

## Structuring the rotatable repair control system

***Citation for published version (APA):***

Haas, de, H. F. M. (1993). *Structuring the rotatable repair control system*. (TU Eindhoven. Fac. TBDK, Vakgroep LBS : working paper series; Vol. 9303). Technische Universiteit Eindhoven.

***Document status and date:***

Published: 01/01/1993

***Document Version:***

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

***Please check the document version of this publication:***

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

***General rights***

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

[www.tue.nl/taverne](http://www.tue.nl/taverne)

***Take down policy***

If you believe that this document breaches copyright please contact us at:

[openaccess@tue.nl](mailto:openaccess@tue.nl)

providing details and we will investigate your claim.

**Structuring the Rotable Repair Control system**

H.F.M. de Haas

Research Report TUE/BDK/LBS/93-03  
march, 1993

Graduate School of Industrial Engineering and Management Science  
Eindhoven University of Technology  
P.O. Box 513, Paviljoen F15  
5600 MB Eindhoven  
The Netherlands  
Phone +31.40.474443

*This paper should not be quoted or referred to without the prior written permission of the author*

## ABSTRACT

In general, maintenance organizations need an inventory of spare parts to carry out their activities. A subset of those parts is recoverable, the so-called rotables. Rotables are waiting for repair, under repair, waiting for use or in use. To control the rotatable repair process cost-effectively, various interacting control decisions are taken in practice. These control decisions are of a different nature and affect the repair process on a different term. To improve the co-ordination of the various control decisions they are embedded in a hierarchical framework. In this paper, an outline of a hierarchical control framework is presented. The framework is referred to as the rotatable control structure.

(keywords: rotables, hierarchical control structure)

## 1. Introduction

In practice, valuable production time is lost due to substantial downtime of the production equipment. To reduce this valuable downtime, spare parts are used in the maintenance process. During maintenance, the failed parts are exchanged by the spare parts. A subset of the spare parts is recoverable, the so-called rotatables. A rotatable can adopt two states; the failed and the recovered. The failed rotatables queue up in front of a repair capacity. After repair the recovered rotatables are available for the maintenance process, see exhibit 1. The rotatable repair process, the lower loop in exhibit 1, contributes to the efficiency of the maintenance process, which in turn augments the uptime of the production equipment. Therefore the rotatable repair process must be properly controlled.

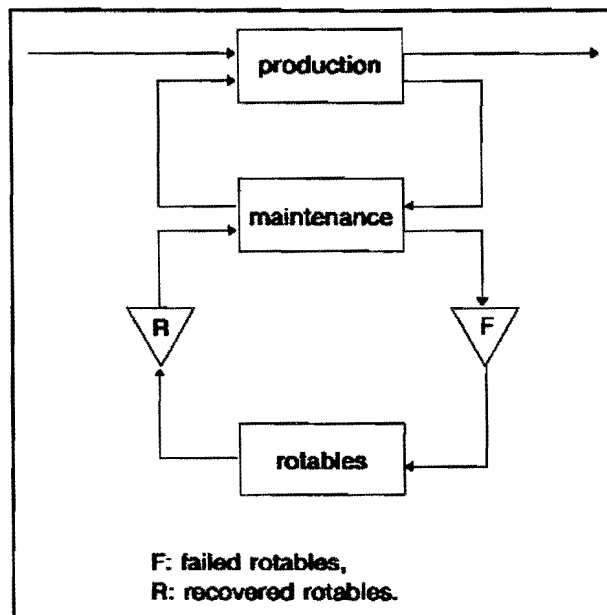


Exhibit 1: The maintenance process.

To better understand the essentialities of rotatable repair we carried out a survey in dutch rotatable repair industry. The survey revealed, among others, that the rotatable repair problem is a production control problem with the following essentialities:

- a demand pattern derived from corrective or preventive maintenance,
- a demand pattern for recovered rotables which is, although not necessarily in phase, equal to the supply pattern of failed rotables.
- a closed loop inventory which is composed of failed and recovered rotables, that must be procured well ahead,
- a large number of "slow movers",
- a great uncertainty of the repair job content.

The maintenance demand is either preventive or corrective. Particularly when maintenance demand is corrective, the demand for recovered rotables varies and its composition is uncertain on the short term. We restrict ourselves to such problems. When the demand for recovered rotables is irregular, the supply of failed rotables is irregular as well. If no control is exercised, an irregular supply of failed rotables leads to an irregular loading of the repair capacity. This in turn results in unreliable leadtimes if the repair capacity is limited. To overcome this problem, control must be exercised. In controlling rotatable repair various control decisions can be taken. Some of these control decisions affect the material aspect, others affect the capacity aspect of rotatable control. To co-ordinate all control decisions with relation to the material and the capacity aspect, they are integrated in a hierarchical framework, the so-called rotatable control structure. Such a control structure is presented in this paper.

A brief review on rotatable repair control is presented in section 2. The review reveals that the majority of the relevant literature addresses the material aspect of rotatable repair control. Only few papers address the capacity aspect of rotatable repair control. A rotatable control structure which integrates both aspects has not been presented yet. Such a structure is presented in section 3. In the control structure much attention is directed to operator flexibility. This paper concludes with a discussion, section 4.

## **2. Relevant Literature.**

An excellent survey of the early literature which addresses the rotatable control literature is presented by Nahmias (1981). According to Nahmias, the vast majority of the literature has been directed to the composition of the closed loop inventory. The inventory affects the stock out risk. The joint object is to minimize the stock out risk, subject to a budget constraint. The problem is referred to as the "initial stocking problem". Early solutions have been published under the collective noun METRIC. The most important representatives of METRIC are Sherbrooke (1968, 1986), Muckstadt (1973) and Slay (1984). METRIC solves the initial stocking problem, assuming compound Poisson demand and ample repair capacity. More recently the ample capacity restriction has been relaxed and the initial stocking problem is solved using closed queuing network theory. In the analytical models to match, failed rotables are scheduled into repair according to a first-in-first-out sequence. The most important representatives of this approach are Gross (1982, 1983), Balana et al. (1989) and Ebeling (1991). Queuing theory is more accurate than METRIC, however more intricate too. Therefore, lately, attention has been called to METRIC again. The gap between both approaches has recently been closed by means of approximations, Ahmed et al. (1992).

Hausman and Scudder (1982) improve the composition of the closed loop inventory with the help of a simulation study. The authors describe a simulation model for a hierarchical three layered rotatable repair process; final assembly repair, sub-assembly repair and component repair. Such repair processes are met within aircraft maintenance. All final assemblies, sub-assemblies and components are rotatables. Hausman

and Scudder show that if the rotables budget decreases, it is economical to remove those rotables first which are either capacity intensive or expensive. In other words it is economical to stock a surplus of low cost rotables which consume capacity. Applying their inventory composition rule without a short-term sequencing-rule, the high cost rotatable are expected to run out of recovered inventory first. To overcome this problem, the failed rotables on a component level are scheduled into repair according to a recovered-inventory runout-risk sequencing-rule.

Similar results are found for a single layered repair process by Schneeweiß and Schröder (1992). The authors however do not minimize the stockout risk subject to a budget constraint, but minimize the budget subject to an overall service level constraint. They not only deal with the mathematical but also with the organisational aspects of rotables repair control. The authors decompose the control problem in a planning problem and a shopfloor decision problem. On the planning-level the most economical rotatable levels are determined in two steps: (1) A rotatable vector is determined subject to an overall service level constraint, (2) The vector is adjusted using a marginal analysis on costs. Like in METRIC the result of the marginal analysis will be an expected shortage of high cost rotables. Therefore, on the shopfloor-level the individual service levels must be balanced, taking into account the actual state of the repair process. The failed rotables are scheduled in sequence of runout risk. According to Schneeweiß and Schröder, the planning rule affects rotatable repair on the medium term and the shopfloor decision rule affects rotatable repair on the short term. The planning rule however affects the total maintenance life cycle with a duration of at minimum four years in practice. In our opinion, the planning rule is considered to be long term.

Scudder (1985) presents some introductory research to overtime policies. For that purpose he adjusts his simulation model to measure the results, of proactive and reactive overtime, on the stockout risk. The results indicate that overtime affects the stockout risk most effectively when reactive final assembly overtime is paired with proactive component overtime. De Haas (1992) compares two single-item rotatable repair models. One model with one capacity level; the other model with two capacity levels, the upper capacity level being an overtime level. In the latter model, the capacity levels can be changed on a long term. Either the upper or the lower capacity level is allocated on the short term. In both models, the average capacity and the demanded service level are equal. Under a Poisson demand distribution, the model with two capacity levels uses less inventory. We conclude that variable capacity levels, which is a result of operator flexibility, can be economical when a varying demand pattern must be satisfied.

The review shows that the relevant literature addresses the material and capacity aspect of rotatable control. The literature dealing with the *material aspect*, particularly addresses the rotatable inventory. The rotatable inventory must be procured well ahead and as a consequence this decision affects the rotatable repair on a long term. Actual corrective maintenance demand is uncertain. To account for the actual demand a sequencing rule, which affects rotatable control on a short term, is introduced. The literature which addresses the *capacity aspect* of rotatable control is scarce and in general the capacity levels are fixed. Only some overtime policies are analysed. The use of overtime, a short-term decision, results in different

capacity levels. However different capacity levels affect the rotatable inventory which is a long term decision. Thus, like the material aspect, also the decisions related to the capacity aspect can be separated in the long and the short term.

Long term decisions are usually of a more aggregate nature than short term decisions, e.g. Schneeweiß and Schröder use an overall service level on the long term and detailed service levels on the short term. Because the decisions which affect different terms are made on different levels in an organization, we suppose that a hierarchical approach is appropriate. Such an approach is used by Bertrand, Wijngaard and Wortmann (BWW, 1990) in designing production control structures which integrate both the material and the capacity aspect. Using their theory, control structures have been developed for a variety of production control situations, however not yet for a rotatable repair control situation. Such a structure, for the elementary repair process of exhibit 1, is presented in section 3.

### 3. Rotatable Control Structure.

In this section we present a rotatable control structure. The structure is based on the literature of BWW which addresses the design of production control structures. According to BWW, the design of a production control structure is based on three basic design aspects:

1. The distinction between *goodsflow control* and *production unit control*.
2. The distinction between *detailed, item-oriented control* and *aggregate, capacity-oriented control*.
3. The relation between *production* and *sales*.

Ad.1: The first step in designing a production control structure is to distinguish production units (PUs). A PU is a production department which, on the short term, is self-contained with respect to the use of its resources and responsible for the production of a set of products. A PU is defined by a class of PU end items with for each PU end-item a class of operations with corresponding material and resource requirements. The production control is decomposed into PU-control which looks after the control of a PU and goodsflow control which looks after the co-ordination of the PUs with respect to the quantity and timing of production and sales. Goodsflow control decides which work orders must be released to the PUs.

Ad.2: On the goodsflow control level two aspects are decomposed: The aggregate production planning and the detailed co-ordination of individual product items. The aggregate production planning, which addresses the capacity control aspect, encloses the bottle neck capacity, the inventory budget, the sales budget etc. According to BWW, the capacity can only be changed on the medium or long term and is allocated to individual product items on the short term. On the medium term only aggregate capacity and budgets must be controlled. Material co-ordination, which deals with the material control aspect, mainly involves the timing (the release and due date) of work orders.

Ad.3: The co-ordination between production and sales affects production control at all levels. We distinguish *structural co-ordination*, which deals with the static characteristics of both production and sales, and *operational co-ordination*, which deals with the dynamics. BWW state that organizing the co-ordination between production and sales, in a variety of situations, can be very different and moreover difficult. The difficulty is caused by the flexibility of sales which often is only vaguely known.

We compare the above basic design aspects with the essentialities of rotatable repair in section 1 and the results of the literature review in section 2.

As stated in the design approach, designing a control structure starts with the definition of the PUs. The PU definition is based on material and capacity considerations. In case of rotatable repair, which essentially contains a large number of slow movers with different material and capacity needs, this PU definition leads to the distinction of many PUs and consequently a very complex goodsflow control structure. However, if the material aspect is simple and the repair capacity is flexible, a few but extensive families can be defined. Thus when the bottle neck capacity is operator capacity, the definition of PUs is dependent on the operator flexibility. We make a distinction between volume flexibility and mix flexibility. Volume flexibility is the possibility to increase the throughput rate. Mix flexibility is the ability of operators to execute several tasks. The PU definition depends on the mix flexibility. The greater the operator mix flexibility, the smaller the number of PUs that are distinguished. In the example of exhibit 1, we assume a repair shop with a plain repair process and a high level of operator mix flexibility. In that case the total repair shop capacity is regarded as one PU. Because of the simplicity of this repair process, the PU control problem is ignored. We restrict ourselves to the goodsflow control problem and the goodsflow control structure to match.

In general, goodsflow control concerns the co-ordination of production and sales. In a maintenance environment, not production and sales, but production and maintenance must be co-ordinated. Maintenance in a maintenance environment can be compared with production in a production environment. Production in a maintenance environment can be compared with sales in a production environment. As, in a production environment, sales provides production with predictions in respect of sales behavior; In a maintenance environment, production provides maintenance with predictions in respect of the production equipment failure behavior. In a production environment, production satisfies sales by producing products; In a maintenance environment, maintenance satisfies production by reducing downtime. Thus, co-ordination means that maintenance and production negotiate on an acceptable downtime. To realize, the agreed downtime, the maintenance department depends on the availability of rotatables. Thus the maintenance department in turn negotiates with the rotatable department on an acceptable availability of rotatables, the so-called aggregate service levels. The aggregate service levels are the result of a *structural co-ordination*.



The downtime costs of production equipment are usually high. Thus downtime must be restricted and consequently high service levels for the recovered inventory of rotables are required. When demand uncertainty is substantial and repair leadtimes are unreliable, high service levels are met by having an excessive inventory and/or an excessive capacity. The inventory must be procured well ahead, thus the inventory levels are more or less fixed. On the other hand, if operator volume flexibility is present, the capacity levels are not fixed and can be to some extent adjusted to the actual demand. To meet the agreed service levels economically, a joint consideration on cost of capacity, operator flexibility and inventory is necessary. Before such a consideration can be made, the decisions that affect the available operator flexibility and the inventory composition must be filled in.

The inventory composition decision is a detailed decision which affects the long term. Based on the great amount of literature which addresses this decision, we know this decision combines demand, cost and workload aspects. With the help of the inventory composition, the cost of an hour of inventory can be calculated.

The *operational co-ordination* between maintenance and production is less flexible than the co-ordination between production and sales. If the actual sales underscores the sales forecast, the sales department can lower the sales price in order to increase the sales rate or the production department can build up temporary inventory. However if the actual failure behavior of the production equipment underscores the predicted failure behavior, the maintenance department is left with an excessive capacity; the rotatable department with an excessive inventory. Reversed, if the actual sales exceeds the sales forecast, the sales department can increase the sales price in order to slow down sales or the production department can phase out excessive inventory or expand the production capacity. However, if the actual failure behavior of the production equipment exceeds the forecast, the rotatable department can only (temporarily) expand the capacity of the PU. We remark that if the demand dynamics cannot be predicted in great detail, as usually is the case in a situation with corrective maintenance, there exists no *operational co-ordination* between maintenance and production.

If no operational co-ordination exists between maintenance and production, the operator volume flexibility is the only measure to counter demand uncertainty on the short term. The short term is defined as the leadtime to effectuate operator flexibility. The decision which flexibility measure to employ on the short term is made by the rotatable department alone. This decision can be attached, for instance, to the size of the actual aggregate failed inventory. The operator flexibility that will be employed on the short term, establishes the permitted workload of the PU on the short term.

The permitted workload constitutes the input of a workload control decision. The decision subtracts the remaining workload, which is left behind in the PU, from the permitted workload. The difference represents the maximum workload which is allowed to be released the next work order release moment. It can be argued whether or not the workload decision is significant in rotatable repair, because: (1) The job

content of a work order is unreliable and as a result the workload cannot be determined in great detail and (2) in a closed loop inventory, the rotables are either failed or repaired. Only recovered rotables contribute to the service levels. In that case releasing all failed rotables avoids capacity from being idle and results, in theory, in the smallest closed loop inventory. On the other hand if the priorities are laid down in the PU, the probability of making faulty decisions in the choice of a next job increases. The second motive can be annulled by setting high workload norms.

The material co-ordination in a production environment looks after the timing of work orders. To support the material co-ordination, due-date sequencing-rules are used. Those rules assume to some extent that production times are known. When considering rotatable repair, the repair times depend on the job content which is uncertain (one of the essentialities of rotatable repair). If the uncertainty in repair times is great and the rotatable repair process is simple, the material co-ordination is supported by sequencing rules which make use of the release dates alone. The sequencing rules are affected by the actual repaired inventory and the inventory composition.

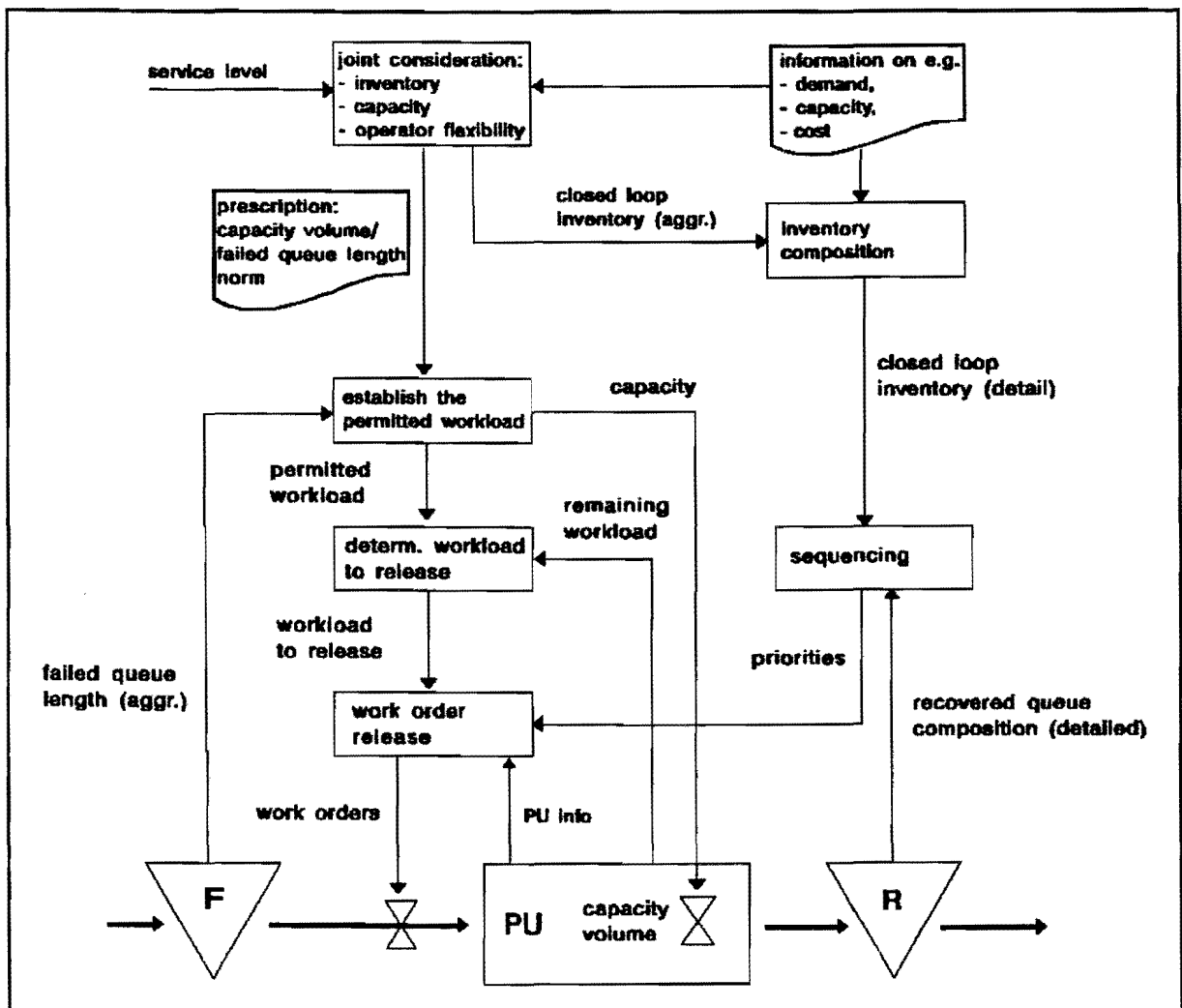


Exhibit 2: The rotatable control structure.

A workorder release decision finally takes care of the release of work orders to the PU. For that purpose the capacity decision and the material decision are integrated. The capacity decision determines which workload to release to the PU: The sequencing decision determines which work orders to release. The latest information, for example with respect to a small number of work orders which hail from a preventive maintenance demand, can be included in the workorder release decision. The rotatable control structure is depicted in exhibit 2.

#### 4. Discussion.

In the previous section we presented a rotatable control structure. The structure is composed of several interacting decisions. The decisions are aggregate when they deal with the repair capacity and detailed when they deal with the rotatables. The specific content of the decisions depends on the characteristics of the rotatable repair problem on hand. We emphasize that the most important decision in the structure is the joint consideration on costs of capacity, operator volume flexibility and inventory. This decision requires that all lower level decisions are filled in. The joint consideration can be carried out with the help of a stepwise computer simulation approach. In the approach below, we assume a minimum capacity with an utilization rate nearly one.

- Step 1:** Introduce demand distributions, repair time distributions, a basis capacity level, costs and an aggregate service level.  
Carry out the demand composition, e.g. Hausman and Scudder (1982); Introduce a very large inventory.  
Introduce a sequencing rule, e.g. Schneeweiß and Schröder (1992). Run the simulation. Measure the distribution of the aggregate failed inventory (in hours).
- Step 2:** Introduce a workload norm. Run the simulation. Measure the distribution of the aggregate failed inventory. If the distribution equals the distribution in step 1, then implement the norm and go to step 3. Else increase the norm and repeat step 2.
- Step 3:** Determine on the basis of the distribution of the aggregate failed inventory and the service level the cost of inventory. Initialize a variable "x". x equals the inventory costs.
- Step 4:** Introduce the most economical measure of operator volume flexibility. Introduce the maximum flexibility that annually can be employed of this measure. Introduce a broad aggregate failed inventory norm which determines when to employ flexibility. Run the simulation. If the maximum flexibility is exceeded then lower the norm and repeat step 4, else go to step 5.
- Step 5:** Determine on the basis of the distribution of the aggregate failed inventory and the service level the cost of inventory. Initialize a variable "y". y equals the inventory costs. Add variable x. Subtract the cost of the flexibility measure. If the result is positive, then implement the flexibility measure, give variable x the value of variable y and go to step 6, else go to step 7.
- Step 6:** Introduce the next most economical measure of operator flexibility. Go to step 4.
- Step 7:** Stop the procedure.

In this procedure the aggregate service level, which equals one minus the overall stock out risk, is based on the distribution of the *aggregate* failed inventory. In other words, we assume that at a certain point of time, the actual service level only depends on the aggregate repaired inventory, not on the composition

of the repaired inventory. By doing so, we are likely to over estimate the service level. To compensate for this over estimation, some closed loop inventory should be added.

In co-operation with a multi-national maintainer of business electronics the simulation approach is being tested. The repair process of this maintainer is rather straight forward and we can restrict the research to a single repair unit. The simulation approach will be extended, in co-operation with a dutch aircraft maintainer, for a complex two level rotatable repair problem with final and subassembly repair. On the final assembly repair level we come across two PUs, disassembly and assembly, which are decoupled by means of a small final assembly repaired inventory. on the subassembly level we distinguish one PU: rotatable repair.

#### REFERENCES

- Balana A.R., D. Gross and R.M. Soland, 1989, Optimal Provisioning for Single-Echelon Repairable Item Inventory Control in a Time-Varying Environment. *IIE Transactions*, vol.21, no.3, pp.202-212.
- Bertrand J.W.M., J. Wijngaard and J.C. Wortmann, 1990, Production Control, A structural and Design Oriented Approach. *Elsevier*, Case Study pp.291-312.
- Ebeling C.E., 1991, Optimal Stock Levels and Service Channel Allocations in a Multi-Item Repairable Asset Inventory System. *IIE Transactions*, vol.23, no.2, pp.115-120.
- Gross D., 1982, On the Ample Service Assumption of Palm's Theorem in Inventory Modelling. *Management Science*, vol.28, no.9, Sept., pp.1065-1079.
- Gross D., D.R. Miller and R.M. Soland, 1983, A Closed Queuing Network Model for Multi-Echelon Repairable Item Provisioning. *IIE Transactions*, vol.15, no.4, pp.344-352.
- Haas, H.F.M. de, 1992, Rotable Control: A Markov Approach. Presented at the second annual meeting for research in the field of industrial engineering and management science. Amersfoort 1992.
- Hausman W.H. and G.D. Scudder, 1982, Spares Stocking Policies for Repairable Items with Dependent Repair Times. *Naval Research Logistics Quarterly*, vol.29, no.2, June, pp.303-322.
- Muckstadt J.A., 1973, A Model for a Multi-Item, Multi-Echelon, Multi-Indenture Inventory System. *Management Science*, vol.20, no.4, pp.472-481.
- Schneeweiß Ch.A. and H. Schröder, 1992, Planning and Scheduling the Repair Shops of the Deutsche Lufthansa AG: A Hierarchical Approach. *Production and Operations Management*. vol.1, no.1, pp.22-33
- Scudder G.D., 1984, Priority Scheduling and Spares Stocking Policies for a Repair Shop: The Multiple Failure Case. *Management Science*, vol.30, no.6, June, pp.739-749.
- Scudder G.D., 1985, An Evaluation of Overtime Policies for a Repair Shop. *Journal of Operations Management (APICS)*, vol.6, no.1, Nov., pp.87-98.
- Sherbrooke C.C., 1968, METRIC: A Multi-Echelon Technique for Recoverable Item Control. *Operations Research*, vol.16, pp.122-141.
- Sherbrooke C.C., 1986, VARI-METRIC: Improved Approximations for Multi-Indenture, Multi-Echelon Availability Models. *Operations Research*, vol.34, no.2, March-April, pp.311-319.
- Slay M., 1984, VARI-METRIC: An Approach to Modelling Multi-Echelon Resupply when the Demand Process is Poisson with a Gamma Prior. Working Note AF 301-3, *Logistics Management Institute*, Washington D.C., July.