "inrichting" en op het laagste nivo "operationele beheersing".

In de *strukturele afstemming* worden de gewenste servicegraden voor de voorraadlokaties en de reparatieafdelingen vastgesteld. Deze *interne* servicegraden worden afgeleid van een *externe* servicegraad met behulp van een "grof" wiskundig model van het gehele RIS. De externe servicegraad is de servicegraad die aan de klant van het RIS, dat is de onderhoudsdienst, wordt geleverd. De interne servicegraden worden afgeleid op basis van bestelnivo's. Met behulp van deze bestelnivo's kunnen de voorraden op de voorraad-lokaties worden bestuurd. De bestelnivo's worden niet gebruikt voor de besturing van de werkvoorraad in en tussen de reparatieafdelingen. De interne servicegraden worden gebruikt voor de aansturing van de inrichting van de reparatieafdelingen.

In de *inrichting* van de reparatieafdelingen wordt een aantal alternatieven waarmee de interne servicegraad kan worden gerealiseerd tegen elkaar afgewogen. De alternatieven verschillen van elkaar met betrekking tot de mix van initiële voorraad, capaciteit, prioriteitsregels en (flexibele) werkdagregels. De afweging vindt plaats op basis van kosten en andere, praktische, motieven. Het voorraadnivo en capaciteitsnivo, behorend bij het geselecteerde alternatief wordt ter goedkeuring voorgelegd aan het hogere management nivo waar de strukturele afstemming plaatsvindt. De geselekteerde prioriteitsregel en werkdagregel worden afgegeven aan de managers die verantwoordelijk zijn voor de operationele beheersing van de reparatieafdeling.

In de *operationale beheersing* worden werkopdrachten vrijgegeven binnen de verschillende reparatieafdelingen. Monteurs worden toegewezen aan het reparatiewerk. De voortgang van deze werkopdrachten wordt gecontroleerd aan de hand van plandata. De daglengte van de verschillende werkdagen wordt steeds bepaald aan de hand van een vergelijking van de voorraad onderhanden met de parameters uit de werkdagregel. Door de onafhankelijke besturing is het mogelijk dat voor verschillende reparatieafdelingen een verschillende werkdag wordt vastgesteld op dezelfde dag. Indien dit niet gewenst is, en indien monteurs in staat zijn om aktiviteiten in andere afdelingen te verrichten, kan het raamwerk worden uitgebreid met een extra beslisfunktie "de (re)allokatie van monteurs". De beslisfunktie balanceert de daglengten over de afdelingen.

Om de resultaten van de logistieke beheersing te verbeteren is het noodzakelijk dat informatie regelmatig wordt teruggekoppeld. Het management dat verantwoordelijk is voor de strukturele afstemming dient te worden voorzien van informatie over de gerealiseerde servicegraden van de reparatieafdelingen en de voorraadlokaties. Het management dat verantwoordelijk is voor de inrichting van een reparatieafdeling dient te worden ingelicht omtrent de gerealiseerde servicegraden voor de individuele wisseldeeltypen, de initiële voorraadnivo's, de capaciteitsnivo's en de gerealiseerde werkdaglengten. Het management dat verantwoordelijk is voor de operationele beheersing van een reparatieafdeling, tenslotte, dient te worden voorzien van informatie ten aanzien van de snelheid en kwaliteit van de gerealiseerde reparaties.

Om de bruikbaarheid voor de praktijk te toetsen hebben we de logistieke beslissingsstruktuur van een RIS in Nederland met het raamwerk geëvalueerd. De evaluatie toonde sommige tekortkomingen in de huidige beslissingsstruktuur en dus heeft het raamwerk bewezen bruikbaar te zijn voor de praktijk.

Curriculum Vitae

The author of this dissertation was born on January 16, 1966 in Eindhoven. In 1984 he received his high school diploma from the "Eckart College" in Eindhoven, after which he started his study Industrial Engineering at Eindhoven University of Technology. During his study he received a scholarship for a traineeship in Xi'an, PR China. The traineeship was carried out together with students from the Jiao Tong University. He received his Master's Degree in 1990 after a research project concerning the operational control of a repair shop. This project was supervised by prof.dr. Jacob Wijngaard and by dr. Hans Geurts. After his graduation he left for a year of travel.

Since 1991, he conducted research at the Graduate School of Industrial Engineering and Management Science concerning the embedding of flexible manpower in the planning and control of Repairable Item Systems. The project was overseen by prof.dr.ir. Will Bertrand of the Department of Operations Planning and Control. This dissertation concludes this research. During his research he was involved with projects in industry. Since 1991 he was on a parttime basis involved in consultancy work together with Rijnconsult, a medium size consultancy firm in the Netherlands.

STELLINGEN

behorende bij het proefschrift

The Coordination of
Initial Stock and Flexible Manpower in
Repairable Item Systems

I

Essentieel in de strukturele beheersing van "Repairable Item Systems" is een afweging tussen de hoeveelheid initiële voorraad en (flexibele) capaciteit tegen een gewenste doelstelling op basis van kosten door één instantie.
- *dit proefschrift; hoofdstuk 4*

II

Flexibilisering van de arbeid heeft een substantiële bijdrage in de (lokale) servicegraad van "Repairable Item Systems" die opereren onder een scherpe servicegraad-doelstelling en een hoge werkdruk. Afhankelijk van de gekozen flexibiliteitsregel is deze bijdrage positief of negatief.
- *dit proefschrift; hoofdstuk 3*

III

Flexibilisering van de arbeid is niet effektief in "Repairable Item Systems" waarvoor geldt dat de reparatiecapaciteit wordt gevolgd door een complexe voorraadketen.
- *dit proefschrift; hoofdstuk 6*

IV

Het begrip "bezettingsgraad" is ongeschikt als besturingsparameter voor menscapaciteit.

V

Fundamentele discussies over het gebruik van gedetailleerde dan wel geaggregeerde modellen leiden tot verwarring omdat enerzijds alle gedetailleerde modellen gebruik maken van geaggregeerde informatie en anderzijds alle geaggregeerde modellen in staat zijn om gedetailleerde informatie te leveren.

VI

Om de duur van het promotietrajekt drastisch te verkorten verdient het aanbeveling om alleen gepromoveerden het trajekt te laten doorlopen.

VII

Het ontbreken van een woord voor het tegengestelde van "overwerk" is kenmerkend voor de arbeidsethos in Nederland.

VIII

De eenzijdige berichtgeving in ons land heeft geleid tot een zwart-witte kijk op Zuid-Afrika.

IX

In derde wereldlanden dient men beducht te zijn voor industriëlen op zoek naar nieuwe afzetgebieden.

X

Ook Duitsers hebben het recht om trots te zijn op hun vaderland.

XI

Het aanstellen van deeltijdhoogleraren vertoont meer en meer gelijkenis met de selektie van Formule 1 coureurs.