INVESTIGATION OF JOINT DECISION MAKING IN FLEET SYSTEM RELIABILITY DESIGN AND MAINTENANCE PLANNING

Ph.D. Thesis

By

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INVESTIGATION OF JOINT DECISION MAKING IN FLEET SYSTEM RELIABILITY DESIGN AND MAINTENANCE PLANNING

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**Investigation of Joint Decision Making in Fleet System Reliability Design and Maintenance Planning**" in the partial fulfillment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from January-2012 to August 2016 under the supervision of Dr. Bhupesh Kumar Lad, Associate Professor Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

20.01.2017

Signature of the student with date
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This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

20/01/2017

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for, Convener, DPGC

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Date: 20/01/2017

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Date: 20/1/2017

Signature of External Examiner

Date: 20/01/2017

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Abstract

Present thesis aims to investigate the joint decision making for fleet system reliability design and maintenance planning. Optimal reliability design and efficient maintenance planning are important aspects for capital-intensive industrial equipment/systems such as wind turbines, aircrafts, mining earth movers and defense systems, in which the unexpected failure creates massive repair and downtime costs. The selection of an optimal reliability design configuration and maintenance decisions are major constituent of the Life Cycle Cost (LCC) of these systems. Users of these industrial systems know this, and they increasingly take the LCC and availability into account in their purchasing decisions. As a consequence, Original Equipment Manufacturer (OEM) is now liable not only to deliver an optimal reliable design but also associated optimal maintenance decisions under Contractual Service Agreement (CSA). Mostly, OEM has multiple alternatives for various components of these systems at the early design decisions process. Designer's job is to choose the optimal reliability design for components from the available alternatives that meets user's budget constraints while minimizing LCC of the system. These systems are operated and maintained as a fleet and also known as fleet systems.

The fleet system is generally consists of multi-indenture (i.e. assembly, module and part) equipments. These types of equipments are supported by the multi-echelon maintenance network of base, depot and OEM. This multi-echelon and the multi-indenture system is known as a fleet maintenance system. In the fleet maintenance system, corrective maintenance decisions are taken based on the Level of Repair (LOR) analysis. Now, under the CSA, OEM decides optimal LOR decisions like; where i.e. at which echelon (base or depot or OEM) to perform maintenance action; at which indenture level (i.e. assembly or module or part) to perform the maintenance action and what maintenance actions (i.e., repair or move or discard) to perform on the selected indenture level. The LOR analysis is generally done to decide these variables such that the LCC of the fleet maintenance system is minimized. Moreover, for the effective maintenance planning, the availability of the spare parts plays a significant role in making

effective LOR decisions. Besides of that, industries also perform preventive maintenance to reduce the failure rate of the components and increase the life of such industrial system. Therefore, the LOR, PM and the spare level are important decisions in fleet maintenance planning.

Usually, optimal reliability design and LOR decisions are taken sequentially or independently, i.e., first design is selected, and then the LOR is decided. On the other hand, maintenance planning aspects i.e. spare parts stocking and preventive maintenance, the degree of restoration also have interdependencies with LOR decisions. Additionally, simplistic assumptions are taken during the LOR optimization in the existing literature. Such as, the constant failure rate assumption is used during LOR optimization. It does not allow consideration of the degree of repair during the LOR decisions such as repair/discard. Also, it does not reflect the actual life behavior of the components. The consideration of time-dependent failure rate of the components while optimizing the level of repair and spare parts stocking decisions is not done in the available literature. Besides, such equipment also receives preventive maintenance during the useful life of the equipment. However, the effect of PM during LOR decisions is not studied in the literature. This is mainly due to constant failure rate assumption and complexities to estimating the number of failures of the multi-indenture systems with time dependent failure rate of parts. In existing literature no work is found that considers the effect of preventive maintenance while optimizing the LOR decisions. While optimizing the LCC of the fleet maintenance system, a detailed LCC model to investigate the effect of various costs parameters i.e. maintenance facility cost, consumable cost, downtime cost, transportation cost and spare holding cost and stock-out cost is required. Such models are not elaborated adequately in literature.

Apart from theses, the problem of LOR optimization has been solved considering the single base, single OEM, and identical machine. Indeed, different systems or types of equipment may have different and more complex fleet structure. For example, in machine tools, multiple bases are associated with a multi-echelon maintenance network and these bases are associated with multiple OEMs for their machines. However, in some cases, these machines may not be identical, and it is enclosed with modular and non-modular components. On the other hand, system specific issues are not adequately addressed in the reported works. Therefore, the problem of multi-bases, multi-OEM and non-identical machine and the system structure related issues need to be addressed more efficiently.

Therefore, different fleet approaches are required to address all these issues in a fleet maintenance planning. Thus, the detailed investigation of joint decision making for system reliability design and maintenance decisions i.e. LOR, PM and spare level is essential for development of any fleet maintenance system. Present thesis aims to bridge these gaps while developing following methodologies.

- Methodology for simultaneous selection of reliability design and LOR for the fleet system.
- Methodology for joint optimization of LOR and spare parts decisions.
- Methodology for integrated strategy for preventive maintenance and level of repair.
- Methodology for machine tool maintenance modeling using the fleet maintenance architecture.

In the first methodology, an integrated approach for optimal reliability design and LOR decisions is developed. The methodology is solved for the constant failure rate and time dependent failure rate of the components while optimizing the reliability design and LOR decisions. It considers identical machines with modular assembly and more complex system design in a fleet maintenance system. The detailed model to estimates the effect of user's cost structure on LCC is also presented. These models are useful in the study the effect of user specific parameters on optimal reliability design and level of repair decisions. Results indicate that the most reliable design may not always result in best system performance. In other words, in some cases, lower reliability configuration with appropriate LOR decisions for a system may give better life cycle performance at the fleet. Therefore, the integration of reliability design and LOR decisions is important at the early design stage for the fleet systems. Results also demonstrate that the design and LOR decisions depend on users cost structure. Thus, the proposed approach helps in providing a user specific and integrated design and LOR decisions solution for fleet systems. Some thumb rules have also been suggested to ease the decision-making processes in the absences of sufficient data and time. The proposed approach may be adopted by any fleet user or OEM in optimizing the LCC performance of their fleet.

In the second methodology, a joint optimization approach is developed for the LOR and spare parts decisions in multi-echelon maintenance network. An important addition to the body of knowledge is the use of time-dependent failure rate model for the parts.

As discussed earlier, due to the constant failure rate assumption, the consideration of PM optimization with LOR analysis was not addressed, the same assumption is relaxed in this research. Base on this, third methodology presents a joint approach that finds an optimal solution for preventive maintenance schedule and level of repair decisions. The results identify that the proposed integrated strategy leads to better LCC performance in comparison to dis-integrated strategy. The different cases of restoration during the PM action have been considered. It is also identified that the degree of restoration also affects the PM schedule as well as LOR decisions of the fleet system. The problem has been solved for single base (single user) associated with single OEM in a fleet structure.

The fourth methodology provides a novel approach for the machine tool maintenance modeling considering fleet system architecture. This is demonstrated through the integrated decision making for the level of repair and preventive maintenance discussed in the third methodology. The approach has been solved for the multiple users (i.e. multiple bases) in fleet maintenance system. The approach considers the effect of the user's cost structure and shop floor planning parameters on the level of repair and preventive maintenance decisions. It considers the non-identical machine operated at different user's site and these users site are associated with different OEMs in fleet. Different PM approaches (i.e. high, medium and low degree of restoration) have been applied for the different machine tool users. The integrated approach shows 0.18 % to 63 % improvements in LCC of the different users compare to dis-integrated approach. The result shows the importance of the preventive maintenance strategy in level of repair analysis of machine tool fleet. The importance of user's cost structure and quality control policy parameters is also evident from the results. The proposed approach is expected to provide a new dimension to conventionally done maintenance planning in machine tool industry.

LIST OF PUBLICATIONS

List of Journal Publications

- Rawat M. and Lad B.K., “An Integrated Approach for Fleet Level Maintenance Planning”, *International Journal of Performability Engineering*, RAMS Consultant, Vol. 11, No. 3, May 2015, pp. 229-242.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND NOTATIONS

Abbreviations

Alt	Alternative
AACC	Annual Average Consumables Cost
AADTC	Annual Average Downtime cost
AAFC	Annual Average Failure Cost
AAPMC	Annual Average Preventive Maintenance Cost
AARC	Annual Average Recurrent Cost
AASOC	Annual Average Stock-out Cost
AATC	Annual Average Transportation Cost
ASHC	Average Spare Holding Cost
CCPM	Consumables Cost for Preventive Maintenance
CFR	Constant Failure Rate
CNC	Computer Numerical Control
CSA	Customer Service Agreement
DDNRC	Decision Independent Non-Recurrent Cost
DINRC	Decision Independent Non-Recurrent Cost
FC1	Failure Consequence 1
FC2	Failure Consequence 2
FC3	Failure Consequence3
LCC	Life Cycle Costs
LOR	Level of Repair

LORA	Level of Repair Analysis
MTTR	Mean time to repair
NPV	Net Present value
NRC	Non Recurrent Cost
OEM	Original Equipment Manufacturer
OEMs	Original Equipment Manufacturers
PM	Preventive Maintenance
RF	Restoration Factor
SHC	Spare Holding Cost
SL	Service Level
TDFR	Time-Dependent Failure Rate
TMTTR	Total Mean Time to Repair

Notations

B	Total number of base in a fleet
(ijk)	k^{th} part of j^{th} module of i^{th} assembly
(ij0)	j^{th} module of i^{th} assembly
(i00)	i^{th} assembly of a machine/system
λ(ijk)	failure rate of part(ijk)
A	Design alternative for an assembly (i00)
(ijk) $_d$	Design alternative for a part (ijk)
S (ijk)	Quantity of spare parts decision of the indenture item (ijk).
D	Design matrix of an assembly

r	Repair action
e	Echelon decision
R	Annual discounted factor for cost
L	Expected life of machine
C_{mf}	Cost of maintenance facility
C_{aq}	Cost of acquisition
CC	Cost of consumables
m_b	Total number of machine at base "b"
C_{dt}	Cost of down time per hour
$TC(i00)$	Transportation cost for an assembly (i00)
$TC(ij0)$	Transportation cost for a module (ij0)
$TC(ijk)$	Transportation cost for part (ijk)
$S(i00)$	Quantity of the spares of an assembly (i00)
$h(i00)$	Holding cost of an assembly (i00)
α_b	annual arrival rate of assembly failures at base "b"
μ_b	service rate of failed assembly for base "b"
$MTTR_d$	Mean time to repair at depot level
$MTTR_{OEM}$	Mean time to repair at OEM level
$[T_{Delay}]_{b-d}$	Transportation delay between base level to depot level
$[T_{Delay}]_{d-OEM}$	Transportation delay between depot level to OEM level
$P_{(0)}$	probability of "no assembly" in the queue at each base
$P_{S(i00)}$	probability of $S(i00)$ number of repaired assembly in queue at

	base "b"
$P_{(>S(i00))}$	probability of more than S (i00) quantity required at base "b"
$\left(PP_{S(i00)}\right)_b$	Poisson probability of exactly S(i00) spare of repaired assembly at base "b"
$\left(PC_{S(i00)}\right)_b$	Poisson cumulative probability of the exactly S(i00) or less spares of repaired assembly at base "b"
$P_{(ijk)}$	k^{th} Part of j^{th} module of i^{th} assembly
a	Number of assemblies in a machine
b_i	Number of modules in i^{th} assembly
c_j	Number of parts in j^{th}module
η_{ijk}	Scale parameter of $P_{(ijk)}$
β_{ijk}	Shape parameter of $P_{(ijk)}$
PV_{fm}	Present Value of LCC for the machines in a fleet system maintenance
I	Decisions of the level of indenture
E	Decisions of the level of echelon
S	Number of spares for various indentures at a given echelon
$S_{(i)_e}$	Number of i^{th} spare assembly at echelon e
$S_{(ij)_e}$	Number of j^{th} spare module of i^{th} assembly at echelon e
$S_{(ijk)_e}$	Number of k^{th} spare part of j^{th} module of i^{th} assembly at echelon e
V_e	Total space available for keeping the spare inventory at

	echelon e
$v_{(i)}$	Space required for i^{th} assembly
$v_{(ij)}$	Space required for j^{th} module of i^{th} assembly
$v_{(ijk)}$	Space required for k^{th} part of j^{th} module of i^{th} assembly
$C_{(ijk)}$	Cost of consumables against the failures of each part (ijk)
$NF_{y\,(ijk)}$	Number of failure of part (ijk)
m	Number of identical machines at operated at base
$TTR_{(ijk)}$	Time to repair against the failure of each part (ijk)
$TTT_{(ijk)}$	Total transport time against the failure of each part (ijk)
C_{dt}	Downtime cost per hour
$TC_{(ijk)}$	Total cost of transportation against the failure of part(ijk)
$Q_{(i)_e}$	Annual quantity of assembly of i^{th} assembly at echelon e
$Q_{(ij)_e}$	Annual quantity of assembly of j^{th} module of i^{th} assembly at echelon e
$Q_{(ijk)_e}$	Annual quantity of assembly of k^{th} part of j^{th} module of i^{th} assembly at echelon e
T_{Delay}	Time delay in getting the shortage quantity of required indenture at echelon e
$h_{(i)_e}$	Holding cost per i^{th} assembly at echelon e per year
$h_{(ij)_e}$	Holding cost per j^{th} module of i^{th} assembly at echelon e per year
$h_{(ijk)_e}$	Holding cost perk^{th} part of j^{th} module of i^{th} assembly at echelon e per year

RF	Restoration Factor
$t_{pm}(ijk)$	Decision of PM schedule for enclosed k^{th} part of j^{th} module of i^{th} assembly.
$L_{r,e}(ijk)$	LOR decision for enclosed k^{th} part of j^{th} module of i^{th} assembly
PV_{LCC}	Present Value of LCC for the machines in a fleet system maintenance
l	Expected life of each machine
R	Annual discount rate;
$[C_{mf}]_{r,e}(ijk)$	One time maintenance facility cost for the indenture level (ijk) based on selected repair action r and echelon e
$[CC(ijk)]_{PM}$	Cost of consumables for indenture level(ijk) during preventive repair action;
$CC_{r,e}(ijk)$	Cost of consumables for the indenture level(ijk)based on selected repair action r and echelon e
$\left[NPM(ijk)_{t_{pm}(ijk)}\right]_y$	Number of preventive repair action for the indenture level(ijk)in y^{th} year based on given PM schedule $\mathbf{t_{pm}(ijk)}$
$\left[nof(ijk)_{t_{pm}(ijk)}\right]_y$	Number of failures of the indenture level(ijk)in y^{th} year based on given PM schedule $\mathbf{t_{pm}(ijk)}$
$TTRPM(ij0)$	Time to repair for the module (ij0) during the preventive repair action
C_{dt}	Down time cost per hour

$[TC(ijk)]_{b-d}$	Cost of transportation for the indenture level(ijk) from the base to depot level
$[TC(ijk)]_{d-OEM}$	The cost of transportation for the indenture level(ijk) from the depot level to OEM level
$t_{opert.}$	Total operating time of the machines
$(T_{Delay})_{b-d}$	Transportation time between base and depot
$(T_{Delay})_{d-OEM}$	Transportation time between depot level and OEM level
$h(ijk)$	Holding cost per year of an indenture items (ijk)
$PP_{Q(ijk)}$	Poisson probability of an indenture items (ijk)
$PC_{Q(ijk)SL}$	Poisson cumulative probability for "Q" quantity of an indenture items(ijk);
$PC_{>Q(ijk)_{SL}}$	Probability of more than "Q" quantity of an indenture item (ijk) with predefine service level
$(m_n)_b$	Numbers of "n^{th}" machine tools operated at base b
η_{ijk}	Scale parameter of k^{th} part of j^{th} module of i^{th} assembly
β_{ijk}	Shape parameter of k^{th} part of j^{th} module of i^{th} assembly
$(LCC_{PV})_b$	Present Value of the life cycle cost incurs by the base "b" in the fleet structure
$L_{r,e}(ijk)_{m_n}$	LOR decision for enclosed k^{th} part of j^{th} module of i^{th} assembly of n^{th} machine
$t_{pm}(ijk)_{m_n}$	PM interval for enclosed k^{th} part of j^{th} module of i^{th} assembly of n^{th} machine

$\mathrm{AAFC_b}$	Annual average cost of failures that incurs whenever a machine tool fails at user “b”
$(\mathrm{AAPMC_b})$	Annual Average Preventive Maintenance Cost by the user “b”
$\mathrm{FC(ijk)_{m_n}}$	Failure Cost per corrective action for a part (ijk) of n^{th} machine
$\mathrm{CCPM_{m_n}(ijk)}$	Consumable cost incurs during the preventive repair action for a part (ijk) of n^{th} machine
$\mathrm{TTRPM(ij0)}$	Total time to repair consumes during the preventive repair for a module (ij0) of n^{th} machine
$\mathrm{TTRPM(ijk)}$	Time to repair consumes during the preventive repair action
$\left[\mathrm{C_{lp}}\right]_{\mathrm{m_n}}$	Cost of lost production per job for n^{th} machine
$\left[\mathrm{C_{rej.}}\right]_{\mathrm{m_n}}$	Cost of rejection per job for n^{th} machine
$\mathrm{DPR_{m_n}}$	Designed production rate (jobs/hour) of n^{th} machine
$\mathrm{C_{mf}(ijk)_{m_n}}$	Non-recurrent cost for a part (ijk) of n^{th} machine
$\mathrm{CC(ijk)_{m_n}}$	Consumable cost for a part (ijk) of n^{th} machine
$\mathrm{DTC(ijk)_{m_n}}$	Downtime cost for a part (ijk) of n^{th} machine
$\mathrm{TC(ijk)_{m_n}}$	Transportation cost for a part (ijk) of n^{th} machine
$\mathrm{SHC(ijk)_{m_n}}$	Spare holding cost for a part (ijk) of n^{th} machine
$\mathrm{SOC(ijk)_{m_n}}$	Stock-out cost for a part (ijk) of n^{th} machine
$\mathrm{S_{m_n}}$	Sample size for n^{th} machine
$\mathrm{ts_{m_n}}$	Time between samples for n^{th} machine
$\mathrm{C_{FC1}(ijk)_{m_n}}$	Cost of failure for a part (ijk) of n^{th} machine when failure leads to FC1

$C_{FC2}(ijk)_{m_n}$	Cost of failure for a part (ijk) of n^{th} machine when failure leads to FC2
$C_{FC3}(ijk)_{m_n}$	Cost of failure for a part (ijk) of n^{th} machine when failure leads to FC3
RPR_{m_n}	Reduced production rate (jobs/hour) of n^{th} machine
$t_{FC2_{m_n}}$	Time to detect the failure consequences 2 for n^{th} machine
IRR_{m_n}	Increasing rejection rate for n^{th} machine
$t_{FC3_{m_n}}$	Time to detect the failure consequences 3 for n^{th} machine
β'_{m_n}	Type II error for n^{th} machine
$\left(ARL_{\beta'}\right)_{m_n}$	The average runs length for n^{th} machine
δ_{m_n}	Process shift for n^{th} machine
$P_{FC1}(ijk)_{m_n}$	Probability of failure consequences1
$P_{FC2}(ijk)_{m_n}$	Probability of failure consequences2
$P_{FC3}(ijk)_{m_n}$	Probability of failure consequences3
$[nof(ijk)]_{m_n}$	Number of failure of part (ijk) of n^{th} machine
$[TTRPM(ij0)]_{m_n}$	Time to repair of part (ijk) of n^{th} machine

Chapter 1

Introduction

1.1 Preamble

Failures of capital-intensive systems, like wind turbines, gas turbines, machine tools, aircrafts, ships, mining earth movers, etc. create huge downtime losses which result into high maintenance and repair cost. In many situations, the cost of maintenance is about 35% of the total operating cost of the equipment, and it can be as high as 50%–60% when both direct and indirect costs are taken into account (Roy et al., 2001). For example, the failure of a $5000 wind turbine bearing may result into a $250,000 maintenance operation, as replacement requires specialized repair equipment and service crew, in addition to the loss of power generation (Kusiak and Li, 2011). Thus, maintenance cost is a significant contributor to the Life Cycle Cost (LCC) of such capital-intensive systems (Saranga and Kumar, 2006).

Recently, users are making Original Equipment Manufacturers (OEM) more responsible for the failures by engaging into Contractual Service Agreement (CSA) with them. CSA is a written commitment between the OEM and the user for certain availability level of the equipment over a given period. In other words, users pay a certain amount of money to OEM to get the availability assurance. In fact, this has provided OEMs new business opportunities to "Servicizing" their product-centric businesses, where OEMs can sell their products/equipment as well as associated maintenance services.

The reliability and availability are therefore major factors affecting the profitability of business of OEMs. Reliability is applicable at the design stage of equipment, while availability comes into existence after installing the equipment or after a steady state of operation is reached (Murty and Naikan, 1995). Therefore, improved reliability design and efficient maintenance planning have potential to minimize the LCCs to the OEMs thereby increasing profit from availability contracts.

OEM provides maintenance support to various users or bases (locations where one or more of its equipment are installed and operating) through multi-level repair facility. In literature, it is referred to as fleet maintenance system. Present research work focuses on the investigation of the value of joint decision making for reliability design and maintenance planning in fleet maintenance systems.

1.2 Problem Details

In this section, fleet system reliability design and maintenance planning aspects are discussed in details and research problem is defined. The problem complexity is also discussed.

1.2.1 Fleet Maintenance System

Fleet is a group of complex systems operating at one location or different locations that share some common maintenance facilities (Alfredsson, 1997). Complex systems are usually represented as multi indenture system. Indenture is generally composed of several components linked with each other through father-son relationship and it is also known as the modular systems. The indenture refers to the physical configuration of a system like assemblies, modules/subassemblies and parts/components. Figure 1.1 shows an example of a multi-indenture system. The maintenance of the multi-indenture systems is generally supported by multi-echelon maintenance network. Figure 1.2 shows a multi-echelon maintenance network of base, depot and OEM. Such multi-echelon and multi-indenture system is called as fleet maintenance system (Saranga and Kumar, 2006). “Base” is considered as the operating site of the users where identical/non-identical systems are installed and operated. Next level is the “depot”, which is a central maintenance facility to support various bases/users in a fleet. The depot has more advanced fault diagnosis, maintenance and repair facility compared with base level maintenance facility. The depot is supported by OEM level repair facility. This is the facility at the manufacturer's site and it is capable of performing almost all kind of maintenance and repair actions required by the equipment.

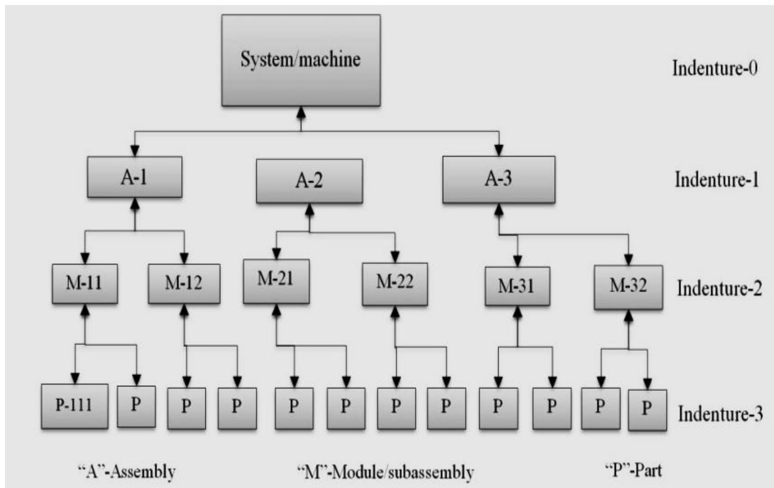

Figure 1.1: Multi-Indenture system

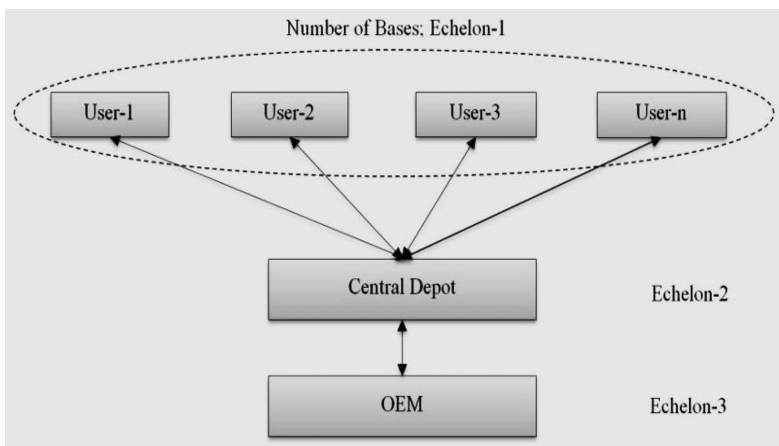

Figure 1.2: Multi-echelon maintenance network

1.2.2 Optimal Reliability Design

Modern systems are becoming more and more complex, sophisticated and automated, and a measure of effectiveness that cannot be sacrificed in their reliability. Reliability has become a mandatory requirement for customer satisfaction and is playing an increasing role in determining the competitiveness of the products. Because of these reasons, system reliability optimization is important in any system design (Lad and Kulkarni, 2008). In literature, reliability optimization problems are broadly put into three categories according to the type of their decision variables: reliability allocation, redundancy allocation, and reliability-redundancy allocation. If the component reliabilities are only the variables (Salazar et al., 2006 and Yalaoui et al., 2005) the problem is called reliability allocation; if the number of redundant units is the only variable (Scarf) the problem becomes redundancy allocation problem; if the decisions variable of the problem include both the component reliabilities and redundancies (Nakagawa, 1978) the problem is called a reliability-redundancy allocation problem. For repairable systems, reliability and maintainability both are allocated to each of the components in the system. It is sometimes also referred to as optimal availability design (Misra, 1970). However, various other factors related to repair like spare parts, degree of repair, level of repair, preventive maintenance schedules, etc. also affect the overall availability of the system and must be considered while designing for the reliability or availability (McQuiggan, 1996; Markeset and Kumar, 2003).

In the case of industrial equipment, which is generally operated and maintained under fleet system architecture, optimal reliability design actually boils down to the selection of assemblies, modules and parts, from the available alternatives (Lad and Kulkarni, 2013). All these alternatives while satisfying the functional requirements of the system differ in their inherent failure and repair characteristics, like time-to-failure distribution, time-to-repair distribution, and cost. For example, in aircraft design, a designer may have two alternatives for landing wheel braking system viz. mechanically powered system and hydraulic powered system. Even though both these alternatives may satisfy the functional requirements of the aircraft, they will have a different failure and repair characteristics and associated costs. Similarly, inherent failure and repair characteristics also vary among alternatives of the different make. Therefore, each of these alternatives will contribute differently to the reliability performance of the system (Lad and Kulkarni, 2013). Alternatives may also vary on the modularity. Modularity, apart from the cost of the equipment, also affects the maintainability of the system. A modular design of the system provides an ease of maintenance as it reduces the service time in terms of fault diagnosis, access and repair (Karmarkar and Kubat, 1987). Hence, the designer job is to select an optimal design configuration from the available alternatives for the fleet equipment in such way that it minimizes the LCC of fleet maintenance system.

1.2.3 Fleet maintenance planning

Following are three of the most important aspects of fleet maintenance planning.

- Level of repair analysis
- Preventive maintenance planning
- Spare planning

These are discussed in details in following subsections.

1.2.3.1 Level of Repair Analysis

LOR analysis is used to obtain the optimal decisions pertaining to:

- what maintenance action (repair or move or discard) to perform;
- at which indenture level (assembly or module or parts) to perform these actions;
- and where i.e. at which echelon level (base or depot or OEM) to perform these actions.

These decisions have cost consequences. For example, the cost of installing particular maintenance facility at the base will be higher than that at the depot as depot supports multiple bases. Similarly, the cost of holding spare inventory at the base is generally higher than that at depot or OEM. However, moving maintenance decisions to higher level echelons incurs extra transportation and downtime cost. Thus, the level of repair analysis aims at making these decisions such that the LCC is minimized.

1.2.3.2 Preventive Maintenance Planning

Preventive maintenance is done to reduce the failure rate and extend the useful life of the machine components. However, PM requires the time and cost which could otherwise be used for production. On the other hand, ignoring PM may lead to unexpected failures resulting into excessive downtime costs. Therefore, PM optimization is done to obtain the optimum interval for preventive maintenance that minimizes the LCC or cost of maintenance. For a modular system like the multi-indenture system, it is often preferable to perform PM at the module level. Optimization of PM schedule is essential for efficient system performance.

1.2.3.3 Spare Optimization

Keeping too less spare parts involves stock out cost which includes excessive downtime costs due to unavailability of the repair spares. On the other hand, keeping excessive inventory may lead to increase in spare holding cost. Thus, spare optimization aims at obtaining the optimal number of repair spare inventories of different indentures at the base, central depot and OEM according to the LOR decisions. Sometimes, Spares are maintained at a predefined service level. For example, a 95 % service level requires the quantity of spares sufficient to meet the demand for 95 % of the time.

1.3 Problem Definition

Traditionally, optimal reliability design and LOR decisions are taken sequentially or independently, i.e. first the design is selected and then the LOR is decided. However, the set of decisions has interactive effects. For example, modularization may affect the decisions of indenture level at which repair should be performed. Reliability of parts within a module may affect the repair/discards decisions. Thus it is hypothesized here that the joint optimization of reliability design and LOR will be economical for the users. The same is investigated in detailed in this research.

Apart from reliability design and LOR interaction, other maintenance planning aspects like spare parts stocking and preventive maintenance planning, degree of restoration also have interdependencies with LOR decisions. For example, LOR and spare stocking decisions are interdependent as they jointly affect the life cycle cost of any fleet maintenance system (Basten et al., 2015). If replacement decisions are made at the assembly level and at first echelon, and if sufficient inventory of assemblies is not available at that echelon then it may lead to excessive downtime costs. On the other hand keeping excessive inventory at any echelon may result in more holding costs. Similarly, if the decision of replacement is made at higher echelons, then it may involve additional transportation cost and may also increase downtime cost. However, the cost of holding the spares at higher echelons may be lesser than that at lower echelons and it may be economical to send the indenture to higher echelons for further maintenance decisions. Thus, investigation of joint decision making for LOR and spare parts stocking is important for fleet maintenance system. The problem becomes more challenging for parts having time dependent failure rate distributions. Also, industries perform Preventive Maintenance (PM) based on predefined schedule to reduce the failure rate and extend the life of the components. Optimization of PM plays a major role in the effectiveness of the system performance and many authors have studied it (Levitin and Lisnianski, 2000; Ahmad and Kamaruddin, 2012; Aghezzaf et al., 2016; Aghezzaf et al., 2016; Liu et al., 2014; Regattieri et al. 2015). PM schedule affects the failure rates as well as the cost of maintenance which in turn affects the LOR decisions. Therefore, PM schedule and LOR decisions are two activities, which have interaction effect but are often planned separately in a fleet. In fact, the constant failure rate assumption used in existing literature during LOR analysis does not allow consideration of the effect of PM or degree of repair.

Existing research on fleet maintenance considers simplistic assumptions in terms of fleet structure, modularity of systems, types of maintenance and repair facilities at various echelons. These assumptions may not be valid for a particular fleet system and needs to be relaxed while modeling the fleet maintenance problem. For example, most of the literature consider single base (i.e., single-user site) which is being supported with single OEM. Similarly, in most of the fleet maintenance planning literature, types of equipment are considered as identical and modular. However, fleet having multiple bases (or users) with identical or non-identical types of equipment from more than one OEMs is common in a machine tool fleet.

Similarly, the possible repair facilities at various echelons of the repair network may also vary based on the type of system. For example, a wind turbine fleet may have only basic repair facility to remove the failed assembly from the system. On the other hand, machine tools fleet have a dedicated maintenance department at the shop floor of the users to perform routine corrective and preventive maintenance tasks while being also supported by central repair facility and OEMs. Thus, exploring the fleet maintenance modeling for various fleet structures will widen the scope of application of the research in fleet system reliability design and maintenance planning.

Motivated from the above discussion, the research problem can be stated as: "Investigation of the value of joint decision making for reliability design and maintenance planning in various fleet systems."

1.4 Problem Complexity

The problem complexity can be seen from two points of views viz., modeling and solution. The complexity in modeling arises mainly due to consideration of time dependent failure rate models, imperfect maintenance and stochastic natures of parameters. In case of time dependent failure rate, getting a close form solution for number of failures is not possible (Block et al., 2013; 2014). The complexity further increases with the consideration of imperfect maintenance which brings partial restoration to the components/systems. This precludes possibility of any analytical modeling. Apart from number of failures, other parameters like time to repair etc. are also stochastic in nature. Hence, a simulation based approach is required. For example, in the case of joint optimization of LOR and design decisions, the size of solution space depends on number of possible design configurations for assembly and modules. The solution space further gets multiplied by possible level of repair decisions for selected design configuration. The total design configuration at system/machines depends on the number of design alternatives available at enclosed part level. Similarly, the size of LOR decisions for system/machine depends on number of enclosed indenture items and the possible maintenance actions at each echelon. For example, system/machine has “k” number of enclosed indenture items and number of maintenance actions available at base, depot and OEM for each indenture item are “r”. Therefore the total number of LOR decision would be r^k. Therefore possible alternatives of design and LOR for system/machines would be the multiplication of total design configuration at system level and total number of level of level of LOR decisions. Thus, it can be easily realized that, even for a moderate size of possible decisions, the total problem size may become very high to be solved by any exact optimization technique. Thus a simulation based genetic algorithm is used in this research to solve the problems discussed in chapter 3 to 6. However, one may explore the use of any other metaheuristic to get improved solution. The present research does not focus on comparison for various metaheuristic rather it focuses on investigation of importance of joint decision making in fleet maintenance system.

1.5 Industrial Relevance

Maintenance services have created exciting business opportunities for product manufacturers and it is becoming their key business models. This is true not only for industrial or asset intensive products like aircrafts, ships, machine tools, gas turbines, etc., but also for consumer durable goods, like water purifier, cars, inverters, etc. Maintenance operations of these types of equipment can easily be justified to be following fleet maintenance system architecture with expected deviations in the performance criteria, system architecture, criticality of various maintenance planning issues, etc. Thus, the present research area is very relevant and contemporary for both capital goods industries and consumer durable goods industries. In this research more focus is given on industrial goods or capital goods industries. In chapter 6 an attempt is made to discuss and model the problem for machine tools industries point of view. This further confirms the importance and feasibility of the proposed research for such industries.

1.6 Research Gaps and Objective of the Research Work

In this section, research gaps identified from literature review are presented and research objectives are mentioned. A detailed literature review is provided in Chapter 2. The following research gaps are addressed in this research.

Gap 1: Despite the interaction effect, the reliability design and Level of Repair (LOR) decisions are made sequentially or independently.

Gap 2: Effects of degree of repair and preventive maintenance are not considered during Level of Repair (LOR) analysis.

Gap 3: Consideration of time dependent failure rate models in fleet system decision making is not reported in the literature.

Gap 4: Simplistic assumptions like single base, single OEM and identical machines for fleet structures are generally used in the existing literature.

Gap 5: Investigation of the effect of various parameters of life cycle models on fleet system reliability design and maintenance planning is not addressed in the literature.

Based on the above discussions, the objectives and sub-objectives of the present research are stated as follows:

Overall Objective

"Modeling and investigation of joint decision making in fleet system reliability design and maintenance planning".

Sub-objective 1: To investigate the effect of reliability design alternatives on the level of repair decision making.

Sub-objective 2: To investigate the effect of preventive maintenance and degree of restoration on the level of repair decisions.

Sub-objective 3: Solving fleet system reliability design and maintenance planning problems using time-dependent failure rate models.

Sub-objective 4: Development of detailed life cycle cost models for fleet maintenance system.

Sub-objective 5: Exploring the fleet system reliability design and maintenance planning decision making for various fleet system structures.

Sub-Objective 6: Modeling of machine tools maintenance planning under fleet system architecture.

1.7 Methodology

Figure 1.3 summarizes the overall research work done in this thesis.

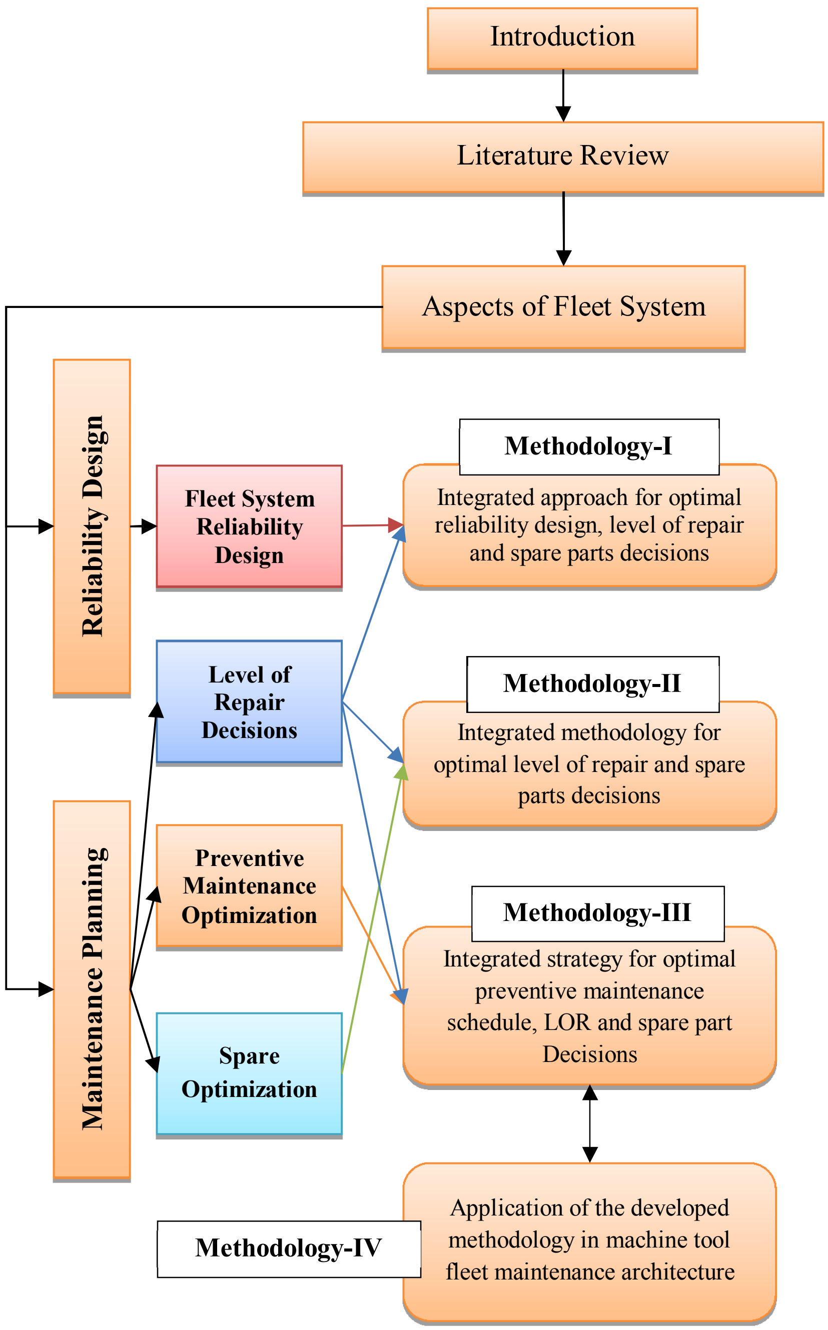

Figure 1.3 Research Methodologies

1.8 Thesis Outlines

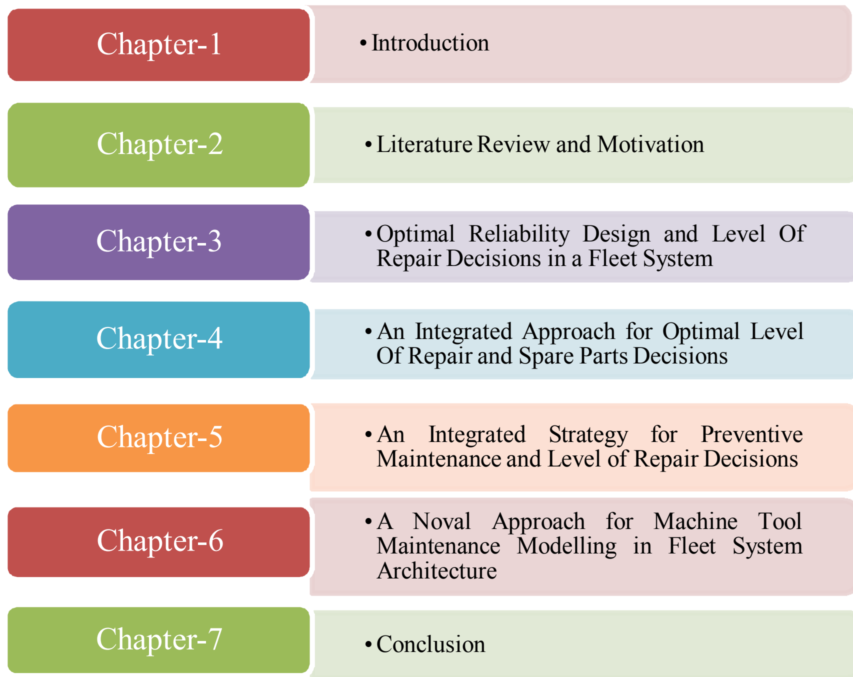

Figure 1.4: Thesis Outlines

The thesis has been structured in the seven chapters. Figure 1.4 provides the content of the each chapter presented in this thesis.

The present chapter has provided an overview of the research problem. A summary of rest of the chapters is as follows;

Chapter 2 provides the literature review on different aspects of the reliability design and maintenance planning for fleet systems. First the chapter reviews literature on optimal reliability design and summarizes the gaps from multi-indenture system point of views. Level of repair optimization, optimal preventive maintenance plan and spare parts optimization literature are also reviewed. The literature is focused on the system/machines operated in a fleet maintenance environment.

Chapter 3 provides a methodology for the simultaneous selection of optimal reliability design configuration and level of repair decisions for system/machine operated at different user's site in a fleet. A detail model to estimate the effect of users cost structure on LCC is also presented. A queuing model is provided for calculating the fill rate of spares at the base level (i.e. user's site). The effect of modularization in the fleet system design is investigated. The effect of reliability vs. cost curve in the design of the fleet system is also identified. Additionally, the same approach is solved by considering the time-dependent failure rated of the components. A time-dependent failure rate model for the LOR analysis is presented. More complex fleet system design configuration is considered while optimizing the reliability design and LOR. The proposed time-dependent failure rate model helps to consider the Preventive Maintenance (PM) for the fleet machine.

Chapter 4 develops a joint optimization methodology for the level of repair and spares parts decisions for the fleet system. It provides the optimal decisions for the location of maintenance, the level of indenture for maintenance and level of repair spares inventory at different echelons. Interdependency between the LOR and spare decisions are presented considering the different user's cost structure.

In **Chapter 5** an integrated strategy is presented that finds an optimal solution for integrated preventive maintenance schedule and level of repair analysis. A different case of the degree of restoration is presented, which investigates the effect of degree of restoration on the LOR and PM schedule decisions.

Chapter 6 identifies a novel approach for the machine tool maintenance fleet system. The approach is provided an optimal integrated solution of PM schedule and LOR decisions for different machine tool users in the fleet maintenance architecture. The integrated strategy proposed in Chapter 5 is used to solve this approach. In this chapter, an effect of user's shop floor policies and cost structure is investigated on the integrated solution for LOR and PM.

Chapter 7 outlines a chapter wise summary of the research reported in this thesis. It provides research findings and significant contributions made to the body of knowledge. Future scope is also provided the same chapter.

1.9 Summary

This chapter provides an overview of the research problem i.e. “investigation of the value of integrated decision making in fleet system reliability design and maintenance planning”. Different aspects of the research problem, problem complexity and industrial relevance are discussed. The motivation for the research, research gaps and objectives are also provided in this chapter. Finally, the thesis outline along with the chapter-wise summary of the entire thesis is also given in this chapter.

Chapter 2

Literature Review

2.1 Introduction

The main objective of the present research, as mentioned in the previous chapter is to develop various methodologies to investigate the value of integrated reliability design and fleet maintenance decisions. Fleet maintenance decisions considered in this research are level of repair, preventive maintenance and spare level. Keeping the objective in mind, a literature review is carried out to gain an insight into the present research i.e. joint decision making in fleet system reliability design and maintenance planning. The literature review is categorized in the two parts as follows;

- Fleet maintenance planning,
- Optimal reliability design.

Literature pertaining to these two aspects is discussed in details in following sections and observations are summarized.

2.2 Fleet Maintenance Planning

In fleet maintenance planning, the literature review is done in the area of Level of Repair (LOR) optimization, spare parts decisions and PM optimization. Also, the integrated approaches in fleet maintenance planning are reviewed.

2.2.1 Level of Repair Analysis

LOR optimization for multi-indenture and multi-echelon system has received significant attentions in literature. It mainly focus on optimizing level of repair decisions like, where to perform maintenance, which indenture should go for maintenance and what maintenance action (repair/replace/discard) should be performed. Researchers have mainly focused on development of more efficient models. Alfredsson (1997) presents a model for the integrated problem of LORA and spare parts stocking. It considered single indenture level only and two echelons levels. Furthermore, author assumed that each component has its own tester (resource) and one multi-tester exists. This multi-tester can be used for one component and adapters can be added in a fixed order. The adapters enable the multi-tester to be used for the repair of additional components. Barros (1998) for example, has proposed an integer- programming based Level of Repair Optimization Model (LOROM). It considers fixed and variable maintenance costs for optimizing the level of repair decisions for two indentures system. It also considered the single base and single OEM problem. Similar problem for multi-echelon and multi-indenture level system is formulated by Barros and Riley (2001). Saranga and Kumar (2006) used a Genetic Algorithm based optimization approach for optimal decisions of LOR for multi-indenture and multi-echelon fleet maintenance system. It aims to optimize decisions like, where to perform maintenance, which indenture should go for maintenance and what maintenance action (repair /replace/discard) should be adopted on failure of a part. It also considers the single base and single OEM fleet maintenance system. It does not give the detailed models to estimate various constituents of LCC such as such downtime, consumable, transportation etc. A mixed-integer programming model for level of repair decision and location of repair facilities is proposed by Brick and Uchoa (2009). It optimizes the location of installation of maintenance facilities. It also optimizes the decisions of repair and discards for the components. It combines the LORA problem with the decision of which facilities to open at each location. They assume a two-echelon network structure and a two-indenture product structure. Basten et al. (2009) presented an integer programming model for LOR decisions. It generalizes the LOR decisions model given by Saranga and Kumar (2006). For example, Basten et al. (2009) consider that the fixed costs are borne by any arbitrary set of components. However Saranga and Kumar (2006) considered that the fixed costs are borne by a single component. The authors do not provide a detailed model for LCC calculation for example; it also ignores costs like, downtime, transportation, consumables etc.

Apart from this, the LOR optimized with the assumption of constant failure rate of the components. Basten et al. (2011a; 2011b) proposed a minimum cost flow model for the level of repair analysis. The model requires less computational effort than solving existing models and it achieve high model flexibility, i.e., many practical extensions can be added such as it includes repair probabilities, no-fault-found probabilities and equipment with a finite capacity. The problem has solved instances much faster using new formulation than using the formulation of Basten et al. (2009). In the discussed literature, majority of the researchers considered a simplistic assumption such as single base and single OEM problem. An identical machine with modular structure is considered in their research problem. Most importantly, a constant failure rate is considered while optimizing the LOR decisions. The system specific issues are ignored in the literature. Most of the works have considered the LCC as an objective function to optimize the LOR decisions. In which the LCC is considered as fixed and variable cost only. Detailed model to estimate various constituents of LCC are not used.

Most of the works such i.e. Barros (1998); Barros and Riley (2001); Saranga and Kumar (2006); Brick and Uchoa (2009); Basten et al. (2009); Basten et al. (2011a; 2011b) are optimized the LOR problem considering a fixed spare inventory. For example, in the work of (Alfredsson, 1997) a model is presented for optimizing quantity of spare parts and number of test equipment. It also aims at identifying optimal repair location. The approach aims at minimizing the number of backorders while meeting the life cycle cost constraints.

2.2.2 Integration of Level of Repair and Spare Level

The importance of spare parts optimization has increased in the past decades. One reason is the fact that system availability and high quality after sales service has become important criteria when selecting OEM of industrial equipment. A second reason is the increasing value of service part inventory investment. A survey by Cohen et al. (1997) reports that service parts inventories equal 8.75% of the value of product sales in their sample, being over $23 million inventory investment on average. In this survey, the following characteristics and trends in service delivery organizations are observed:

- a large and geographically dispersed installed base (users);
- a large number of multi-indenture items to be stocked, varying between 2500 and 300,000 in the sample;
- increasing costs of service parts due to increasing complexity and modularity, in the sample being \$270 on average with exceptions up to several hundred thousands of dollars;

As a consequence of the increasing costs of spare parts (third characteristic above), it is worthwhile to consider discard rather than repair. Repair spare parts are often supplied via a multi-echelon maintenance network, i.e. a hierarchical network of stocking locations through which repair spare are supplied to the customer's site. The outcomes of LOR analysis is generally be used for deciding the optimal spare level. The integrated decisions for level of repair and spare level may arrive with efficient maintenance planning.

Therefore, recently more focus has been given to joint optimization of level of repairs and spare parts inventory. The joint optimization of LOR and spare parts are not significantly reported in the existing literature. However, researchers have addressed this joint problem with constant failure rate of the components. Basten et al. (2011b) proposed a model for optimizing quantity of spare parts and test equipment. It also aims at identifying optimal repair location. The approach aims at minimizing the number of backorders while meeting the life cycle cost constraints. It considers single indenture system. Basten et al. (2012) proposed a joint optimization model for LOR analysis and spare parts decisions considering the base problem of (Alfredsson, 1997). The difference in this proposed model is that it considers the infinite resource capacity as compare finite resource capacity considered in Alfredsson (1997). It considers the two echelons and single indenture system and constant failure rate of the components. The trade-off curve of spare investments costs vs. backorders and target availability of the system has been considered for the measures of the model performance. It considers the spare holding cost and number of backorders for the decision of stocking the spare parts. Authors compare the results of joint approach with sequential approach considering the computational time, cost reduction and average availability. It is observed that the join optimization gives better performance in terms of cost reduction and average availability. An iterative algorithm for joint optimization of level of repair and spare part stocking decision is presented in the work of (Basten et al., 2015). It considers the multi-indenture and multi-echelons system and constant failure rate. In this approach, the basic idea is to first solve a Level of Repair Analysis (LORA), next solve the spare parts stocking problem considering the target availability, and then use the results of spare parts stocking decision to add an estimate of the holding costs to the LORA inputs and start a second iteration. In this way, it continues until a different improved solution is obtained. It performs better compared to the sequential and integrated approach highlighted in the work of (Basten et al., 2012). Fan et al. (2013) presented a multi-indenture and single echelon model considering the relationship between maintenance time (i.e. spares waiting time) and spare stock level. It highlights the contradiction between spare waiting time and spare stock level. (Juan et al., 2014) proposed a marginal analysis based multi-item, multi-echelon inventory allocation model considering the availability of the fleet airlines. It develops the relationship between the availability and backorders. The negative binomial distribution is considered for the backorders and suggested the binomial distribution is more suitable as compare to Poisson distribution for backorders. In the work of Cranshaw et al. (2014) a multi-objective genetic algorithm based Monte Carlo simulation optimization considering the LORA and optimal number of spares is proposed. The optimization considers the repair cost and spare parts availability as objective function. Monte Carlo simulation is used to generate scenarios based on a dataset which includes the expected failures of the equipment and their associated probabilities. The repair cost is consisted of cost of spare parts, cost of spares transportation and cost of spares storage.

Further, the preventive maintenance optimization is performed in maintenance planning for system effectiveness. The next section discussed the key literature related to preventive maintenance optimization for multi-indenture modular system.

2.2.3 Preventive Maintenance Optimization

A vast majority of maintenance models assume either perfect repair (renewal), or minimal repair. Perfect repair implies that the equipment is as ‘good as new’ after repair. Minimal repair implies that the equipment is ‘as bad as old’ after repair, i.e. the equipment has the same age as it did at the time of the failure. Cui et al. (2004) studied optimal maintenance problems to maximize the expected system lifetime under fixed resources when repair actions can only be selected between perfect and minimal repairs.

Recently, more attention has been given to the concept of imperfect maintenance (Cassady and Kutanoglu, 2005). Imperfect repair makes a system “better than old” but not as “good as new”. Research focusing on imperfect repair has been summarized in a survey by Pham and Wang (1996). Imperfect maintenance includes a wide variety of models.

Malik (1979) introduced the concept of virtual age to model the imperfect maintenance, which essentially says that the system is younger than that before the action by some interval T_y. A similar formulation is offered by Kijima (1989). Kijima has given two system improvement models that are used to describe preventive maintenance preventive overhaul process in this research. The details of the Kijima’s models are provided in Appendix A.

Kijima (1989) used the first model to obtain optimal replacement interval under imperfect corrective repair. The model aims at minimizing the long run expected cost per unit time. Several other studies have added to the body of knowledge on virtual age. Uematsu and Nishida (1987) have used use a nonhomogeneous Poisson process to determine interval reliability, and develop optimal replacement models based on various costs. They have used a more general repair model, including the Kijima models as special cases, where each interval of equipment function is subject to the influence of all previous failure history. Subsequently, Dagpunar (1997, 1998) extends Kijima’s second model by showing repair rates with respect to both chronological & virtual age. In a recent work, Cassady and Kutanoglu (2005) defined a model of repairable equipment behavior based on the concept of virtual age with specific focus on availability function behavior. A simulation model was used to estimate the availability performance of equipment described by this model and based on the results of the simulation a generic approximate availability function is proposed. Linear regression has been used to estimate the parameters of this function. They further provided a meta-model for the approximate availability function parameters in terms of the reliability and maintainability parameters of the equipment.

On the other side, Nakagawa's failure rate model assumes that an imperfect repair returns the system to as "bad as old" with a probability 'a' and "as good as new" with a probability 1-a (Nakagawa, 1979; Nakagawa, 2008). It says that the failure rate function after an imperfect repair is different from the function before repair. However this model has some limitations: if the original failure rate without overhauls of the system is a power function, the failure rate of the system with overhauls is always bounded. This characteristic restricts the applicability of the model. Zhang and Jardine (1998) proposed a new system improvement model by considering a direct reduction on the system's failure rate due to the maintenance action of an overhaul. The improvement model assumes that each imperfect preventive action makes the system's failure rate between "bad as old" and "good as previous overhaul period" with a fixed degree. As a result, the model allows that the systems' failure rate function changes from overhaul period to overhaul period. Also, they have showed that if the original system failure rate is unbounded (follows power law), the system failure rate after overhauls is also unbounded. This property confirms to situation in many maintenance cases that, although maintenances are performed, a system needs to be replaced when it is too old. Zang and Jardine (1998) used system improvement models to establish two optimization models for finding optimal preventive maintenance interval and life cycle of the system: one minimizes the expected unit-time cost and the other minimizes the total discounted cost. Recently, Pascual et al. (2008) used the Zang and Jardine (1998) model and formulated a non-linear mixed integer problem that minimizes the expected overall cost rate with respect to repair, overhauls and replacement times. The model considers a production system which is protected against demand fluctuations and failure occurrence with elements like stock piles, line and equipment redundancy, and the use of alternative production methods thereby making the cost functions discontinuous.

Zhang (2002, 2004), Wang and Zhang (2006) have used a geometric process to describe a deteriorating simple repairable system with two and three states respectively, and then the optimal policies are given in terms of the minimal average cost. Zheng et al., (2006) considered a single-unit Markov repairable model.

Apart from this, the problem of repairable system maintenance is also approached in the literature using shock models. For example, Tang and Lam (2006) have proposed a δ-shock maintenance model for deteriorating system, in which it is assumed that shocks arrive according to a renewal process and the inter-arrival times of shocks have a Weibull or gamma distribution.

Wu and Clements-Croome (2005), studied optimal maintenance policies under different operational schedules, in which three models are presented and cost functions are more developed. Pascual and Ortega (2006) have proposed a model to determine optimal life cycle duration and intervals between overhauls by minimizing global maintenance costs. The authors have considered three kinds of maintenance actions, namely, minimal repair, imperfect overhaul and perfect replacement. Imperfect overhaul is modelled using system improvement model of Zang and Jardine (1998).

Bai and Pham (2006) have presented some results for multi-component systems on renewable full-service warranty policies. Similarly, optimal preventive maintenance (PM) schedule for a multi-component system is presented by Tam, et al. (2007). Some of the authors illustrated how to find optimal preventive maintenance policies in a modular system. However, Maillart and Fang (2006); Laggoune et al. (2009; 2010); Scarf and Cavalcante (2010); Van Horenbeek et al. (2010) provides significant development in the field of multi-components preventive maintenance optimization. Maillart and Fang (2006) studied the replacement problem for multi-systems towards the series structure. Where optimal replacement time of the system is determined considering a budget constraint and throughput requirement. Laggoune et al. (2009; 2010); Scarf and Cavalcante (2010) studied the optimization of the replacement for a multi-component series system subjected to random failures. Weibull distribution parameters were considered to model the random failure of the components. A Monte Carlo simulations technique is used to determine the optimal replacement time.

2.2.4 Observations

The optimization of the level of repair, preventive maintenance and spare are the important issues in fleet maintenance planning. In the above literature, more emphasis has been given in the development of efficient LOR optimization technique. Moreover, the problem of LOR optimization has been solved considering the single base, single OEM, and identical machine. Different systems or types of equipment may have different and more complex fleet structure. For example, in machine tools, multiple bases are associated with a multi-echelon maintenance network and these bases are associated with multiple OEMs for their machines. Moreover, in some cases, these machines may not be identical, and it is enclosed with modular and non-modular components. Additionally, type of maintenance and repair facility at various echelons is also varied with specific systems. In the case of wind turbine system, the operating site (i.e. base) does not have the sufficient maintenance & repair facility whereas, in the case of machine tool users, they have significant repair facility at shop floor. Therefore, the problem of multi-bases, multi-OEM and non-identical machine and the system structure related issues need to address more effectively.

A detailed LCC model to investigate the effect of various costs i.e. maintenance facility, consumable, downtime, transportation cost and spare holding and stock-out on LOR analysis requires more attention from the researchers. Also, component failures are considered to follow constant failure rate models. It does not give the actual life behavior of the components. The consideration of time-dependent failure rate of the components while optimizing the level of repair and spare parts stocking decisions has not reported. Similarly, the actual demand rate for the spare parts is dependent on the number of working systems, which changes over time. Hence, the actual demand rate varies with time as results it affects the spare parts decisions. A time-dependent failure rate model would make the analysis more practical. Besides, the preventive maintenance optimization is done on the fleet system but the effect of PM to optimize the LOR decisions is totally ignored. This is mainly due to constant failure rate assumption and complexities to estimating the number of failures of the multi-modular systems. None of the work has been reported which considered the effect of preventive maintenance while optimizing the LOR decisions. Thus, there is a need to investigate all these issues while deciding the joint decisions making in the fleet maintenance planning.

2.3 Optimal Reliability Design Configuration

It has been estimated that 80% of poor quality products and over 90% of field failures are the result of poor design (Misra, 2008). Therefore, if there is any phase in the entire life cycle of a product that has maximum impact on field performance, it is the design phase. Modern systems are becoming more and more complex, sophisticated and automated, and a measure of performance that cannot be sacrificed is their reliability. Reliability has become a mandatory requirement for customer satisfaction and is playing an increasingly important role in determining the competitiveness of products. Because of these reasons, system reliability and availability optimization is important in any system design. There are several alternatives available to a system designer, to improve system reliability and availability. The most known approaches are (Misra, 1986):

1. Reduction of the complexity of the system.
2. Use of highly reliable components through component improvement programs.
3. Use of structural redundancy.

4. Putting in practice a planned maintenance, repair schedule and replacement policy.
5. Decreasing the downtime by reducing delays in performing the repair.

System complexity can be reduced by minimizing the number of components in a system and their interactions. However, a reduction in the system complexity may result in poor stability and transient response. It may also reduce the accuracy and eventually result in the degradation of product quality (Misra, 1986).

The product improvement program requires the use of improved packaging, shielding techniques, derating, etc. Although these techniques result in a reduced failure rate of the component, they nevertheless require more time for design and special state-of-the-art production. Therefore, the cost of a part improvement program could be very high and may not always be an economical way of system performance improvement. Also, this way the system reliability can be improved to some degree, but the desired reliability enhancement may not be attained (Misra, 1986).

On the other hand, the employment of structural redundancy at the subsystem level, keeping system topology intact, can be a very effective means of improving system reliability to any desired level. Structural redundancy may involve the use of two or more identical components, so that when one fails, the others are available and the system is able to perform the specified task in the presence of faulty components. Depending upon the type of subsystem, various forms of redundancy schemes viz. active, standby, partial, voting, etc., are available. The use of redundancy provides the quickest solution, if time is the main consideration. It is the cheapest method, if the cost of redesigning a component is too high (Misra, 1986). Thus, much of the effort in designing a system is applied to allocation of resources to incorporate structural redundancies at various subsystems which will eventually lead to a desired value of system reliability.

Maintenance, repairs and replacements, wherever possible, undoubtedly enhance system reliability (Misra, 1974) and should be employed in an optimal way. Further, decreasing the downtime by reducing delays in performing the repair can also be used to improve the availability of the system (Markeset and Kumar, 2003). This can be achieved by optimal allocation of spares, choosing an optimal repair crew size, improving maintainability, etc.

Therefore, the basic problem in optimal reliability design of a system is to explore the extent of the use of the above mentioned means of improving the system reliability within the resources available to a designer. Such an analysis requires an appropriate formulation of the problem. The models used for such a formulation should be both practical and amenable to known mathematical techniques of solution. Considerable amount of work has been done to systematize reliability design procedure.

Tillman et al. (1977) reviewed the system reliability optimization literature pre 1977, while Misra (1986) presented a survey of literature on system reliability design pre 1986. Several interesting papers and books on reliability optimization have been published thereafter. Recent reviews have been presented by Kuo and Prasad (2000); Kuo *et al.* (2001). In the present section, some of the relevant works in the area of optimal reliability design which reflect the philosophy of the design techniques are reviewed. The literature review is classified under following headings.

In literature, reliability optimization problems are broadly put into three categories namely reliability allocation, redundancy allocation, and reliability-redundancy allocation according to the types of their decision variables. If component reliabilities are the decision variables, the problem is called reliability allocation (Ivanovic, 2000; Allella et al., 2005; Yalaoui et al., 2005; Zhang and Liao, 2009); if the number of redundant units is the decision variable, the problem becomes redundancy allocation problem (Agarwal and Gupta, 2006; Limbourg and Kochs, 2008; Yeh, 2009; Ouzineb et al., 2010); if the decision variables of the problem include both the component reliabilities and redundancies; the problem is called a reliability-redundancy allocation problem (Dhingra, 1992; Chen, 2006; Ha and Kuo, 2005). Reliability allocation is usually easier than redundancy allocation, but it may be more expensive to improve the component reliability than to add redundant units. Redundancy allocation, on the other hand, results in increased design complexity and increased costs through additional components, weight, space, etc. Also, as mentioned earlier, it is not always technically feasible to add redundancy at each level in the assembly hierarchy. Redundancy allocation problem also increases the computational complexity of the problem, and is classified as NP-hard in the literature (Nahas and Thien-My, 2010). The complexity further increases in case of reliability and redundancy allocation problem. In general, the optimization criteria used in these types of problems are reliability, cost, weight or volume. One or more criteria are considered in an objective function, while the others are considered as constraints.

Reliability and/or redundancy allocation problems have been researched for different system configurations like multi-indenture modular system. Kuo et al. (2001), in their review classified the reliability optimization research on the basis of system configurations. Researchers have also considered issues like: types of redundancy (Yu et al., 2007), mixing of components (Coit and Smith, 1996a), multi-state system (Meziane et al., 2005; Tian et al., 2009a; Tian et al., 2009b), etc. Most of these problems are demonstrated using some theoretical system structure, like series or parallel or some complex configuration. The illustration of these problems to some real life mechanical equipment, considering system specific issues i.e. fleet equipment are scarcely addressed in the exiting literature. Ivanovic (2000) applied the reliability allocation problem for a new vehicle design. Similarly, Zhang and Liao (2009) also studied the problem of reliability allocation in the context of a mechanical system. They applied it for direct-drive hobbing machine. However, in most of the practical situations, customers generally do not specify their reliability requirements explicitly. Reliability performance and specification have not received proper attention in the reliability and the engineering design literature (Murthy et al., 2008). Majority of literature on reliability and/or redundancy optimization, in general, it does not consider the effect of the LOR. However, there are many fleet systems, such as wind turbines, aircrafts, ships, machine tools, gas turbines, which undergo LOR analysis upon failure. Some approach is required to systematize the reliability design of equipment operated in the fleet maintenance architecture. It requires considering other issues, like, users specific reliability design, LOR, spare parts etc. at the design stage. However, some of researchers considered the other issues, like, maintainability, maintenance, support, etc. at the design stage. Where, reliability as well as availability is considered as performance criteria in such systems. Therefore, in literature such problems are many times also referred as optimal availability design of system. The work of Misra (1974), Gurov et al. (1995), Monga et al. (1995), Kumar and Knezevic (1997), Nourelfath and Dutuit (2004), Yu et al. (2007), Ouzineb et al. (2006), Nourelfath and Ait-Kadi (2007), Lins and Droguett (2009), etc. deserve attention in this regard. The problems considered in such literature in general aim at obtaining the optimal number of one or more the followings: redundancy level, number of spares, and number of repair facilities. For example, Misra (1974) proposed a joint failure and repair rate allocation problem in order to maximize system availability and/or reliability under system cost constraints. Lins and Droguett (2009) considered the effects of repair while allocating redundancy. A multi-objective optimization approach is applied that compromise between system reliability and cost. Monga et al. (1995) proposed a joint optimization problem for obtaining optimal system configuration, PM interval and system economic life. Nourelfath and Ait-Kadi (2007) have extended the classical redundancy allocation problem to find, under reliability constraints, the minimal cost configuration of a multi-state series–parallel system, subject to a specified maintenance policy. The component is selected from the discrete choices made from components available in the market. Kumar and Knezevic (1997) presented three models for spares optimization. The objective is to maximize the availability (or minimize the space) subject to space constraint (or availability constraint). Yu et al. (2007), used probability analysis, and formulated the system design problem as minimizing the system cost rate subject to an availability constraint to find the optimal reliability in terms of the mean time to failure of the components and the optimal intervals of as-good-as-new maintenances. However, as mentioned earlier, the user's reliability design requirements can also be met by incorporating an appropriate LOR decisions. In such cases, optimizing reliability design and LOR decisions simultaneously will be more significant for repairable systems.

2.3.1 Optimal Reliability Design Formulation

Amongst the various design problems that have been considered in the literature, the following formulations are widely discussed.

2.3.1.1 Reliability Allocation Problem

Formulation 1: From mathematical point of view, reliability allocation problem is a Non-Linear Programming (NLP) problem. It can be shown as follows (Kuo *et al.* 2001).

Maximize

$$R_S = f(R_1, R_2, \dots, R_n)$$

Subject to

$$g_i(R_1, R_2, \dots, R_n) \leq b_i; \quad \text{for } i = 1,2, \dots, m,$$

$$R_{j_{min}} \leq R_j \leq R_{j_{max}}; \quad \text{for } j = 1,2, \dots, n.$$

where, n is the number of components/subassemblies in a system,

R_S is the system reliability, R_j is the component/subassembly reliability of stage j,

$R_{j_{min}}$ and $R_{j_{max}}$ are the lower and upper limit on R_j,

$g_i(.)$ is the i^{th} constraint function,

b_i resource allocated to i^{th} constraint.

m is the number of constraints in the system, In above formulation reliability of components takes any continuous value between 0 and 1. In case the possible values of reliability are discrete, the following formulation can be used.

Formulation 2: Suppose there are u_j discrete choices for component reliability at stage j or $j = 1, \dots, k(\leq n)$ and the choice for component reliability at stage $k+1, \dots, n$ is on a continuous scale. Let, $R_j(1), R_j(2), \dots, R_j(u_j)$ denote the component reliability choices at stage j for $j = 1, \dots, k$, then the problem of selecting optimal component reliabilities that maximize system reliability can be written as (Kuo *et al.,* 2001):

Maximize

$$R_S = h[R_1(x_1), \dots, R_k(x_k), R_{k+1}, \dots, R_n],$$

Subject to

$$g_i[R_1(x_1), \dots, R_k(x_k), R_{k+1}, \dots, R_n] \leq b_i, \text{ for } i = 1,2, \dots m,$$

$$x_j \in \{1,2, \dots, u_j\}, \qquad \text{for } j = 1,2, \dots, k,$$

$$R_{j_{min}} \leq R_j \leq R_{j_{max}}; \qquad \text{for } j = k+1, k+2, \dots, n.$$

2.3.1.2 Redundancy Allocation Formulations

Formulation 3: It is generally formulated as pure Integer Nonlinear Programming Problem (INLP) (Misra, 1971).

Maximize

$$R_S = f(x_1, x_2, \dots, x_n),$$

Subject to

$$g_i(x_1, x_2, \dots, x_n) \leq b_i; \quad \text{for } i = 1,2, \dots, m,$$

$$x_{j_{min}} \leq x_j \leq x_{j_{max}}; \quad \text{for } j = 1,2, \dots, n,$$

x_j being an integer.

Formulation 4: Redundancy allocation for cost minimization (Elegbede and Adjallah, 2003).

Minimize

$$C_S = \sum_{j=1}^{n} c_j(x_j),$$

Subject to

$$g_i(x_1, x_2, \dots, x_n) \le b_i; \quad \text{for } i = 1,2,\dots,m,$$

$$x_{j_{min}} \le x_j \le x_{j_{max}}; \quad \text{for } j = 1,2,\dots,n,$$

x_j being an integer.

Similarly, the reliability allocation and reliability-redundancy allocation problem can also be formulated in the form of cost minimization problem.

2.3.1.3 Reliability and Redundancy Allocation Formulations

Formulation 5: It can be considered as mixed Integer Nonlinear Programming Problem (MINLP) (Kim *et al.,* 2006).

Maximize

$$R_S = f(x_1, x_2, \dots, x_3; R_1, R_2, \dots, R_n),$$

Subject to

$$g_i(x_1, x_2, \dots, x_3; R_1, R_2, \dots, R_n) \le b_i; i = 1,2,\dots,m,$$

$$R_{j_{min}} \le x_j \le R_{j_{max}}; \quad \text{for } j = 1,2,\dots,n,$$

$$x_{j_{min}} \le x_j \le x_{j_{max}}; \quad \text{for } j = 1,2,\dots,n,$$

x_j being an integer.

2.3.1.4 Multi-Objective Optimization Formulations

Formulation 6: A multi-objective formulation for reliability-redundancy allocation problem can be shown as (Sakawa, 1981):

Maximize

$$[f_1(x_1, \dots, x_n; R_1, \dots R), \text{and} - f_2(x_1, \dots, x_n; R_1, \dots, R_n)],$$

where, f_2 represents a convex cost function.

Subject to

$$g_i(x_1, x_2, \dots, x_3; R_1, R_2, \dots, R_n) \leq b_i; i = 1,2, \dots, m,$$

$$R_{j_{min}} \leq x_j \leq R_{j_{max}}; \quad \text{for } j = 1,2, \dots, n,$$

$$x_{j_{min}} \leq x_j \leq x_{j_{max}}; \quad \text{for } j = 1,2, \dots, n,$$

x_j being an integer.

Similarly, the multi-objective formulation for redundancy allocation and reliability allocation can also be formulated. Wang *et al.* (2009) have used a multi objective problem for RAP in parallel-series systems.

2.3.1.5 Formulations For Repairable System

Formulation 8: In designing the systems for reliability and maintainability, one may be interested in determining the pair (MTBF, MTTR), for which availability reaches a maximum value subject to a cost constraint. This problem of failure and repair rates allocation can be formulated as (Misra, 1974):

Maximize

$$A_{SS} = \prod_{j=1}^{n} \left(\frac{MTBF}{MTBF + MTTR} \right)_j,$$

Subject to

$$\sum_{j=1}^{n} C_j(MTBF, MTTR) \leq C_s$$

$$(MTBF)_j \geq 0, (MTTR)_j \geq 0;\ \forall_j$$

Alternatively a dual problem can also be formulated,

Formulation 9: Yu *et al*. (2007) have seen the reliability allocation problem of a cold-standby system from maintenance point of view. They formulated the problem as:

Minimize

$$t_M \geq 0, \mu_F \geq 0$$

$$\alpha_s(t_M, \mu_F)$$

Subject to

$$A_s(t_M \mu_F) \geq A_0$$

where, various symbols used above are defined as given in the notation.

Formulation 10: Nourelfath and Ait-Kadi (2007) have extended the classical redundancy allocation problem to find, under reliability constraints, the minimal configuration and maintenance costs of a multi-state series-parallel system with limited maintenance resources. They formulated the problem as:

Minimize

$$C_s = \sum_{j=1}^{n} \sum_{v=1}^{V_j} x_{j,v} C_{j,v}$$

Subject to

$$R_s(x_1, x_2, \dots, x_n, D, T, MP) \geq R_0$$

2.3.2 Solution Methods for Optimal Reliability Design

From the previous sections it can be seen that reliability optimization is a nonlinear optimization problem. The solution methods for these problems can be categorized into following classes:

1. Exact methods
2. Approximate method
3. Heuristics
4. Metaheuristic
5. Hybrid heuristics
6. Multi-objective optimization techniques

Exact methods provide exact solutions to reliability optimization problems. Dynamic programming (DP) (Bellman and Dreyfus, 1995; Misra, 1971), branch and bound (Sup and Kwon, 1999; Misra and Sharma, 1969), implicit enumeration search technique (Geoffrion, 1969) and partial enumeration search technique (Lawler and Bell, 1966) are typical approaches in this category. These methods of course provide high solution quality but higher computational time requirement limits their application to simple system configurations and systems with only a few constraints.

On the other hand many heuristics have also been proposed in the literature to provide an approximate solution in relatively short computational time (Kalyan and Kumar, 1990; Sharma and Venkatwswaran, 1971). A heuristic may be regarded as an intuitive procedure constructed to generate solutions in an optimization process. The theoretical basis for such a procedure in most cases is insufficient and none of these heuristics establish the optimality of the final solution. These methods have been widely used to solve redundancy allocation problems in series systems, complex system configuration, standby redundancy, multi-state system, *etc*.

Recently, meta-heuristics have been successfully used to solve complex reliability optimization problems. They can provide optimal or near optimal solution in reasonable time. These methods are based on artificial reasoning than classical mathematics-based optimization. GA (Genetic Algorithm) (Hsieh, 1998; Coit and Smith, 2002; Yu *et al.,* 2007), SA (Simulated Annealing) (Kim *et al.,* 2006), TS (Tabu Search) (Hansen and Lih, 1996; Kulturel-Konak *et al.,* 2003), Immune Algorithm (IA) (Chen, 2006), Ant Colony (AC) (Liang and Smith, 2004) are some of the approaches in this category, which have been applied successfully to solve the reliability optimization problem. Meta-heuristic methods can overcome the local optimal solutions and, in most cases, they produce efficient results. However, they also cannot guarantee the global optimal solutions. In literature, hybrid heuristics (Coit and Smith, 1996; Zhao and Liu, 2005) have also been proposed to solve redundancy and reliability-redundancy allocation problem. Hybrid heuristics generally combine one or more meta-heuristics or a meta-heuristic with other heuristics.

In reliability optimization with single objective function, either the system reliability is maximized subject to limits on resource constraints or the consumption of one of the resources is minimized subject to the minimum requirement of system reliability along with other resource constraints.

2.3.3 Integrated Aspects of Reliability Design and Maintenance

The integration of reliability design and maintenance decisions is important for repairable systems. An approach for design and development of product support and maintenance concept for industrial systems is proposed by Markeset and Kumar (2003) for a multinational environment. Wang et al. (2009) proposed different reliability based design optimization models considering the various maintenance policies. Similarly, Huang and Yue (2009) developed a method for simultaneous optimization of part reliability and part replacement schedule that minimizes the LCC of the system under system reliability goal. Moghaddass and Zuo (2011) investigated the possible trade-offs between the configuration of a repairable system and its maintenance strategy. Lad and Kulkarni (2013) proposed a methodology for selection of optimal machine tool configuration by simultaneously considering reliability and maintenance decisions. Basten (2010) in his dissertation highlighted issues that the proposed LOR decision models of Basten et al. (2009), Basten et al. (2011a), Basten et al. (2011b), Basten et al. (2012) can be used in the development process of fleet systems, to gain insights into the impact of design decisions on the LCC of the system. The LCC of each system design is compared, possibly together with other characteristics of each system design. Based on this comparison, the best system design configuration can be selected. In that way, users can decide, for example, if he should use a more costly, but more reliable part, or a less costly, less reliable part. Zheng et al. (2015) considered the relevant maintenance issues at early stages of product development and presented a novel methodology based on the simultaneous consideration of maintenance and modularity characteristics of product design. Lad et al. (2008) highlighted that the system design process must be considered from a whole life cycle point of view by extending the reliability design by integrating it with the other constituent's criteria of Performability to give a true optimal design.

In peep, the above literature clearly indicates that the integration of reliability and maintenance decisions is important. Maintenance decisions should be decided at the early design stage.

2.3.4 Observations

Indeed, there is no methodology available for simultaneous selection of reliability design and LOR decisions for the fleet system. As far as LOR decisions are concerned, most of the researchers have devoted their efforts to develop the efficient models for LOR decisions as discussed in section 2.2.1. Study of the effect of reliability design on LOR decisions is neglected in the literature. Similarly, research on reliability design is mainly focused on allocating reliability and /or redundancy to system components. Less amount of work has been reported for selecting appropriate reliability component from the available alternatives for multi-indenture system. Study the effect of modularization on reliability design is not address adequately in literature, which is an important characteristic for a multi-indenture system.

2.4 Summary

It can be observed that the optimal reliability design and maintenance planning are widely studied topics in the literature. However, moderately less attention has been given in the case of industrial equipment, which is operated and maintained under fleet maintenance architecture. As far as the optimal reliability design is concerned, various approaches are available that deal with reliability allocation, redundancy allocation, and reliability-redundancy allocation problems for the series, series-parallel configuration. For the multi-indenture modular system, scare amount of work is reported for optimal reliability design in the existing literature. The significant amount of work is reported for fleet maintenance decisions i.e. LOR, PM and spare level. The integration of the reliability design and maintenance is necessary, and it is evident from the discussed literature. The selection of the optimal reliability design for indenture while optimizing the LOR decisions is not addressed. Different integrated approaches to see the interaction effect between the decisions of "LOR and spare parts" and "PM and LOR," are scarcely reported in the discussed literature. The LOR optimization is done considering the constant failure rates for the components. However, an approach is required to address the time dependent failure rate of the components while optimizing the LOR. Due to this assumption, the joint consideration of LOR and PM optimization is not studied in literature. Apart from this, the detailed fleet structure problems need to be addressed while developing the integrated fleet maintenance approach. Moreover, the system's specific issues have not addressed in optimizing the LOR, PM and spare level. More work is required to address a system specific issue in the context of fleet maintenance architecture. These observations are summarized and presented in the form of research gaps in Chapter 1.

Chapter 3*

Optimal Reliability Design and Level of Repair Decisions in a Fleet System

3.1 Introduction

It is clear from the discussion presented in chapter 1, that the optimal reliability design and level of repair analysis are two of the important aspects in the fleet maintenance system. Also, it is discussed that both these aspects have interdependencies. However, literature on fleet maintenance system mainly focuses on level of repair analysis only. Improved reliability design and efficient level of repair strategies if optimized jointly may lead to better life cycle performance of the fleet maintenance system. Also, conventional approach on optimal reliability design focused on allocating reliability and /or redundancy to various components of the system. However, the most of the industrial systems are designed by selecting optimal reliability component from the available alternatives. Such type of optimal reliability design problems are also scarcely reported in the literature. Further, in case of fleet systems, the equipment is modular in design. Hence, effect of modularity on reliability design and level of repair decision needs to be investigated. In the present chapter, an approach is developed to investigate the fleet of reliability design on level of repair decision. It jointly optimizes these two decision variables for modular system structure. The effects of modularity and reliability vs. cost curve are also investigated. The problem is extended for components having time dependent failure rate distribution.

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3.2 Problem Description

Let us consider a three echelon fleet maintenance system. Let echelon 1 be "Base", echelon 2 be "Depot", and echelon 3 be "OEM". Base is the operating site of the machines. Let there be "b" (where, b=1,2,…B) such operating sites or "bases", situated at different geographical locations and let m_b be the number of identical machines required at base "b". These machines are required to operate t_{Opert} hours per year. As mentioned earlier, each of these machines is a multi-indenture system. Let these indenture items be represented by an order triplet i.e."ijk" . Where,

- "i" denotes the i^{th} assembly at the first indenture item,
- "j" denotes the enclosed j^{th} module at the second indenture item and
- "k" denotes the enclosed k^{th} part of j^{th} module of i^{th} assembly, at the third indenture item.

The time to failure of each part follows constant failure rate distribution and $\lambda(\text{ijk})$ represents the failure rate of part(ijk). In this work a business scenario is considered where OEM provides required machines and associated life cycle maintenance contract to each users. Thus, the OEM needs to select an optimal "reliability design" and associated optimal level of repair decisions for the machines at a particular base.

Let the number of design alternatives of an assembly (i00) be denoted by "A" for the machine m_b and the number of design alternatives of the enclosed parts (ijk) is represent by (ijk) $_d$. However, each of the configurations will result different acquisition cost depending on the cost of selected alternatives for assembly or modules. The cost of higher level indenture items i.e. assembly and module will be estimated based on the selected design alternatives for lower level indenture items plus fixed cost to assemble the lower level indenture items. The cost of module will be decided based on the cost of selected alternatives of their enclosed parts and assembling cost of these parts. Similarly, the cost of assembly will be calculated based on the cost of selected design of the enclosed modules and cost of assembling of the enclosed modules. Generally, the some percentage of summation of the cost of enclosed parts is considered as the fixed cost of assembling the module. Thus, the reliability design problem boils down to selecting optimal reliability configuration for the machine from the available alternatives that meet user's reliability requirements and cost constraints, if any.

A LOR analysis is used to decide the optimal LOR decisions in the fleet maintenance system. The details of the LOR decisions are discussed in section [1.2.3.1] of the previous chapter. As far as the LOR decisions are concerned, the following decision making process is considered in the present problem. Whenever an assembly in a machine fails, the same is replaced by spare assembly available at the base. Therefore, it is assumed that the OEM maintains a certain level of spare inventory of assemblies at each of the bases. In the current research, it is considered that the inventories of spare assembly are maintained at some fixed service level at each of the bases. Further, a failed assembly is sent to depot level. At depot level, a failed module is removed from the assembly for further maintenance decisions. The failed module can be "repaired", "moved" or "discarded" at depot level. "Repair decision" of the module at depot level will require the "discard" of the failed part. This "discard" can be done either at depot level itself or at OEM level. In the second case, "move" decision for the failed part is made at depot level. The "discarded" indenture item is replaced by the new item form the spare items at that particular echelon. If the "move" decision is made for failed module at depot level, then it is sent to OEM level, where the failed module can be either repair or discard. The repair of a module at OEM level will require the discard of the failed part. These LOR decisions and its echelon specific constraint are summarized in table 3.1. The repaired assembly is transported back to respective base again. Thus, it creates refilling of the inventory of assembly at each base.

Table 3.1: LOR decisions constraints

Indenture levels	Base (b=1,2,3…5)	Depot (e=2)	OEM (e=3)
Assembly (i00)	Replacement of failed assembly by "spare" assembly	X	X
Module (ij0)	X	Repair, Move, Discard	Repair, Discard
Part (ijk)	X	Move , Discard	Discard

The obvious difference in various decisions for LOR is in the repair and transportation time and associated costs. For example, replacement at module level will require lesser time in documentation, fault isolation, repair action compared to replacement at part level. It will also reduce maintenance skill requirement and amount of repair equipment. However, replacement of module will require more cost of consumable compared to replacement at parts level. Similarly, it may cost more to transport the failed indenture to next echelon level. However, it may save on the cost of inventory holding. Thus, the LOR aims to select the optimal mix of these decisions. Figure 3.1 provides a pictorial view of LOR decisions process considered in the present problem.

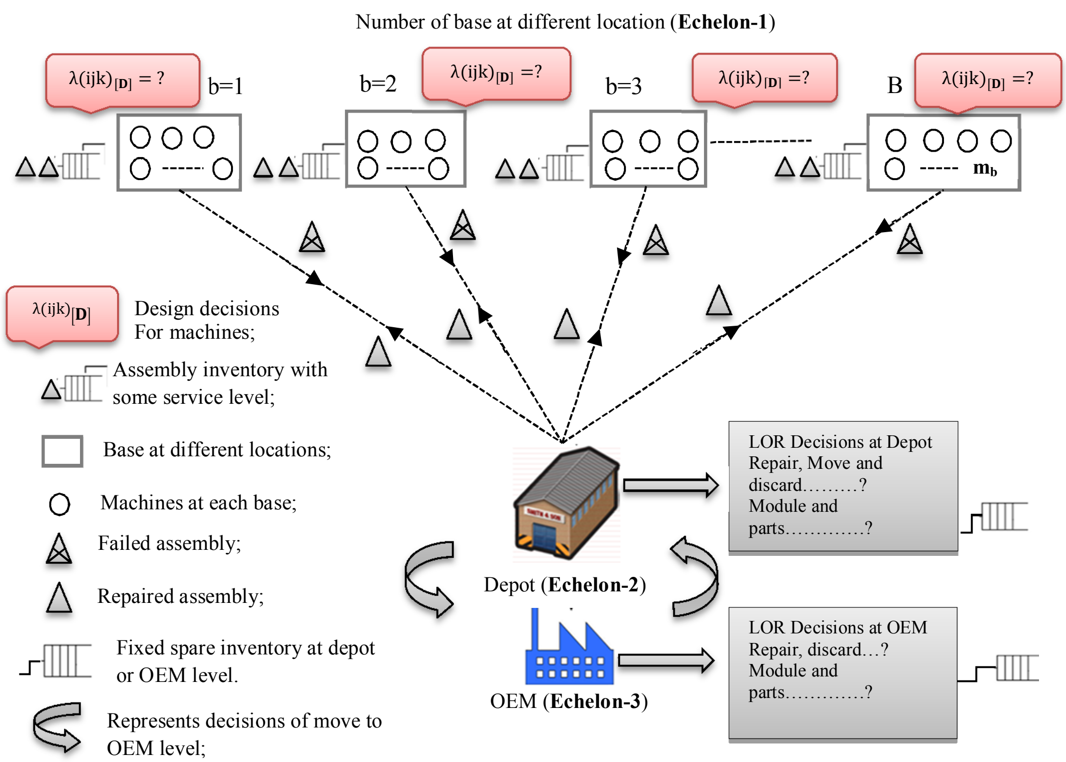

Figure 3.1: Pictorial view of the decision making process in the fleet maintenance system

3.2.1 Simultaneous Selection of Reliability Design, LOR and Spare Parts

Generally, reliability design and LOR decisions are made sequentially, i.e., first design is selected and then LOR & spare parts decisions are made. However, moments we choose reliability design configuration, the cost of maintenance requirement almost freezes, as the failure and repair characteristics are fixed. Moreover, in the current scenarios where OEM shares the responsibility of the failure in terms of maintenance contracts, it may be interesting and important to see the value of joint optimization of reliability design and LOR decisions. Thus the problem in hand is to simultaneously select optimal reliability configuration as well as LOR decisions such that total LCC of the fleet maintenance system is minimized.

In this research work, a predefined Service Level (SL) is considered for the repair spare parts of the assembly at the base level. It is considered here that the central depot and OEM maintenance facility have sufficient spares of the indenture item (ijk). S (ijk) represents the quantity of spare parts decision of the indenture item (ijk).

3.3 Problem Formulation

In this section, formulation of the above discussed problem is presented. This section covers the development of the integrated optimization model. Further, model assumptions and conditions are discussed in detail. The life cycle models of the proposed integrated fleet maintenance approach are presented in details.

3.3.1 Optimization Model

The problem of simultaneous selection of reliability design, LOR and spare decisions for the base or user "b" can be formulated as:

Minimize

$$[\mathrm{PV}_{\mathrm{fm}}]_{\mathrm{b}} = \mathrm{f}\left([\boldsymbol{D}], \left[\boldsymbol{L}_{\boldsymbol{r},\boldsymbol{e}}(\boldsymbol{ijk})\right]_{[\boldsymbol{D}]}\right) \tag{3.1}$$

Subject to,

- LOR decisions constraints;
- System configuration constraints;
- Acquisition cost constraints for the particular base, if any.

where, $[\mathrm{PV}_{\mathrm{fm}}]_{\mathrm{b}}$ is the present value of the LCC in fleet maintenance system for the user "b" and $[\boldsymbol{D}]$ is the design decisions matrix representing system configuration selected from the available design alternatives. $\left[\boldsymbol{L}_{\boldsymbol{r},\boldsymbol{e}}(\boldsymbol{ijk})\right]_{[\boldsymbol{D}]}$ represents LOR decision matrix for the indenture item (ijk) for selected design decisions matrix. Where "$\mathbf{r}$" denotes to the maintenance action decisions; with $\mathbf{r} = \mathbf{1}$ denoting to "repair", $\mathbf{r} = \mathbf{2}$ denoting to "move" and $\mathbf{r} = \mathbf{3}$ denoting to discard. These maintenance actions are perform at different echelons represented by "$\mathbf{e}$"; $\mathbf{e} = \mathbf{2}$ denotes to "depot level" (echelon 2) and $\mathbf{e} = \mathbf{3}$ denotes to "OEM level" (echelon 3). The LOR decisions variable for the indenture item (ijk) for design decisions matrix will be considered as follows;

$$\left[\boldsymbol{L}_{\boldsymbol{r},\boldsymbol{e}}(\boldsymbol{ijk})\right]_{[\boldsymbol{D}]} = \begin{cases} 1, & \text{if the maintenance action r at echelon e is selected for indenture item (ijk)} \\ & \text{for design decision matrix } [\mathbf{D}] \text{ for an assembly ;} \\ 0, & \text{otherwise.} \end{cases}$$

The constraints in the optimization problem are discussed below;

LOR Decisions Constraints: The LOR decision constraints denotes to possible maintenance action i.e. repair/move/discard at base, depot and OEM level as discussed in the table 3.1. According to the table 3.1, it is considered that at base level only replacement of a failed assembly is possible due to lack of maintenance and repair facility. It is mainly because the base level generally is considered as operating site, where the maintenance and repair facility of the assembly is not available. But the depot and OEM level are having sufficient maintenance and repair facility take maintenance actions on the failed assembly. However these constraints may not be applicable to some particular system of equipment for example machine tools generally have sufficient repair facility at base.

System Configuration Constraints: The system configuration constraints denotes to the physical constraints in terms of number of indenture items in a system. System configuration constraints vary with number of enclosed assemblies, modules and parts. For example, if the more modular design is selected for an assembly means it has more number of modules than the less modular design.

Similarly, the numbers of parts also vary from module to module in an assembly. Some of the module may have more number of enclosed parts then the other enclosed modules.

Acquisition Cost Constraints: Financial concerns of the users can be taken into account when formulating reliability specifications. A proper balance of financial goals and realistic asset reliability performance expectations are necessary to develop a detailed and balanced reliability specification. Therefore, this integrated model also incorporates an acquisition cost constraint, which represents the user's budget constraints, if any.

Assumptions

The following assumptions have been made for the proposed integrated optimization model;

(a) The indenture levels i.e. assembly(i00), modules(ij0) and parts(ijk) of the machine are arranged reliability wise in series.
(b) The failures of the machine occur because of failure of the part i.e. lowest level indenture item(ijk).
(c) It is assumed that the failures of different parts of the machine are independent to each other.
(d) It is assumed that only one maintenance action i.e., repair, move and discard will be taken at each echelon for each indenture items.
(e) If the "move" decision is made at echelon 2 (i.e. at depot) then at least one maintenance action is made at echelon 3 (i.e. at OEM). Because OEM is the final maintenance location where the maintenance action on the components should be finalized.
(f) If higher indenture item i.e. module(ij0) is discarded or moved then their enclosed lower indenture item i.e. part (ijk) are also discarded or moved at same echelon. For example, if discard decision is made for module at depot level then enclosed parts are also be discarded at depot level.
(g) It assumed that the lower indenture item i.e. part(ijk) is discarded.

(h) It considered that the spares of the assembly $(i00)$ are stocked at base level only with some Service Level (SL) probability. Whereas, it is also assumed that the quantity of the spares of the indenture items are enough to perform the discard decisions at depot and OEM level.

3.4 Life Cycle Cost Models

Life Cycle Cost (LCC), in general, includes design and development cost, production and construction cost, operation and maintenance cost, system retirement and phase out cost. A comprehensive cost break down structure for LCC can be found in Blanchard (2004). LCC may be categorized in many different ways, depending on the type of system and purpose of the analysis. In present work, LCC is expressed as the sum of non-recurrent cost and recurrent cost and is measured in terms of Net Present Value (NPV). Non-recurrent costs are onetime investment required to develop the maintenance facility. Recurrent cost includes failure costs such as consumable, downtime, transportation and spare holding and stock out, which incurs recurrently in each year throughout the life of machine. Therefore LCC at any base in a fleet maintenance system is the discounted sum of Non Recurrent Cost (NRC) and Annual Average Recurrent Cost (AARC) over the life of the system. Let the life of each machine at base "b" be L years and discounting factor for money be R % which remains constant throughout the life of machine. Thus the Present Value (PV) of LCC in fleet maintenance for given base "b" can be expressed as equation (3.2).

$$[\mathrm{PV_{fm}}]_\mathrm{b} = (\mathrm{NRC})_\mathrm{b} + \sum_{\mathrm{y}=1}^{\mathrm{L}} \left\{ \frac{1}{(1-\mathrm{R})^{\mathrm{y}}} \times \left([\mathrm{AARC}]_\mathrm{y} \right)_\mathrm{b} \right\} \qquad (3.2)$$

Detailed models to calculate NRC and AARC costs are presented in next subsections.

3.4.1 Non-Recurrent Cost Model

Non recurrent cost is the one time investment made in installing the maintenance facility. It is further divided into two parts i.e. Decision Independent Non-Recurrent Cost (DINRC) and Decision Dependent Non-Recurrent Cost (DDNRC).

Decision Independent Non-Recurrent Cost $(DINRC)$

It is the sum of total cost for acquiring and installing the general maintenance equipment and other facilities at each base, depot and OEM level. Some general purpose maintenance equipment and facilities will always be required at each echelon irrespective of fleet maintenance decisions. However, it does not affect the decisions variables. Therefore this cost is not included in estimating the LCC in the present work.

Decision Dependent Non-Recurrent Cost $(DDNRC)$

Decision dependent non-recurrent cost is one time investment required based on given design and LOR decisions. This cost mainly includes two costs i.e. acquisition cost $(\mathrm{C_{aq}})$ of machines based on selected design decision matrix and cost of repair equipment and cost of installing other maintenance facility $(\mathrm{C_{mf}})$ at the based on given LOR decisions. This cost of maintenance facility will depends on LOR decisions. For example, cost of maintenance facility for repair of a module will be more as compare to discard of module. Whereas cost of maintenance facility for repair at depot level is more as compare to repair at OEM level. It is considered here that if discard decision is made for module level at depot or OEM level, than only discard cost of maintenance facility for module will be considered at depot or OEM level. Whereas if individual part is discard at depot or OEM level, than only discard cost of maintenance facility for particular part will be considered at depot or OEM level. This cost is considered only once considering the LOR decisions for the base. Thus non recurrent cost for base “b” can be written as:

$$(\mathrm{NRC})_{\mathrm{b}} = \left[\sum_{\mathrm{ijk}} \mathrm{C_{aq}}(\mathrm{ijk})_{[\mathbf{D}]}\right] \times \mathrm{m_b} + \sum_{\mathrm{ijk}}\sum_{\mathrm{r=1}}^{3}\sum_{\mathrm{e=2}}^{3} [\mathrm{C_{mf}}]_{\mathrm{r,e}}(\mathrm{ijk})_{[\mathbf{D}]} \cdot \left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{D}]} \tag{3.3}$$

3.4.2 Annual Average Recurrent Cost Models

The Annual Average Recurrent Cost (AARC) is the cost that incurs every year throughout the life of the machines. It mainly includes:

- Annual Average Failure Cost(AAFC);
- Annual Average Spare Holding and Stock out Cost(AASHSC).

Thus, the annual average recurrent cost can be calculated as the summation of the annual average failure cost and annual average spare holding and stock out cost. Mathematically it is expressed by the equation (3.4).

$$\mathrm{AARC_b} = \mathrm{AAFC_b} + \mathrm{AASHSC_b} \tag{3.4}$$

The following subsection presents the detailed models to calculate the annual average failure and annual average spare holding and stock out cost.

3.4.2.1 Annual Average Failure Cost Models

Annual average failure cost is the cost that incurs whenever machines fails at each base. It includes costs such as Annual Average Consumables Cost (AACC), Annual Average Downtime Cost (AADTC) and Annual Average Transportation Cost (AATC). Thus, the annual average failure cost can be written as the summation of annual average consumables cost, annual average downtime cost, annual average transportation cost. Mathematically, it is expressed by equation (3.5).

$$(\mathrm{AAFC})_\mathrm{b} = (\mathrm{AACC})_\mathrm{b} + (\mathrm{AADTC})_\mathrm{b} + (\mathrm{AATC})_\mathrm{b} \tag{3.5}$$

These costs are calculated as follows.

Annual Average Consumable Cost$(AACC)$

The cost of consumable in case of repair decision includes the cost of grease, seals and other minor repair spares etc. Similarly, for the move decisions, it includes the cost of packing, documentation etc. Whereas the cost of consumables in case of discards decision mainly includes the cost of new indenture. The equation (3.6) used to calculate the annual average cost of consumables for base "b".

$$\mathrm{AACC_b} = \sum_{\mathrm{ijk}} \sum_{\mathrm{r=1}}^{3} \sum_{\mathrm{e=2}}^{3} \left(\mathrm{CC_{r,e}(ijk)_{[\mathbf{D}]}} \times \lambda(\mathrm{ijk})_{[\mathbf{D}]} \times \mathrm{m_b}\right) \cdot \left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{D}]} \tag{3.6}$$

Annual Average Down-Time Cost$(AADTC)$

The annual average down time cost is the cost of unavailability of the machine at each base during the replacement of a failed assembly by spare assembly from available inventory. It mainly includes the production loss cost during the down time of the machine at each base. The down time is the total time for replacing the failed assembly to spare assembly. Let time to repair of an assembly at each base "b" is $\mathrm{TTR(i00)}$ hr. and cost of down time per hour is $\mathrm{C_{dt}}$. The equation (3.7) describes the annual average down time cost against the failure of assembly at base "b".

$$\mathrm{AADTC_b} = \ [\mathrm{TTR(i00)}] \times \lambda(\mathrm{ijk})_{[\mathbf{D}]} \times \mathrm{m_b} \times \mathrm{C_{dt}} \tag{3.7}$$

Annual Average Transportation Cost $(AATC)$

The annual average transportation cost is the total cost that includes the cost of transporting a failed assembly from each base to depot level and transporting the lower enclosed indenture item of a failed assembly based on LOR decisions from depot to OEM level and send the repaired assembly back to the respective base. Base level is considered as onsite therefore from each base to depot level only cost of transporting the failed assembly is considered. However if move decision is made for any lower enclosed indenture item of a failed assembly at depot level, then cost of transportation for that indenture item will be considered from depot level to OEM level. For example, if move decision is selected for module level, then only transportation cost of module will be considered from depot to OEM level. The total cost of transportation is calculated as cost of transporting the failed assembly and cost of transporting the lower indenture item to OEM level (i.e. if decision of move selected at depot level). The equation (8) describes the transportation cost against the failure of an assembly at base "b".

$$(\mathrm{AATC})_{\mathrm{b}} = \left\{ \left[\mathrm{TC}(\mathrm{i00})_{[\mathbf{D}]}\right] \times \lambda(\mathrm{i00})_{[\mathbf{D}]} \times \mathrm{m_b} + \sum_{\mathrm{ijk}} \sum_{\mathrm{r=1}}^{3} \sum_{\mathrm{e=2}}^{3} \left(\left(\mathrm{TC}(\mathrm{ijk})_{[\mathbf{D}]} \times \lambda(\mathrm{ijk})_{[\mathbf{D}]} \times \mathrm{m_b}\right) \cdot \left[\boldsymbol{L}_{\boldsymbol{r},\boldsymbol{e}}(\boldsymbol{ijk})\right]_{[\boldsymbol{D}]} \right) \right\} \tag{3.8}$$

3.4.2.2 Annual Average Spare Holding and Stock out Cost Model

The Annual Average Spare Holding and Stock out Cost(AASHSC) includes the Annual Spare Holding Cost (AASHC) and Annual Average Stock-Out Cost(AASOC). Thus the annual average spare holding and stock out cost for the base "b" can be calculated as follows:

$$(\mathrm{AASHSC})_b = (\mathrm{AASHC})_b + (\mathrm{AASOC})_b \tag{3.9}$$

Annual Spare Holding Cost $(AASHC)$

Annual spare holding cost is the cost of carrying the spare inventory of indentures items at different echelons. It includes annualized insurance, physical handling, inventory storage cost such as cost to rent, lease, or finance for storage facility and inventory risk cost (i.e. cost of obsolescence, damage, shrink, deterioration etc.). Holding cost generally depends on the cost of the indenture items. Costly items require more holding cost than the less costly items. The annual average spare holding cost of fleet includes the holding cost at each base, depot level and OEM level. However, it is assumed that the annual spare quantity and holding cost at depot and OEM level is fixed. A fixed holding cost per year is considered at depot and OEM level and which does not affect the LOR decisions therefore it is not included in annual spare holding cost estimation in the present work. Whereas to calculate the holding cost at each base a queuing model is proposed in the present work. The cost of holding for an assembly at base is estimated based on the percentage of assembly cost.

A single server with finite calling population queuing model is proposed between base "b" and depot level. In the current problem the aim of this queuing model is to calculate the fill rate i.e. expected number of "repaired" assembly, which arrives at base "b" from depot after completing the maintenance actions. Therefore the cost of holding at base "b" is estimated based on the expected number of repaired assemblies in a queue. The subsection [3.4.2.2.1] describes details about the implementation of single server with finite calling population queuing model between base "b" and depot. Thus, the annual average spare holding cost for base "b", is calculated by equation (3.10).

$$\mathrm{AASHC_b} = [\mathrm{S(i00)}] \times [\mathrm{h(i00)}]_{[\mathbf{D}]} \times \mathrm{P_{S(i00)}} \tag{3.10}$$

Annual Average Stock-Out Cost$(AASOC)$

Annual average stock-out is the cost of down time due to the unavailability of spares of repaired assembly, at base "b". The stock out is the situation where there is no spare available at base "b". In this problem the stock out situation is considered based on estimating the probability of more than S (i00) quantity required at base "b". As we know, that the probability of S (i00) quantity of repaired assembly in queue at base "b". Therefore the probability of more than S (i00) quantity required at base "b" is expressed as follows;

$$\mathrm{P_{(>S(i00))}} = 1 - \mathrm{P_{S(i00)}} \tag{3.11}$$

Therefore the annual average stock out cost at base "b" can be calculated as follows:

$$\mathrm{AASOC_b} = \left[\mathrm{P_{(>S(i00))}}\right] \times \left(\left[\mathrm{T_{Delay}}\right]_{\mathrm{b-d}} \times \mathrm{C_{dt}} + \left[\mathrm{TC_{(i00)}}\right]_{[\mathbf{D}]}\right) \tag{3.12}$$

In the current problem the quantity of the repaired assembly i.e. $\mathrm{S(i00)}$ at base "b" is estimated based on 95 % service level (SL) considering the Poisson approximation method. Whereas, single server with finite calling population queuing model estimates the probability of having $\mathrm{S(i00)}$ quantity of repaired assembly in a queue i.e. $\mathrm{P_{S(i00)}}$. The next subsection provides details about the single server with finite calling population queuing model for fill rate.

3.4.2.2.1 Single Server with Finite Calling Population Queuing Model for Fill Rate

At each base the numbers of machines are finite therefore a single server with finite calling population queuing system is considered in this research work. In the current problem, the base level maintenance facility is considered as single server. It receives failed assembly from the respective bases and replaces from the inventory available at base. The replacements also depends on the fill rate and fill rate depends on repaired assembly received from depot after repair action at depot or OEM. Figure 3.2 describes the pictorial representation of the queuing system for base “b”. In this queuing model, the arrival rate is estimated based on annual demand of failed assembly at base “b” and service rate at base “b” estimated based on average time to receive the repaired assembly from the depot repair taken by a failed assembly.

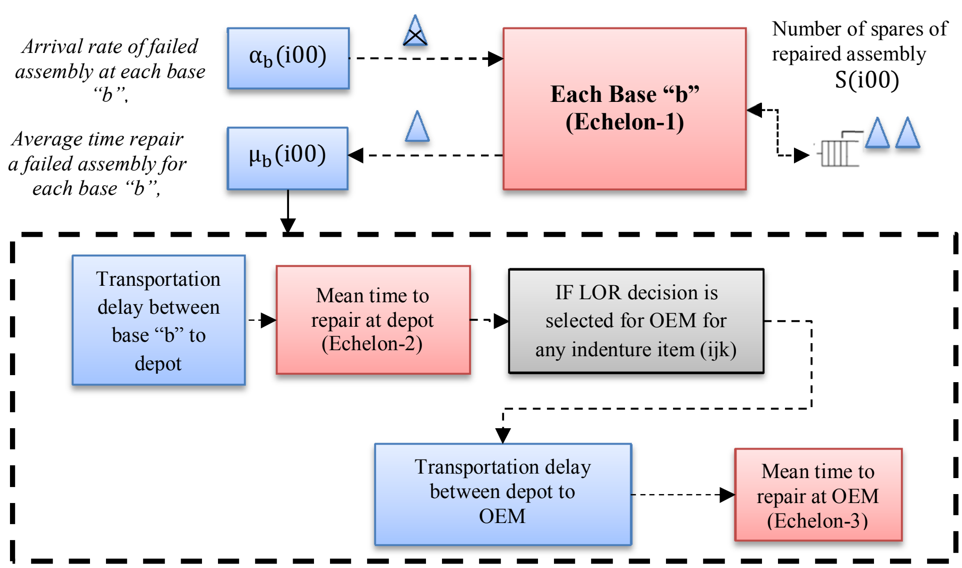

Figure 3.2 single server with finite calling population queuing model for base “b”

However average time taken to repair of a failed assembly for base “b” includes:

(1) Transportation delay time between base “b” and depot; which includes the time taken to transport the failed assembly from base “b” to depot and revert back to base “b” after completing maintenance.

(2) Mean time to repair at depot level; which includes average time taken to do the maintenance actions at depot.

However, if “move” maintenance action is selected at depot (i.e.$\left[\mathbf{L_{2,2}(ijk)}\right]_{[\mathbf{D}]} = \mathbf{1}$) for any enclosed lower indenture (ijk) of failed assembly then the average time to repair of a failed assembly for base “b” also includes:

(1) Transportation delay time between depot and OEM; which includes the time taken to transport the enclosed lower indenture (ijk) of failed assembly from depot to OEM and revert back to depot after completing maintenance action;

(2) Mean time to repair at OEM; which includes average time taken to do the maintenance actions at OEM.

Therefore selected maintenance actions for enclosed lower indenture (ijk) of failed assembly at depot will decide the total average time to repair. It is assumed that the mean time to repair at depot and OEM follows the normal distribution. In the current problem, the transportation delay includes the both for “too and fro” time between the base “b” and depot and similarly between depot and OEM.

Let α_b denotes the annual arrival rate of assembly failures at base “b”. It depends on failure rate per year of machines at base “b”. Therefore the arrival rate is the multiplication of number of machines required and failure rate per year per machine at base “b”. Mathematically, it is represents as:

$$\alpha_b = \lambda(i00)_{[\mathbf{D}]} \times m_b \qquad (3.13)$$

Let μ_b denotes to service rate of failed assembly for base “b”. Therefore the service rate is the reciprocal of the total average time taken by failed assembly to repair at base “b”. Mathematically it is expresses as:

$$\mu_b = \frac{1}{(\text{Average time taken to repair a failed assembly for base "b"})} \qquad (3.14)$$

$$\mu_b = \frac{1}{\left(T_{Delay}\right)_{b-d} + [MTTR_d] + \left\{\left(\left[T_{Delay}\right]_{d-OEM} + [MTTR_{OEM}]\right) \cdot \sum_{ijk}\left[L_{2,2}(ijk)\right]_{[D]} > 0\right\}} \qquad (3.15)$$

Thus probability of “no assembly” in the queue at each base can be calculated by following expression (Russell and Taylor, 2009).

$$P_{(0)} = \frac{1}{\sum_{S(i00)=0}^{m_b}\left[\frac{m_b!}{(m_b - S(i00))!}\right]\cdot\left[\frac{\alpha_b}{\mu_b}\right]^{S(i00)}} \qquad (3.16)$$

Similarly the probability of $S(i00)$ number of repaired assembly in queue at base "b" can be calculated by following expression (Russell and Taylor, 2009).

$$P_{S(i00)} = \left(\left[\frac{m_b!}{(m_b - S(i00))!}\right]\cdot\left[\frac{\alpha_b}{\mu_b}\right]^{S(i00)} \times P_{(0)}\right) \qquad (3.17)$$

3.4.2.2.2 Estimation of Spares Considering Predefined Service Level

The service level is the confidence level of keeping spare of repaired assembly for not hitting the stock out at base "b". Faraci (2008) proposes an optimization algorithm considering the Poisson cumulative probability for estimating the recommended spares with predefined service level. In the current problem, the same algorithm is used to estimate the spares of repaired assembly based on predefined service level (SL %). According to the spares optimization algorithm, the spares of repaired assembly based on predefine service level (SL %) is equal to the summation of Poisson cumulative probability with recommended $S(i00)$ spares of repaired assembly. Thus Poisson probability of exactly $S(i00)$ spare of repaired assembly at base "b" is calculated by (3.18);

$$\left(PP_{S(i00)}\right)_b = \frac{\left(m_b \times \lambda(i00)_{[D]} \times t_{opert.}\right)^{S(i00)} \times e^{-\left(m_b \times \lambda(i00)_{[D]} \times t_{opert.}\right)}}{S(i00)!} \qquad (3.18)$$

Whereas the Poisson cumulative probability of the exactly $S(i00)$ or less spares of repaired assembly at base "b" is calculated by equation (3.19):

$$\left(PC_{S(i00)}\right)_b = \sum_{j=0}^{S(i00)} \frac{\left(m_b \times \lambda(i00)_{[D]} \times t_{opert.}\right)^{j} \times e^{-\left(m_b \times \lambda(i00)_{[D]} \times t_{opert.}\right)}}{j!} \qquad (3.19)$$

Therefore the following equation should be fulfilled for estimating the spares of repaired assembly with predefined service level.

$$\left(PC_{S(i00)}\right)_b \geq SL\% \qquad (3.20)$$

3.5 Numerical Illustrations

To illustrate, let us consider a fleet having five bases $(\text{i.e. } b = 1,2, \dots .5)$ is considered. The numbers of machines m_b required at each base "b" are as follows:

- at first base (i.e. for b=1), 10 machines $(\text{i.e. } m_1 = 10)$;
- at second base (i.e. for b=2), 20 machines $(\text{i.e. } m_2 = 20)$;
- at third base (i.e. for b=3), 5 machines $(\text{i.e. } m_3 = 5)$;
- at fourth base (i.e. for b=4), 5 machines $(\text{i.e. } m_4 = 5)$;
- at fifth base (i.e. for b=5), 10 machines $(\text{i.e. } m_5 = 10)$.

Let each machine at each base are required to operate 8760 hours per year. Each user is supported by a three echelon fleet maintenance repair network. Let echelon 1 be "Base", echelon 2 be "Depot", and echelon 3 be "OEM". The life of each machine at base "b" is $L = 10$ years and discounting factor for money is 5% which remains constant throughout the life of machine. As mentioned earlier each of these machines is a multi-indenture system. In the current work, each machine is considered to be made up of single assembly only (i.e., i=1 only). Table 3.2 shows the design alternatives of the machine for the current problem. As shown in table 3.2, there are two design alternatives at assembly level. Alternative 1 has only three modules $(\text{i.e.} j = 1 \text{ to } 3)$. Alternative 2 has four modules $(\text{i.e.} j = 1 \text{ to } 4)$. Thus, alternative 2 is more modular than the alternative 1. Further, each of the modules in any of the assembly design has different number of enclosed parts. For example, first module $(\text{i.e.} j = 1)$ of first alternative (i.e. A=1) for assembly, has three parts$(\text{i.e.} k = 1 \text{ to } 3)$; second module $(\text{i.e.} j = 2)$ has two parts $(\text{i.e.} k = 1 \text{ to } 2)$; and third module has five parts $(\text{i.e.} k = 1 \text{ to } 5)$. Similarly, table 1 can be read for alternative 2 (A=2) also. Table 3.2 also shows the reliability design alternatives for each of the parts in any module. For example, part 1 of module 1 of first assembly alternative (i.e. A=1) has three alternative designs with different failure rates. The cost of higher level indenture will be estimated based on the selected design alternatives for lower level indenture items plus fixed cost to assemble the lower level indenture items. For example, if a first design alternative of an assembly (i00) is selected and if a first design alternative is selected for each of the enclosed parts i.e. (ijk) of the module (ij0), then cost of module (ij0) will be obtained by summation of cost of first design alternatives of the each part (ijk) plus fixed cost to assemble these parts.

Table 3.2: Design alternative for the system used in numerical illustration

Assembly level alternative 1 (A=1)						Assembly level alternative 2 (A=2)					
Module level alternatives ($\lambda(ijk)_{[D]}$)						Module level alternatives ($\lambda(ijk)_{[D]}$)					
Module	(ijk)	Alt_1	Alt_2	Alt_3	Alt_4	Module	(ijk)	Alt_1	Alt_2	Alt_3	Alt_4
1	(111)	0.015	0.035	0.065	-	1	(111)	0.011	0.022	0.033	-
	(112)	0.059	0.43	-	-		(112)	0.001	0.004	-	-
	(113)	0.022	0.029	0.038	0.048		(113)	0.012	0.015	0.019	0.2
2	(121)	0.038	0.052	-	-	2	(121)	0.023	0.032	-	-
	(122)	0.011	0.027	0.033	0.11		(122)	0.021	0.029	0.035	0.039
3	(131)	0.023	0.052	0.092	0.109	3	(131)	0.056	0.022	0.1	0.2
	(132)	0.012	0.016	-	-		(132)	0.035	0.065	-	-
	(133)	0.022	0.033	0.044	0.074		(133)	0.052	0.088	0.096	0.1
	(134)	0.011	0.022	-	-	4	(141)	0.049	0.089	-	-
	(135)	0.072	0.052	0.11	0.2		(142)	0.064	0.032	0.1	0.4

In this numerical example, if first design decision of an assembly (i.e. A=1) is selected and if first design alternative are selected for each of the parts i.e. (111), (112) and (113) of first module, then cost of module will be obtained by summation of cost of parts (111), (112) and (113) plus fixed cost to assemble these parts. Generally, some percentage of summation of cost of the enclosed parts is considered as the fixed cost of assembling the module. Let 10 % of the costs of enclosed parts are required for assembling of modules. Thus mathematically, we can see from table 3.3 that the cost of module 1 for assembly alternative 1 (i.e., A=1) is (3921+3500+9448) + 10% × (3921+3500+9448) i.e. 18556 INR/-. Similarly, cost of assembly is calculated based on selected design of modules. Table 3.4 describes the cost of maintenance facility based on LOR decision for different design alternatives of the assembly. From the table 3.4, we can see that if first design alternative for an assembly is selected and if LOR decision for module (110) is made for repair at depot i.e. $\left[L_{1,2}(110)\right]_{[D]} = 1$; Then cost of maintenance facility for repair of module (110) at depot (i.e. $[C_{mf}]_{1,2}(110)_{[D]}$) is 1100 INR/- If LOR decision for module (110) is made for discard at depot i.e. $\left[L_{3,2}(110)\right]_{[D]} = 1$. Then cost of maintenance facility for discard of module (110) at depot (i.e. $[\mathrm{C_{mf}}]_{3,2}(110)_{[\mathbf{D}]}$) is 300 INR/-. Similarly for other indenture items the cost of maintenance facility can be read from table 3.4.

Table 3.3: Cost of design alternative used in numerical illustration

Assembly level alternative 1 (A=1)						Assembly level alternative 2 (A=2)					
Cost of Module level alternatives $(\lambda(\mathrm{ijk})_{[\mathbf{D}]})$ (in INR)						Cost of Module level alternatives $(\lambda(\mathrm{ijk})_{[\mathbf{D}]})$ (in INR)					
Module	(ijk)	Alt_1	Alt_2	Alt_3	Alt_4	Module	(ijk)	Alt_1	Alt_2	Alt_3	Alt_4
1	(111)	3921	3132	1947	-	1	(111)	6917	5167	3417	-
	(112)	3500	2800	-	-		(112)	3500	2800	-	-
	(113)	9448	8549	7394	6110		(113)	7395	7356	7304	4946
2	(121)	4250	3850	-	-	2	(121)	4679	4421	-	-
	(122)	4214	3855	3720	1992		(122)	3989	3810	3675	3585
3	(131)	4138	3681	3050	2781	3	(131)	9256	8205	6845	3754
	(132)	5000	4000	-	-		(132)	5000	4000	-	-
	(133)	3833	3596	3359	2713		(133)	4713	3208	2873	2706
	(134)	5000	4000	-	-	4	(141)	6870	4680	-	-
	(135)	7125	7468	6474	4932		(142)	7030	7229	6805	4936

Table 3.4: Cost of maintenance facility based on $[\boldsymbol{L_{r,e}(ijk)}]_{[\boldsymbol{D}]}$ (in INR)

Indenture items	Assembly level alternative 1 (A=1) $[\mathrm{C_{mf}}]_{\mathrm{r,e}}(\mathrm{ijk})_{[\mathbf{D}]}$					Indenture items	Assembly level alternative 2 (A=2) $[\mathrm{C_{mf}}]_{\mathrm{r,e}}(\mathrm{ijk})_{[\mathbf{D}]}$				
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r=1, e=3	r=3, e=3	(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r=1, e=3	r=3, e=3
(110)	1100	0	300	900	100	(110)	1100	0	300	900	100
(111)	-	0	100	-	75	(111)	-	0	100	-	75
(112)	-	0	100	-	75	(112)	-	0	100	-	75
(113)	-	0	100	-	75	(113)	-	0	100	-	75
(120)	800	0	200	700	175	(120)	800	0	200	700	175
(121)	-	0	75	-	70	(121)	-	0	75	-	70
(122)	-	0	75	-	70	(122)	-	0	75	-	70
(130)	1200	0	400	1100	360	(130)	1200	0	400	1100	360
(131)	-	0	100	-	80	(131)	-	0	100	-	80
(132)	-	0	100	-	80	(132)	-	0	100	-	80
(133)	-	0	100	-	80	(133)	-	0	100	-	80
(134)	-	0	100	-	80	(140)	450	0	250	300	200
(135)	-	0	100	-	80	(141)	-	0	100	-	80
						(142)	-	0	100	-	80

Table 3.5 provides the cost of consumables based on LOR decisions for different design alternatives. From the table 3.5, we can see that if first design alternative of an assembly is selected and LOR decision for module (110) is made for repair at depot i.e. $[\boldsymbol{L_{1,2}(110)}]_{[\boldsymbol{D}]} = 1$; then the cost of consumables for repair of module (110) at depot (i.e. $[\mathrm{C_{mf}}]_{1,2}(110)_{[\mathbf{D}]}$) is 200 INR/-. If LOR decision for module (110) is made for discard at depot i.e. $[\boldsymbol{L_{3,2}(110)}]_{[\boldsymbol{D}]} = 1$, then cost of consumables for discard of module (110) at depot is cost of new module based on

design alternative. Similarly cost of consumables for other indenture items based on LOR decisions can be read from table 3.5. The total cost of transportation is calculated as cost of transporting the failed assembly and cost of transporting the lower indenture item to OEM level (i.e. if decision of move selected at depot level).

Table 3.5: Cost of consumables based on $\left[L_{r,e}(ijk)\right]_{[D]}$ (in INR)

Indenture items	Assembly level alternative 1 (A=1)					Indenture items	Assembly level alternative 2 (A=2)				
	$CC_{r,e}(ijk)_{[D]}$						$CC_{r,e}(ijk)_{[D]}$				
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r=1, e=3	r=3, e=3	(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r=1, e=3	r=3, e=3
(110)	200	50	*Cost of new item based on selected design*	200	*Cost of new item based on selected design*	(110)	200	50	*Cost of new item based on selected design*	200	*Cost of new item based on selected design*
(111)	-	50		-		(111)	-	50		-	
(112)	-	50		-		(112)	-	50		-	
(113)	-	50		-		(113)	-	50		-	
(120)	150	50		150		(120)	150	50		150	
(121)	-	50		-		(121)	-	50		-	
(122)	-	50		-		(122)	-	50		-	
(130)	300	50		250		(130)	200	50		200	
(131)	-	50		-		(131)	-	50		-	
(132)	-	50		-		(132)	-	50		-	
(133)	-	50		-		(133)	-	50		-	
(134)	-	50		-		(140)	200	50		200	
(135)	-	50		-		(141)	-	50		-	
						(142)	-	50		-	

Table 3.6 describes the transportation cost between different echelons in a fleet. As shown in table 3.6, generally these are calculated as percentage of cost of indenture items. The cost of holding for an assembly at base is estimated based on the percentage of assembly cost. Table 3.7 shows the holding cost for an assembly considered at base "b". The cost of holding for an assembly at base is estimated based on the percentage of assembly cost. In the current problem the recommended spares for repaired assembly with 95 % service level.

Table 3.6: Transportation cost between different echelons (in INR /item)

Indenture items	Transportation cost between each base and depot					Transportation cost between depot and OEM
	$TC(i00)_{[D]}$					$TC(ijk)_{[D]}$
(ijk)	b=1	b=2	b=3	b=4	b=5	e =2 to e = 3 if $\left[L_{2,2}(ijk)\right]_{[D]} = 1$
(i00)	20%	25%	30%	35%	40%	30%
(ij0)	-	-	-	-	-	20%
(ijk)	-	-	-	-	-	10%

Table 3.8 provides the transportation delay between different echelons and mean time to repair at depot and OEM. In the current problem, the transportation delay

includes the both for "too and fro" time between the base "b" and depot and similarly between depot and OEM.

Table 3.7: Holding cost at each base (in INR/item/year)

Indenture items	$[h(i00)]_{[D]}$
(ijk)	b=1, 2…5
(i00)	20%
(ij0)	-
(ijk)	-

Table 3.8: Transportation delay and mean time to repair for different echelons (in Hr.)

Transportation delay between different Base "b" and depot					Transportation delay between depot and OEM	Mean time to repair at depot	Mean time to repair at OEM
$(T_{Delay})_{b-d}$					$(T_{Delay})_{d-OEM}$	$MTTR_d$ (Normal distribution)	$MTTR_{OEM}$ (Normal distribution)
b=1	b=2	b=3	b=4	b=5	e=2 to e=3	e=2	e=3
60	75	85	95	110	96	μ=20, σ=4	μ=18, σ=4

The values costs corresponding to these repair actions and selected base, as mentioned in Table 3.4, 3.5, 3.6 , 3.7 and 3.8 are the input parameters for the model. In general these parameters are considered based on the guidelines available in literature. For example, the "cost of repair" of components is generally more than the "cost of discard", because "repair" action requires some advance inspection facilities equipments (i.e. fault tester and tools etc.) then required for the "discard" action. Additionally, the cost of maintenance facilities also varies from the base level to OEM level. The cost of installing the maintenance facility at the base is more than that at the depot and OEM level.

The results are specific to the values considered in this work. One will have to capture these parameters from the particular fleet to apply the approach presented in this research.

3.5.1 Optimization Complexities

The size of the solution space depends on number of possible design configurations for assembly and modules. The solution space further gets multiplied by possible level of repair decisions for selected design configuration. In the current problem if design configuration A=1 is selected then possible design configuration at module level would be multiplication of possible design configuration for each of the three modules. For module 1 with three parts the possible design configuration is $3 \times 2 \times 4$ i.e. 24, as part (111) has 3 design alternatives, part (112) has 2 design alternatives and part (113) has 4 design alternatives. Similarly possible design configuration for module 2 and 3 are 8 and 256 respectively. Therefore the total design configuration at assembly level is $24 \times 8 \times 256$ i.e. 49152. Similarly, if design configuration A=2 is selected then total design configuration at assembly level will be also $24 \times 8 \times 32 \times 8$ i.e. 49152, as possible design configurations for module 1, 2, 3 and 4 are 24, 8, 32 and 8 respectively. The size of LOR decisions for the selected assembly depends on number of enclosed indenture items (ijk) and the possible maintenance actions at each echelon. For example, if first design (i.e. A=1) for an assembly is selected then the number of enclosed indenture items is 13 (i.e. 3 modules + 10 parts of corresponding modules) and number of maintenance actions available at depot and OEM for each indenture item are 5 (i.e., 3 at depot + 2 at OEM). Therefore the total number of LOR decision would be 5^{13}. Therefore possible alternatives of design and LOR for A=1 would be $5^{13} \times 49152$. Similarly, if second design (i.e. A=2) for an assembly is selected then the number of enclosed indenture items is 14 (i.e. 4 modules + 10 parts of corresponding modules). Thus, the possible alternative of design and LOR for A=2 would be $5^{14} \times 49152$. Thus the total size of the solution space is $5^{13} \times 49152 + 5^{14} \times 49152 \approx 36 \times 10^{13}$. The next sub-section describes the details to solve this complex problem.

3.6 Solution Methods

The optimization complexities discussed above shows that the proposed problem becomes computationally complex problem to solve it through conventional optimization algorithms. Therefore, Genetic Algorithm (GA) is used in this research to solve this complexity. GA is a search technique that imitates the natural selection and biological evolutionary process. GA has been used in a wide variety of applications, particularly in combinatorial optimization problems, and they were proved to be able to provide near optimal solutions in reasonable time. A GA starts with a population of randomly generated candidate solutions (called chromosomes). A chromosome is represented by a string of numbers called genes. Each chromosome in the population is evaluated according to some fitness measure. Certain pairs of chromosomes (parents) are selected on the basis of their fitness. Each of these pairs combines to produce new chromosomes (offspring), and some of the offspring are randomly modified. A new population is then formed replacing some of the original population by an identical number of offspring. This process repeats until a predetermined number of generations have been generated, and the procedure terminates.

Further, as some of the parameters in the integrated model are stochastic in nature. For example, mean time to repair at depot and OEM has normal distribution. Therefore, Monte Carlo simulation based a Genetic Algorithm is used in this paper that minimize the average LCC of fleet maintenance system. RISKOptimizer software [95] is used for this purpose. RISKOptimizer tool provides different algorithms for adjusting the decisions variables. It generates different permutations of a starting solution and is designed for optimizing rankings of objective function. Table 3.9 describes the pseudo code for simulation based genetic algorithm used for the optimization. The LCC of the fleet maintenance system for the particular user "b" is the objective function in the optimization model. In this illustration the value of genetic algorithm parameters are used as follows: the population size, m= 50, crossover probability, CR= 0.75 and mutation rate, MR= 0.1.

Table 3.9: Pseudo code for simulation based genetic algorithm

Define the GA Parameters: *Population Size 'm', crossover rate 'CR', mutation rate 'MR'*
Define the Objective Function : *Minimize* $(\mathbf{PV_{LCC}})_\mathbf{b}$
// **Formulation**
Set Input Model Parameters();
Define mean as the statistic for the simulation results;
defineDecisionVariables();
defineConstraints();
// **Simulation based optimization**
Initialize ( );
Generate_ random ( ) m individuals;
Compute _fitness (α) ∀ α ∈ m;
1 ***for Trial=1 to termination do***
2 Select two individuals α_a& $\alpha_b$from population by using rank based mechanism;
3 Generate α_c & α_d; by uniform crossover on α_a & α_b under rate *CR*;
4 Select one off spring; apply non-uniform mutation under rate *MR*; // Generate new decision variables
// **Simulation**
5 Determine sample of uncertain parameters using probability distribution functions;
6 Recalculate the model using new sampled values and new decision variables;
7 Calculate and store the new value of $(\mathbf{PV_{LCC}})_\mathbf{b}$;
8 ***If*** Solution is unfeasible **then**
9 Repeat simulation from step 5;
10***Endif***
// Increment
11 Update m: = m+1
12 ***Endfor***
// Resulting minimum $(\mathbf{PV_{LCC}})_\mathbf{b}$
13 return $(\mathbf{PV_{LCC}})_\mathbf{b}$

3.7 Optimization Results

Optimization results for each base are summarized in table 3.10 and 3.11. Table 3.10 describes optimal design decisions for machines required at each base. It can be seen from table 3.10 that for base 1 and 2 optimal alternative for assembly is design alternative 1 (i.e. A=1) and for base 3, 4 and 5 it is alternative 2 (i.e. A=2). Table 3.10 also describes the optimal design decisions for each module of selected optimal assembly. For example, at base 1, module 1 is configured by obtaining the following optimal design alternatives of enclosed parts; for parts (111) and (112), the first design alternative is optimal, whereas for part (113) fourth design alternative is optimal. Similarly the design decisions for other assembly and modules can be read from table 3.10. Table 3.10 also shows the optimal acquisition cost and LCC for each base. The recommended spares of repair assembly with 95 % service level are 6 for base 1 and 2 and 7 for base 3, 4 and 5. Apart from optimal design decisions, acquisition costs, and optimal life cycle cost (for integrated strategy), table 3.10 also shows the acquisition cost and

LCC for most reliable design. This is obtained by fixing the design alternatives at lowest failure rate levels (i.e. most reliable design) and optimizing the level of repair decisions.

Table 3.10: Optimal design decisions for each base based on $\lambda(\text{ijk})_{[\boldsymbol{D}]}$

Base "b"		b = 1	b = 2			b = 3	b = 4	b = 5
Module	(ijk)	Optimal design for modules		Module	(ijk)	Optimal design for modules		
1	(111)	Alt_1	Alt_1	1	(111)	Alt_3	Alt_3	Alt_3
	(112)	Alt_1	Alt_1		(112)	Alt_2	Alt_2	Alt_2
	(113)	Alt_4	Alt_4		(113)	Alt_1	Alt_1	Alt_1
2	(121)	Alt_1	Alt_1	2	(121)	Alt_1	Alt_1	Alt_1
	(122)	Alt_1	Alt_1		(122)	Alt_1	Alt_1	Alt_1
3	(131)	Alt_1	Alt_1	3	(131)	Alt_2	Alt_2	Alt_4
	(132)	Alt_2	Alt_2		(132)	Alt_1	Alt_1	Alt_2
	(133)	Alt_1	Alt_1		(133)	Alt_4	Alt_1	Alt_4
	(134)	Alt_2	Alt_2	4	(141)	Alt_2	Alt_1	Alt_2
	(135)	Alt_2	Alt_2		(142)	Alt_2	Alt_2	Alt_2
Optimal assembly alternative		A=1	A=1			A=2	A=2	A=2
Optimal acquisition cost with integrated approach (in INR/machine)		54975	54975			60621	65699	59411
Spare of assembly with 0.95 SL		6	6			7	6	7
$[\text{PV}_{\text{fm}}]_{\text{b}} \times 10^5$ in INR (With integrated approach)		15.96	28.36			12.07	14.10	18.41
With dis-integrated approach								
Assembly acquisition cost for most reliable design (in INR)				71811				
LCC with most reliable designed assembly (Without integration approach $\times 10^5$ in INR)		18.92	33.17			12.53	14.88	19.12

Table 3.11 provides optimal LOR decisions for enclosed indenture items of obtained optimal designed assembly for base 1, 2, 3, 4 and 5. According to optimal LOR decisions from table 3.11, whenever assembly fails at base 1, then failed assembly will be repaired by the following optimal LOR decisions for enclosed indenture items; Module (110) will be repaired at depot (i.e. r=1, e=2) by discarding the enclosed parts (111), (112) and (113) at depot (i.e. r=3, e=2) as highlighted in table 3.11. Module (120) will be discarded at depot (i.e. r=3, e=2), by discarding the parts (121) and (122) at depot. Similarly module (130) will be repaired at depot by discarding the parts (131), (132), (133) and (135) at depot (i.e. r=3, e=2) and by discarding the part (134) at OEM (i.e. r=3, e=3). However decision of discard at OEM level is followed by the "move" decision selected at depot for indenture items. Similarly, for base 2, 3, 4 and 5, the optimal LOR

decisions can be read form the table 3.11. Table 3.12 shows the optimal LOR decisions achieved considering the dis-integrated approach.

Table 3.11: Optimal LOR decisions of each indenture (ijk) of obtained optimal assembly at base 1, 2, 3, 4 and 5 based on $\left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{D}]}$ in **with integrated approach**

Indenture items	LOR decision for base 1 (b = 1)				
	Optimal assembly alternative			A=1	
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r=1, e=3	r =3, e=3
(110)	1	0	0	0	0
(111)	0	0	1	0	0
(112)	0	0	1	0	0
(113)	0	0	1	0	0
(120)	0	0	1	0	0
(121)	0	0	1	0	0
(122)	0	0	1	0	0
(130)	1	0	0	0	0
(131)	0	0	1	0	0
(132)	0	0	1	0	0
(133)	0	0	1	0	0
(134)	0	1	0	0	1
(135)	0	0	1	0	0

Indenture items	LOR decision for base 2 (b = 2)				
	Optimal assembly alternative			A=1	
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r =1, e=3	r =3, e=3
(110)	1	0	0	0	0
(111)	0	0	1	0	0
(112)	0	0	1	0	0
(113)	0	1	0	0	1
(120)	1	0	0	0	0
(121)	0	1	0	0	1
(122)	0	1	0	0	1
(130)	1	0	0	0	0
(131)	0	0	1	0	0
(132)	0	1	0	0	1
(133)	0	1	0	0	1
(134)	0	0	1	0	0
(135)	0	1	0	0	1

Indenture items	LOR decision for base 3 (b = 3)				
	Optimal assembly alternative			A=2	
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r =1, e=3	r =3, e=3
(110)	1	0	0	0	0
(111)	0	0	1	0	0
(112)	0	1	0	0	1
(113)	0	1	0	0	1
(120)	1	0	0	0	0
(121)	0	1	0	0	1
(122)	0	0	1	0	0
(130)	1	0	0	0	0
(131)	0	0	1	0	0
(132)	0	1	0	0	1
(133)	0	1	0	0	1
(140)	1	0	0	0	0
(141)	0	0	1	0	0
(142)	0	0	1	0	0

Indenture items	LOR decision for base 4 (b = 4)				
	Optimal assembly alternative			A=2	
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r =1, e=3	r =3, e=3
(110)	1	0	0	0	0
(111)	0	0	1	0	0
(112)	0	1	0	0	1
(113)	0	0	1	0	0
(120)	1	0	0	0	0
(121)	0	0	1	0	0
(122)	0	1	0	0	1
(130)	0	0	1	0	0
(131)	0	0	1	0	0
(132)	0	0	1	0	0
(133)	0	0	1	0	0
(140)	1	0	0	0	0
(141)	0	0	1	0	0
(142)	0	1	0	0	1

Indenture items	LOR decision for base 5 (b = 5)				
	Optimal assembly alternative			A=2	
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r =1, e=3	r =3, e=3
(110)	1	0	0	0	0
(111)	0	0	1	0	0
(112)	0	0	1	0	0
(113)	0	0	1	0	0
(120)	0	0	1	0	0
(121)	0	0	1	0	0
(122)	0	0	1	0	0
(130)	0	0	1	0	0
(131)	0	0	1	0	0
(132)	0	0	1	0	0
(133)	0	0	1	0	0
(140)	1	0	0	0	0
(141)	0	0	1	0	0
(142)	0	0	1	0	0

Table 3.12: Optimal LOR decisions of each indenture (ijk) of obtained optimal assembly at base 1, 2, 3, 4 and 5 based on $\left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{D}]}$ in **dis-integrated approach**

Indenture items	LOR Decision for Base 1 (b = 1)				
	Optimal Assembly Alternative			**A=2**	
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r=1, e=3	r =3, e=3
(110)	1	0	0	0	0
(111)	0	0	1	0	0
(112)	0	0	1	0	0
(113)	0	0	1	0	0
(120)	1	0	0	0	0
(121)	0	0	1	0	0
(122)	0	1	0	0	1
(130)	0	0	1	0	0
(131)	0	0	1	0	0
(132)	0	0	1	0	0
(133)	0	0	1	0	0
(140)	1	0	0	0	0
(141)	0	0	1	0	0
(142)	0	1	0	0	1

Indenture items	LOR Decision for Base 2 (b = 2)				
	Optimal Assembly Alternative			**A=2**	
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r =1, e=3	r =3, e=3
(110)	1	0	0	0	0
(111)	0	0	1	0	0
(112)	0	0	1	0	0
(113)	0	0	1	0	0
(120)	1	0	0	0	0
(121)	0	0	1	0	0
(122)	0	1	0	0	1
(130)	0	0	1	0	0
(131)	0	0	1	0	0
(132)	0	0	1	0	0
(133)	0	0	1	0	0
(140)	1	0	0	0	0
(141)	0	0	1	0	0
(142)	0	1	0	0	1

Indenture items	LOR Decision for Base 3 (b = 3)				
	Optimal Assembly Alternative			**A=2**	
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r =1, e=3	r =3, e=3
(110)	1	0	0	0	0
(111)	0	0	1	0	0
(112)	0	0	1	0	0
(113)	0	1	0	0	1
(120)	1	0	0	0	0
(121)	0	0	1	0	0
(122)	0	0	1	0	0
(130)	1	0	0	0	0
(131)	0	0	1	0	0
(132)	0	0	1	0	0
(133)	0	0	1	0	0
(140)	1	0	0	0	0
(141)	0	0	1	0	0
(142)	0	0	1	0	0

Indenture items	LOR Decision for Base 4 (b = 4)				
	Optimal Assembly Alternative			**A=1**	
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r =1, e=3	r =3, e=3
(110)	1	0	0	0	0
(111)	0	0	1	0	0
(112)	0	1	0	0	1
(113)	0	0	1	0	0
(120)	1	0	0	0	0
(121)	0	0	1	0	0
(122)	0	1	0	0	1
(130)	0	0	1	0	0
(131)	0	0	1	0	0
(132)	0	0	1	0	0
(133)	0	0	1	0	0
(140)	1	0	0	0	0
(141)	0	0	1	0	0
(142)	0	1	0	0	1

Indenture items	LOR Decision for Base 5 (b = 5)				
	Optimal Assembly Alternative			**A=2**	
(ijk)	r=1, e=2	r=2, e=2	r=3, e=2	r =1, e=3	r =3, e=3
(110)	1	0	0	0	0
(111)	0	0	1	0	0
(112)	0	0	1	0	0
(113)	0	0	1	0	0
(120)	0	0	1	0	0
(121)	0	0	1	0	0
(122)	0	0	1	0	0
(130)	0	0	1	0	0
(131)	0	0	1	0	0
(132)	0	0	1	0	0
(133)	0	0	1	0	0
(140)	1	0	0	0	0
(141)	0	0	1	0	0
(142)	0	0	1	0	0

3.7.1 Observations

(a) It can be seen from table 3.10 that the LCC obtained with integrated approach is always lesser than that with most reliability design. For example, the LCC obtained with integrated approach for base 1 is 15.96×10^5 INR/- whereas the same with most reliability design is 18.92×10^5 INR/-. Figure 3.3 shows the percentage increase in LCC with most reliability design over the integrated approach for all five bases. Thus it can be concluded that the most reliable design may not always result into best system performance. In other words, lower reliability configuration with appropriate LOR decisions may give better life cycle performance for the fleet. Therefore, the integration of reliability design and LOR decisions is important at early design stage of fleet maintenance systems.

(b) It can be seen from table 3.10 and 3.11 that the design decisions are same for base 1 and 2 but corresponding LOR decisions are different at these two bases. In other words the design and LOR decisions are dependent on user's cost structure also. Seen in this light, the proposed detailed LCC models become very useful in arriving such user specific design and LOR decisions. This will further give an opportunity to perform what if analysis with cost parameters. Users can then work on changing their cost structure to get economic advantages.

(c) As the optimal LCC is less for more modular design of assembly (i.e. A=2) at base 3, 4 and 5 compared to less modular design of assembly (i.e. A=1) at base 1 and 2, it can be concluded from table 3.10 and 3.11 that more modular design leads to better life cycle performance of fleet maintenance system. We expect that this mainly happens because of modularization, as the cost of installing maintenance facilities for discard of module is generally lower than that for discard of enclosed parts of that module creating an opportunity to take LOR decisions on higher indenture item such as selection of discard decision at module level then at enclosed part level. Further, modularization creates an ease of maintenance as it reduces the service time in terms of fault diagnosis, access, and repair.

(d) Further to the discussion on modularization, it can be added with reference to figure 3.3 that in case of more modular design, integrated approach leads to a LCC performance level closer to that of most reliable design LCC performance. Therefore, if the alternative designs are more modular and no additional information or data are available for performing integrated design and LOR approach, as a thumb rule, most reliable design alternatives can be selected for the system configuration. However for lesser modular design, optimal design configuration using the integrated approach should be obtained.

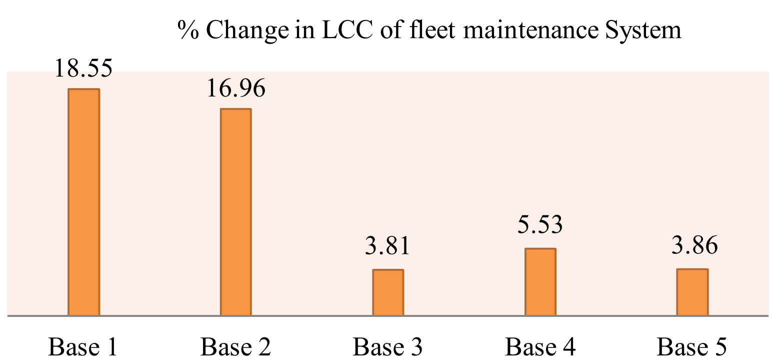

Figure 3.3: % Change in LCC considering the best designed machines at each base

3.7.2 Sensitivity analysis

In order to evaluate the robustness of the proposed solutions, the optimization procedure is repeated with small percentage variation in cost of maintenance facility, cost of consumables and transportation cost between different echelons. These costs are varied in the range of $\pm 10\%$. After conducting the sensitivity analysis, it is found that the design and LOR decisions are sensitive only for maintenance facility cost and it is not sensitive to cost of consumables and transportation cost as shown in table 3.13-a, b and c.

Table 3.13-a : Sensitivity analysis for cost of maintenance facility at different echelons

% Change in maintenance facility cost	Sensitive for LOR decisions (Yes "Y" /No "N")					Sensitive for design decisions (Yes "Y" /No "N")				
$[C_{mf}]_{r,e}(ijk)_{[D]}$	(b = 1)	(b = 2)	(b = 3)	(b = 4)	(b = 5)	(b = 1)	(b = 2)	(b = 3)	(b = 4)	(b = 5)
+10%	N	N	**Y**	N	**Y**	N	N	N	N	**Y**
+5%	N	N	N	N	N	N	N	N	N	N
Base value	-	-	-	-	-	-	-	-	-	-
-5%	N	N	**Y**	N	**Y**	N	N	**Y**	N	**Y**
-10%	**Y**	N	**Y**	N	N	**Y**	N	N	N	N

$[C_{mf}]_{r,e}(ijk)_{[D]}$	Change in LCC for each base "b" $[PV_{fm}]_b$ in `				
	(b = 1)	(b = 2)	(b = 3)	(b = 4)	(b = 5)
+10%	920368	1784614	873054	1065819	1331002
+5%	1029281	1730757	920670	1065657	1297777
Base value	1578844	2830078	1195146	1340028	1840567
-5%	913473	1668773	835501	1065333	1335485
-10%	919958	1730523	834167	1065462	1297559

Table 3.13-b : Sensitivity analysis for cost of consumables at different echelons

% Change in consumables cost	Sensitive for LOR decisions (Yes "Y" /No "N")					Sensitive for LOR decisions (Yes "Y" /No "N")				
$CC_{r,e}(ijk)_{[D]}$	(b = 1)	(b = 2)	(b = 3)	(b = 4)	(b = 5)	(b = 1)	(b = 2)	(b = 3)	(b = 4)	(b = 5)
+10%	N	N	N	N	N	N	N	N	N	N
+5%	N	N	N	N	N	N	N	N	N	N
Base value	-	-	-	-	-	-	-	-	-	-
-5%	N	N	N	N	N	N	N	N	N	N
-10%	N	N	N	N	N	N	N	N	N	N

$CC_{r,e}(ijk)_{[D]}$	Change in LCC for each base "b" $[PV_{fm}]_b$ in `				
	(b = 1)	(b = 2)	(b = 3)	(b = 4)	(b = 5)
+10%	1029635	1731660	920603	1065418	1297621
+5%	1029361	1731111	920567	1065418	1297542
Base value	*1578844*	*2830078*	*1195146*	*1340028*	*1840567*
-5%	1028176	1703374	920493	1065407	1297395
-10%	1029031	1730452	920524	1065410	1297453

Table 3.13-c: Sensitivity analysis for cost of transportation between different echelons

% Change in transportation cost	Sensitive for LOR decisions (Yes "Y" /No "N")					Sensitive for LOR decisions (Yes "Y" /No "N")				
$TC(ijk)_{[D]}$	(b = 1)	(b = 2)	(b = 3)	(b = 4)	(b = 5)	(b = 1)	(b = 2)	(b = 3)	(b = 4)	(b = 5)
+10%	N	N	N	N	N	N	N	N	N	N
+5%	N	N	N	N	N	N	N	N	N	N
Base value	-	-	-	-	-	-	-	-	-	-
-5%	N	N	N	N	N	N	N	N	N	N
-10%	N	N	N	N	N	N	N	N	N	N

$TC(ijk)_{[D]}$	Change in LCC for each base "b" $[PV_{fm}]_b$ in `				
	(b = 1)	(b = 2)	(b = 3)	(b = 4)	(b = 5)
+10%	1030984	1734358	924274	1079620	1305829
+5%	1030035	1732460	923211	1072517	1303265
Base value	*1578844*	*2830078*	*1195146*	*1340028*	*1840567*
-5%	1036679	1745747	923368	1069862	1306629
-10%	1027378	1727145	918616	1051463	1292860

Therefore, it is recommended that cost of maintenance facility should be captured as accurately as possible for a particular fleet maintenance system. It was also observed that the solution obtained did not change with range variation in the genetic algorithm parameters like population size “m” from 50 to 100, crossover probability “CR” from 0.75 to 0.95 and mutation rate “MR” from 0.5 to 1.

3.7.3 Effect of Slope of Reliability vs. Cost Curve

Results discussed in the above section are with respect to a given reliability vs. cost relationships for alternative designs of parts, shown in table 3.2. A closer observation from table 3.2 may reveal a linear relationship between cost and reliability of alternative designs. In other words the relationship has following form:

$$\text{Cost of Alternative Design} = -\text{Slope} \times \text{Failure Rate of Alternative Design} + \text{Intercept}$$

For example, in table 3.2, part (111) of assembly 1(i.e. A=1) has three alternatives having 0.015, 0.035 and 0.065 failure rates with cost of 4000 INR/-, 3000 INR/- and 2000 INR/- respectively. The costs vs. reliability relationships for this part can therefore be expressed as

$$\mathrm{C(ijk)} = -39474 \times \lambda(111) + 4513.2 \qquad (3.21)$$

Similar relationships can be obtained for other parts from table 3.2. Therefore it will be interesting to see the effect of various slopes of cost vs. reliability models of the integrated problem. To investigate this effect following three cases are considered:

- Case-1: with slope as used in the above problem;
- Case-2: with 50% lesser slope for all parts compare to case-1;
- Case-3: with 50% higher slope for all parts compare to case-1.

These three cases are plotted for part (111) of assembly alternative 1 and 2 in figure 3.4-a and 3.4-b. Both integrated and most reliability design approaches discussed in above problem, are then solved for these three cases and compared with most reliability design approach. The comparative results are shown in figure 3.5. It can be seen from fig. 3.5 that even with 50% lower or higher slope the integrated approach gives the better results than the most reliable approach. This further strengthens the findings reported in subsection 3.7.1. Further, it can be commented from figure 3.5 that if the variation in alternatives design costs of parts are more (i.e. case-3) then integrated approach is more important. On the other hand if the variation is less (i.e. case-2) then as a thumb rule designer can go for most reliable design.

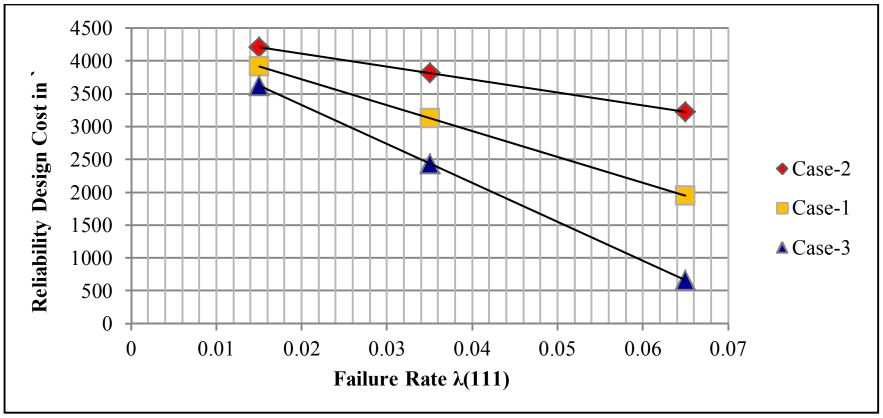

Figure 3.4-a: Trend lines for different cases of part (111) of assembly alternative 1

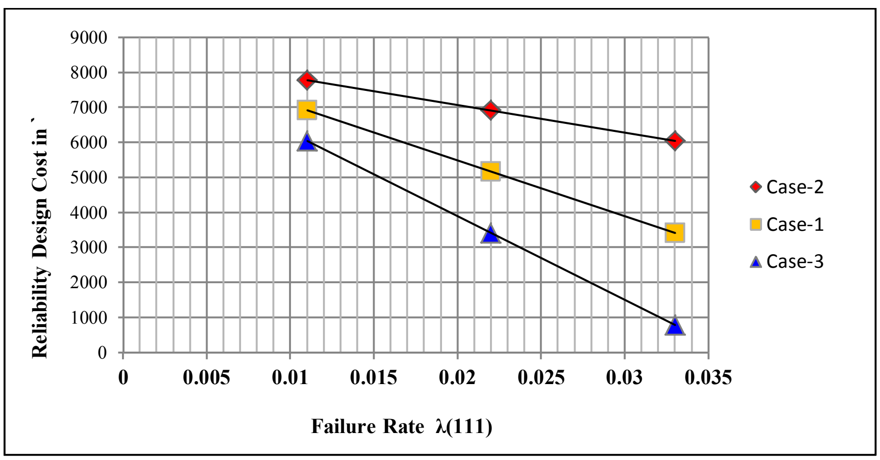

Figure 3.4-b: Trend lines for different cases of part (111) of assembly alternative 2

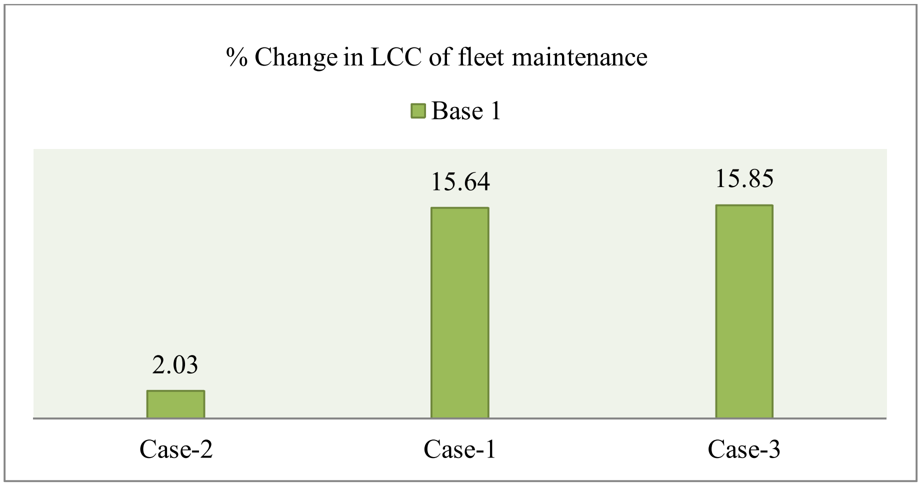

Figure 3.5: % change in LCC considering integrated approach over dis-integrated approach for different cases at base 1

3.8 Integrated Reliability Design and LOR Decisions with the Time Dependent Failure Rate of the Components.

The failure rate values for the components used in the previous approach were considered as constant (not time-dependent). The same problem has been solved considering the time-dependent failure rates of the components thereby making the analysis more practical.

To model the time dependent failure rates of the machine, let us consider the time to failures of each part of the machine follows a two parameter Weibull distribution. Let η_{ijk} indicates the characteristic life of a part (ijk) and β_{ijk} represents the shape parameter of a part (ijk). In this approach more complex system configuration with multiple assemblies is considered, which is shown in figure 3.6.

Compare to previous approach, the machine is considered to be made up of three assemblies (i.e., i= 1 to 3). The focus of this approach is similar to the previous, where the OEM supplies the machine and associated life cycle maintenance contract to users. Entire problem considered in the previous approach is same but the maintenance modelling considering the time dependent failure rate creates more complexities in calculating number of failure in existing LCC.

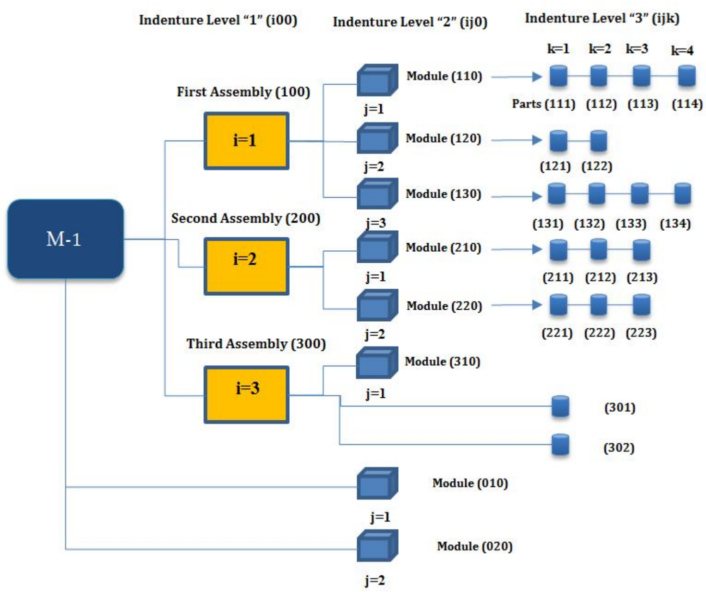

Figure 3.6: Pictorial example of modular multi-indenture system

The decisions making processes is considered in this approach are as follows;

Whenever a machine fails then its enclosed failed assembly (i00) is removed from the machine and sends to the base level maintenance facility. At base level maintenance facility, failed module (ij0) is removed and decision on "repair", "discard" or "move of the module (ij0) to depot" is made. Each of these will further lead to different repair options as indicated in table 3.14. For example, the "repair" decision of the module (ij0) leads to further decision options on "discard of the part (ijk)" at base or "move the part (ijk)" to depot. If part (ijk) is moved to depot then the part can be either discarded at depot itself or can be moved to OEM level maintenance facility for subsequent discard there. In this approach, it is assumed that base level maintenance facility maintains spare parts with a predefined Service Level (SL) for the modules and parts that are discarded at base. Therefore a repair channel is considered for modules or parts at base level maintenance facility for the LOR analysis. But in the previous approach, the spare parts of the assembly are stocked with predefined SL. If the decision of discard is made at depot or OEM then the failed assembly (i00) will have to wait till the replaced module (ij0) or part (ijk) reaches the base. It is assumed that the depot or OEM always has the sufficient spare items to perform the discard decisions.

Table 3.14: Possible LOR decisions for different modules of a machines

Items (ijk)	Base (e=1)	Depot (e=2)	OEM (e=3)
Assembly (i00)	Remove from the machine and send to base repair facility	X	X
Module (ij0)	Repair, Move, Discard	Repair, Move, Discard	Repair, Discard
Part (ijk)	Move, Discard	Move, Discard	Discard

Therefore, the problem is to find out the optimal "reliability design" configuration and associated optimal "level of repair" decisions for a particular base "b" or user.

Now, the integrated problem considering the time dependent failure rate of the components is formulated as discussed earlier in the section 3.3. The present value of the LCC is minimized considering the LOR decision constraints (as shown in table 3.14) and physical system constraints (as shown in figure 3.6). The detailed life cycle cost models considering the LOR analysis is discussed earlier in the section 3.4. The same is reproduced in equation (3.22) to estimates the LCC of the user "b". The only difference is in the annual down time cost model. The Annual Average Down Time Cost (ADTC) considered for this model is calculated as follows.

$$\begin{aligned}
[\mathbf{PV_{LCC}}]_{\mathbf{b}} = &\sum_{ijk} \mathrm{AQC}(\mathrm{ijk})_{[\mathbf{A}_i]} \times \mathrm{m_b} \cdot \left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{A_i}]} \\
&+ \sum_{ijk} \left[\mathrm{NRC_{r,e}}(\mathrm{ijk})\right] \cdot \left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{A_i}]} \\
&+ \sum_{y=1}^{L} \left\{ \frac{1}{(1-\mathrm{R})^{\mathrm{y}}} \right. \\
&\times \sum_{ijk} \Big(\Big[\left[\mathrm{AACC_{r,e}}(\mathrm{ijk})\right] + \left[\mathrm{AADTC_{r,e}}(\mathrm{ijk})\right] + \left[\mathrm{AATC_{r,e}}(\mathrm{ijk})\right] \\
&+ \left[\mathrm{AASHC_{r,e}}(\mathrm{ijk})\right] + \left[\mathrm{AASOC_{r,e}}(\mathrm{ijk})\right] \Big] \times [\mathrm{nof}(\mathrm{ijk})]_{[\mathrm{A}_i]} \\
&\left. \cdot \left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{A_i}]} \Big) \right\}
\end{aligned} \tag{3.22}$$

The annual average down time cost is the cost of unavailability of the machines during the maintenance action. It includes cost of production loss due to unavailability of the machines. In this approach, the down time of the machines are estimated based on time consumed during each maintenance action. It mainly depends on time to repair of the particular indenture item (ijk) of the machine.

During the LOR analysis, the down time of an indenture item (ijk) is estimated based on Total Mean Time to Repair (TMTTR). It is divided in two parts $\mathrm{MTTR}_1$and MTTR_2, as discussed below.

$MTTR_1$: It includes mean time required to remove the failed assembly from the machine; mean time required in removal of failed module from the failed assembly; mean time required in installation of repaired/new module into the assembly and installing the repaired assembly into the machine. $MTTR_1$ for ith assembly is indicated by $MTTR_1(\mathrm{i00})$.

$MTTR_2$: It basically includes the mean service time taken by a failed module based on the LOR decision i.e. discards of an indenture item and replaced with new indenture item from spare inventory at particular echelon. Additionally, if final decision of discard for an indenture item is made at depot or OEM level then the service time also includes the transportation delay (to and fro both) time from base to depot or depot to OEM respectively. Thus, the $MTTR_2$ for an indenture item (ijk) can be calculated as follows;

$$\begin{aligned} MTTR_2(\mathrm{ijk}) = \Big(& [\mathrm{MTTR(ijk)}]_{\mathrm{b}} \cdot \boldsymbol{L_{3,1}(ijk)}_{[\boldsymbol{A_i}]} + \left(\left[\mathrm{T_{Delay}}\right]_{\mathrm{b-D}}\right) \\ & \cdot \left[\boldsymbol{L_{2,1}(ijk)}_{[\boldsymbol{A_i}]}\right] + [\mathrm{MTTR(ijk)}]_{\mathrm{D}} \cdot \left[\boldsymbol{L_{3,2}(ijk)}_{[\boldsymbol{A_i}]}\right] \\ & + \left(\left[\mathrm{T_{Delay}}\right]_{\mathrm{d-OEM}}\right) \cdot \left[\boldsymbol{L_{2,2}(ijk)}_{[\boldsymbol{A_i}]}\right] \\ & + ([\mathrm{MTTR(ijk)}]_{\mathrm{OEM}}) \cdot \left[\boldsymbol{L_{2,3}(ijk)}_{[\boldsymbol{A_i}]}\right]\Big) \end{aligned} \tag{3.23}$$

Therefore, the total mean time to repair for an indenture item (ijk) is the summation of $MTTR_1(\mathrm{i00})$ and $MTTR_2(\mathrm{ijk})$ as shown below.

$$\mathrm{TMTTR(ijk)} = MTTR_1(\mathrm{i00}) + MTTR_2(\mathrm{ijk}) \tag{3.24}$$

Therefore, the AADTC is estimated by the equation 4.18.

$$\mathrm{AADTC} = \sum\nolimits_{\mathrm{ijk}} \left\{\mathrm{TMTTR(ijk)} \times \left[\mathrm{nof(ijk)}_{\boldsymbol{t_{pm}(ijk)}}\right]_{\mathrm{y}} \times \mathrm{m} \times \mathrm{C_{dt}}\right\} \tag{3.25}$$

Actually all these cost are depends on the design decisions (i.e. $\boldsymbol{A_i}$) and LOR decisions (i.e.$\left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{A_i}]}$). Following paragraphs discusses the details of decisions variable considered in this research work.

Design Decision Variables: $\mathbf{A_i}$ denoting to design decision matrix representing system configuration selected from the available design alternatives as shown in table 3.15. In the current problem "**A**" varies based on available alternatives for the $\boldsymbol{i^{th}}$assembly of the machine. The design alternatives of the various assemblies are varies in terms of modularity (i.e. less modular to more modular design). The design decision variable for $\boldsymbol{i^{th}}$assembly of the machine will be considered as follows; if the alternative $\boldsymbol{A}$ is selected for $\boldsymbol{i^{th}}$assembly then $\boldsymbol{A_i} = 1\boldsymbol{;}$ otherwise, $\boldsymbol{A_i} = 0\boldsymbol{.}$ It is considered that at a time only one design decisions is selected for the $\boldsymbol{i^{th}}$assembly of the machine i.e. $\sum_{i=1}^{A} A_i = 1$. For example, if first, second and first alternative is selected for the first, second and third enclosed assembly respectively then $1_1 + 2_2 + 1_3 = 1\boldsymbol{.}$

LOR Decision Variables: $\left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{A_i}]}$ represents LOR decision matrix for the indenture item (ijk) for selected design decisions matrix $\boldsymbol{A_i}$. Where "**r**" denotes to the maintenance action decisions; with $r = 1$ denoting to repair, $r = 2$ denoting to move and $r = 3$ denoting to discard. These maintenance actions are perform at different echelons represented by "**e**"; $e = 1$ denotes to Base level (echelon 1), $e = 2$ denotes to Depot level (echelon 2) and $e = 3$ denotes to OEM level (echelon 3). The LOR decisions variable for the indenture item (ijk) for, design decisions matrix will be considered as if the maintenance action **"r"** at echelon **"e"** is selected for indenture item (ijk) for design decision matrix $\boldsymbol{A_i}$ then $\left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{A_i}]} = 1\boldsymbol{,}$ otherwise $\left[\boldsymbol{L_{r,e}(ijk)}\right]_{[\boldsymbol{A_i}]} = 0.$

3.8.1 Numerical Illustration

In this section a numerical example is presented to investigate the value of proposed integrated approach. In this example five users/bases (i.e. b=1 to 5) are considered. The number of machine required at these bases is 10, 20, 5, 15 and 25 respectively. A machine is composed of three assemblies. The physical structure of the machine is shown in the figure 3.6. However, table 3.15, 3.16 and 3.17 provides the cost and reliability parameters of the different design alternatives of the assembly-1, 2 and 3. Alternatives at assembly level vary on the modularity of the assembly and at module level it mainly varies on the reliability the enclosed parts.

Table 3.15: Reliability and cost parameters for different alternatives of first assembly

First design alternative (i.e. A_1=1)

Modules (ij0)	Part (ijk)	Alternatives at part level: First alternative (Alt_1)			Second alternative (Alt_2)		
		η_{ijk}	β_{ijk}	Cost	η_{ijk}	β_{ijk}	Cost
(110)	111	6000	3.2	3500	7200	2.5	4560
	112	3500	2.6	2500	5500	2	3200
	113	5000	3.1	4000	6000	2.8	5000
(120)	121	5000	2.2	4000	5800	2.5	4550
	122	4000	2.3	3000	4670	2.5	4750
(130)	131	2500	2.6	5000	3200	2.8	5650
	132	2000	2	4000	2700	2.5	3000
	133	3000	2.7	6000	3560	3	3450
	134	4000	3	3000	4850	3	4400
	135	5000	2.5	6500	5750	2.2	5600

Second design alternative (i.e. A_1=2)

Modules (ij0)	Part (ijk)	Alternatives at part level: First alternative (Alt_1)			Second alternative (Alt_2)		
		η_{ijk}	β_{ijk}	Cost	η_{ijk}	β_{ijk}	Cost
(110)	111	2500	2.4	4373	3000	3	5800
	112	3850	2	4665	4800	2.3	5640
	113	3260	2.2	5000	4000	2.5	6200
(120)	121	4500	2.3	10000	5500	2	11500
	122	5000	3.5	8000	6000	2.5	9500
(130)	131	6000	3.2	5500	7000	2.6	6500
	132	2580	2	6500	3500	1.5	7500
	133	3900	2.8	3000	4200	2.5	4500
(140)	141	7600	3	3000	8500	3	4500
	142	6100	2.8	3500	7000	2.5	4200

Third design alternative (i.e. A_1=3)

Modules (ij0)	Part (ijk)	Design alternatives at part level: First alternative (Alt_1)			Second alternative (Alt_2)		
		η_{ijk}	β_{ijk}	Cost	η_{ijk}	β_{ijk}	Cost
(110)	111	3368	3	4000	4500	2.8	5590
	112	3458	2	5000	4000	1.7	6230
(120)	121	7738	2	6500	8500	1.6	7590
	122	6840	3.5	5500	7500	3	6500
(130)	131	2000	2.83	3500	2600	2.5	2850
	132	2670	3.1	4500	3500	2.8	3650
(140)	141	4860	2.5	5550	5600	2.2	6000
	142	3880	3	2000	4400	2.8	5500
(150)	151	5500	2	1500	6200	1.8	6500
	152	6500	2	1500	7000	1.5	7500

Table 3.16: Reliability and cost parameters for different alternatives of second assembly

First design alternative (i.e. A_2=1)

Modules (ij0)	Part (ijk)	Alternatives at part level: First alternative (Alt_1)			Second alternative (Alt_2)		
		η_{ijk}	β_{ijk}	Cost	η_{ijk}	β_{ijk}	Cost
(210)	211	3000	3	5000	3800	2.6	6000
	212	3500	3.2	5650	4500	3	6500
	213	4500	3	7500	5000	2.8	8640
(220)	221	2500	2.2	4550	3500	1.5	5500
	222	2200	2.1	2500	2900	2	3500
	223	3600	3	2500	4200	2.4	3200

Second design alternative (i.e. A_2=2)

Modules (ij0)	Part (ijk)	Alternatives at part level: First alternative (Alt_1)			Second alternative (Alt_2)		
		η_{ijk}	β_{ijk}	Cost	η_{ijk}	β_{ijk}	Cost
(210)	211	3500	3	5000	4000	2.2	5500
	212	4200	3.2	5650	4800	2.5	6500
(220)	221	2800	2.3	6500	3500	2	7000
	222	2600	2	4200	3900	2	5000
(230)	231	3700	3	2500	4500	2.8	5400
	232	3400	1.8	2500	4000	1.5	4800

Third design alternative (i.e. A_2=3)

Modules (ij0)	Part (ijk)	Alternatives at part level: First alternative (Alt_1)			Second alternative (Alt_2)		
		η_{ijk}	β_{ijk}	Cost	η_{ijk}	β_{ijk}	Cost
(210)	211	3750	2.8	5200	4200	2.2	6000
	212	4250	2.2	5340	5200	2	6200
	213	2800	1.5	2560	3500	1.5	3500
(220)	221	3000	3	6500	3400	2.2	7000
	222	3700	3.2	2500	3600	2.5	3500
	223	3400	2	2500	4000	1.8	3000
	224	2000	2	1500	2600	1.8	2800

Table 3.17: Reliability and cost parameters for different alternatives of third assembly

First design alternative (i.e. A_3=1)							
Modules (ij0)	Part (ijk)	Alternatives at part level					
		First alternative (Alt_1)			Second alternative (Alt_2)		
		η_{ijk}	β_{ijk}	Cost	η_{ijk}	β_{ijk}	Cost
(310)	311	2500	2.4	4373	3000	3	5800
	312	3850	2	4665	4800	2.3	5640
	313	3260	2.2	5000	4000	2.5	6200
(320)	321	7600	4	3000	8500	4	4500
	322	6100	2.5	3500	7000	2.8	4200
(330)	331	2000	2.83	3500	2600	2.5	2850
	332	2670	3	4500	3500	3.1	3650

Second design alternative (i.e. A_3=2)							
Modules (ij0)	Part (ijk)	Alternatives at part level					
		First alternative (Alt_1)			Second alternative (Alt_2)		
		η_{ijk}	β_{ijk}	Cost	η_{ijk}	β_{ijk}	Cost
(310)	311	2800	2.3	6500	3500	2	7000
	312	2600	2	4200	3900	2	5000
(320)	321	5000	2.2	4000	5800	2.5	4550
	322	4000	2.3	3000	4670	2.5	4750
(330)	331	2000	2.83	3500	2600	2.5	2850
	332	2670	3	4500	3500	3.1	3650
(340)	341	3700	3	2500	4500	2.8	5400
	342	3400	1.8	2500	4000	1.5	4800

For example, it can be seen from the table 3.15 that third alternative is more modular than second and a first alternative as it has more number of modules in the assembly than the second and first alternatives. Similarly, it can be seen for the other assembly in the table 3.16 and 3.17. As mentioned in table 3.15, there are three design alternatives (A1=1 to 3) for the first assembly (100). Alternative 1 i.e. A1=1 has only three modules (i.e. j=1 to 3). Further, each of these modules in alternative 1 has the different number of enclosed parts. For example, first module (i.e. j=1) has three parts (i.e. k=1 to 3); second module (i.e. j=2) has two parts (i.e. k=1 to 2); and third module has five parts (i.e. k=1 to 5). Let 10% of the costs of enclosed parts be required for assembling of modules.

Let these machines are required to operate 8760 hours per year. These users (bases) are located at dispersed location form single repair depot and single OEM level maintenance facility. Therefore, it is assumed that transportation delay between the different base i.e. user and depot are 60, 75, 85, 95 and 110 hours respectively and from depot to OEM is 96 hours. The transportation cost of indenture items such as modules and parts from the base to depot level is 40% and 20% of the cost of the item respectively. Whereas transportation cost between the depot and OEM level is considered as 20% and 10% for the modules and parts respectively. The cost of holding for modules and parts at base is estimated based on the percentage of item cost i.e. 20% at each base. In the current problem the quantity of the spare part of the modules and parts i.e. S(ijk) at base "b" is estimated considering the Poisson approximation method discussed in the previous approach, based on 95 % service level (SL). The cost of down-time is 1000 INR per hour during unavailability of the machine. Let the life of each machine is $L = 10$ years and discounting factor for money be $R = 5\%$, which remains constant throughout the life of machine.

The mean time to repair is considered with normal distribution parameter for the assemblies and its enclosed modules and parts at different echelons. In the present study, a simulation based approach using BlockSim software [94] is used for obtaining the expected number of corrective action under the following cases for the possible design configuration of the different assemblies for a given η_{ijk} and β_{ijk} during a given evaluation period.

Case-1: Numbers of failures of a part (ijk), if the individual part of the module is discard.

Case-2: Numbers of failures of a module (ij0), if the module consisting of the all enclosed part is discarded.

First cases can be seen as the repair at module level with different degree of restoration. Second is the case of discard at module level. Table 3.18 provides a sample of the number of failures simulated for *Case 1* and *Case 2* under possible configuration design for the machine-1.

Table 3.18: Estimation of number of failures for possible configuration of first assembly considering cases 1 and 2

Indenture items	Design Alternatives	Weibull Distribution		*Case-1*	*Case-2*
(ij0) and (ijk)	Alt_d	(η_{ijk})	(β_{ijk})	nof(ijk)_1	nof(ijk)_1
Possible design configuration-1					
Module (110)	-	-	-	4.6082	2.7758
(111)	Alt_2	7200	2.5	0.9674	-
(112)	Alt_1	3500	2.6	2.4102	-
(113)	Alt_2	6000	2.8	1.2306	-
Module (120)	-	-	-	3.3054	2.3564
(121)	Alt_1	5000	2.2	1.6008	-
(122)	Alt_2	4670	2.5	1.7046	-
Module (130)	-	-	-	13.6954	6.0524
(131)	Alt_2	3200	2.8	2.65	-
(132)	Alt_1	2000	2	4.58	-
(133)	Alt_1	3000	2.7	2.8694	-
(134)	Alt_1	4000	3	2.032	-
(135)	Alt_1	5000	2.5	1.564	-

Table 3.18: Continue.

Possible design configuration-2					
Module (110)	-	-	-	3.909	2.324
(111)	Alt_2	7200	2.5	0.9668	-
(112)	Alt_2	5500	2	1.4452	-
(113)	Alt_1	5000	3.1	1.497	-
Module (120)	-	-	-	3.0136	2.1278
(121)	Alt_2	5800	2.5	1.3114	-
(122)	Alt_2	4670	2.5	1.7022	-
Module (130)	-	-	-	12.8162	5.3932
(131)	Alt_1	2500	2.6	3.548	-
(132)	Alt_2	2700	2.5	3.252	-
(133)	Alt_1	3000	2.7	2.8626	-
(134)	Alt_2	4850	3	1.5918	-
(135)	Alt_1	5000	2.5	1.5618	-

3.8.2 Results and Discussion

The problem of fleet system design considering time dependent failure rate is solved for the different users. Optimization results for the base 1, 2 and 3 are summarized in the tables 3.19 to 3.21. The table 3.19 shows the optimal design decisions of different assemblies for different base. It also identifies the most modular alternatives for each of the assembly.

Table 3.19: Optimal alternatives of different assemblies for different users in fleet

Bases “b”	Assembly (100)	Assembly (200)	Assembly (200)
More Modular Alternative	Alt_3	Alt_3	Alt_2
Base-1	Alt_2	Alt_1	Alt_2
Base-2	Alt_2	Alt_1	Alt_2
Base-3	Alt_3	Alt_2	Alt_2
Base-4	Alt_2	Alt_3	Alt_1
Base-5	Alt_2	Alt_1	Alt_1

The optimal design decision for the enclosed parts of different assemblies for the base-1, 2, and 3 are describes in the table 3.20-a, 3.20-b, and 3.20-c respectively. For example, at base 1, module 1 is configured by obtaining the following optimal design alternatives of enclosed parts; for parts (111) and (112), the second design alternative is optimal, whereas for part (113) first design alternative is optimal. Similarly the design decisions for other assembly and modules can be read from table 3.20-a. Table 3.20-a also shows the optimal acquisition cost of the different assemblies and LCC achieved in different approaches for the base-1. Similarly, the design decisions and optimal LCC for the base-2 and base-3 can be seen form the table 3.20-b, and 3.20-c. Table 3.21-a, 3.21-b, and 3.21-c provides optimal

LOR decisions for enclosed indenture items of obtained optimal designed assembly for base 1, 2, 3 respectively.

Table 3.20-a: Optimal design alternatives for different assemblies of a machine for base-1

First Assembly(i.e. i=1)		Second Assembly (i.e. i=2)		Third Assembly(i.e. i=3)	
(ijk)	Optimal Design Alternative	(ijk)	Optimal Design Alternative	(ijk)	Optimal Design Alternative
(111)	Alt_2	(211)	Alt_2	(311)	Alt_2
(112)	Alt_2	(212)	Alt_2	(312)	Alt_2
(113)	Alt_1	(213)	Alt_2	(321)	Alt_2
(121)	Alt_2	(221)	Alt_2	(322)	Alt_2
(122)	Alt_2	(222)	Alt_2	(331)	Alt_2
(131)	Alt_2	(223)	Alt_2	(332)	Alt_2
(132)	Alt_2	-	-	(341)	Alt_2
(133)	Alt_2	-	-	(342)	Alt_2
(141)	Alt_2	-	-	-	-
(142)	Alt_2	-	-	-	-
Optimal alternative of different assemblies based on i_A	$A_1 = 2$		$A_2 = 1$		$A_3 = 2$
Optimal acquisition cost of different assemblies (in INR)	78214.4		40341.4		45980
$PV_{fm} \times 10^6$ with integrated approach (in INR)	281.87				
Most reliable acquisition cost for different assemblies (in INR)	79666		41382		45980
$PV_{fm} \times 10^6$ with most reliable designed assemblies (in INR)	320.70				

Table 3.20-b: Optimal design alternatives for different assemblies of a machine for base-2

First Assembly(i.e. i=1)		Second Assembly (i.e. i=2)		Third Assembly(i.e. i=3)	
(ijk)	Optimal Design Alternative	(ijk)	Optimal Design Alternative	(ijk)	Optimal Design Alternative
(111)	Alt_2	(211)	Alt_2	(311)	Alt_2
(112)	Alt_2	(212)	Alt_2	(312)	Alt_2
(113)	Alt_1	(213)	Alt_2	(321)	Alt_2
(121)	Alt_2	(221)	Alt_2	(322)	Alt_2
(122)	Alt_2	(222)	Alt_2	(331)	Alt_2
(131)	Alt_2	(223)	Alt_2	(332)	Alt_2
(132)	Alt_2	-	-	(341)	Alt_2
(133)	Alt_2	-	-	(342)	Alt_2
(141)	Alt_2	-	-	-	-
(142)	Alt_2	-	-	-	-
Optimal alternative of different assemblies based on i_A	$A_1 = 2$		$A_2 = 1$		$A_3 = 2$
Optimal acquisition cost of different assemblies (in INR)	78214.4		40341.4		45980
$PV_{fm} \times 10^6$ with integrated approach (in INR)	350.01				
Most reliable acquisition cost for different assemblies (in INR)	79666		41382		45980
$PV_{fm} \times 10^6$ with most reliable designed assemblies (in INR)	546.59				

Table 3.20-c: Optimal LOR decisions for different assemblies of a machine for base- 3

First Assembly(i.e. i=1)		Second Assembly (i.e. i=2)		Third Assembly(i.e. i=3)	
(ijk)	Optimal Design Alternative	(ijk)	Optimal Design Alternative	(ijk)	Optimal Design Alternative
(111)	Alt_2	(211)	Alt_2	(311)	Alt_2
(112)	Alt_2	(212)	Alt_2	(312)	Alt_2
(121)	Alt_2	(221)	Alt_2	(321)	Alt_2
(122)	Alt_2	(222)	Alt_2	(322)	Alt_2
(131)	Alt_2	(231)	Alt_2	(331)	Alt_2
(132)	Alt_2	(232)	Alt_2	(332)	Alt_2
(141)	Alt_2	-	-	(341)	Alt_2
(142)	Alt_2	-	-	(3420	Alt_2
(151)	Alt_1	-	-	-	-
(152)	Alt_1	-	-	-	-
Optimal alternative of different assemblies based on i_A	$A_1 = 3$		$A_2 = 2$		$A_3 = 2$
Optimal acquisition cost of different assemblies (in INR)	56761.1		41382		45980
$PV_{fm} \times 10^6$ with integrated approach (in INR)	86.90				
Most reliable acquisition cost for different assemblies (in INR)	79666		41382		45980
$PV_{fm} \times 10^6$ with most reliable designed assemblies (in INR)	114.60				

According to optimal LOR decisions for base-1 from table 3.21-a, whenever assembly (100) fails and if its module (110) found failed, then module (110) will be repaired at base (i.e. r = 1, e = 1) by discarding the enclosed parts (111) and (112) at depot (i.e. r = 3, e = 2) and discarding the enclosed part (113) at depot (i.e. r = 3, e = 3) as highlighted in table 3.21-a. Accordingly, the optimal decision for the other assemblies can be read from the table 3.21-a. It also shows the recommended spares of the parts and modules (i.e. discarded at base level) of the different assemblies with 95 % service level.

3.8.2.1 Comments

(a) It can be seen form figure 3.7 that the LCC obtained with integrated approach is always lesser than that with dis-integrated approach. In order to see the value of integrated approach over the conventional approach, where, first the design is selected and then the LOR decisions are decided, a comparison of LCC for integrated approach over conventional approach by selection of most reliable design for different users is provided in figure 3.7. Thus it can be concluded that the most reliable design alternative of the enclosed assemblies of the machine may not always result into good LCC performance. In other words, lower reliability configuration with appropriate LOR decisions may give better life cycle performance for the fleet as indicated in the table 3.19. As a result, the integration of reliability design and LOR decisions is essential at early design stage for the fleet system. The same result is obtained in the previous approach with constant failure rate of the components.

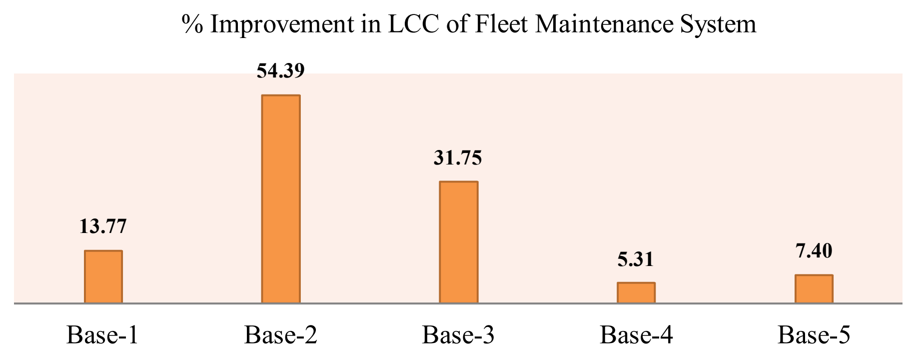

Figure 3.7: % Change in LCC considering the most reliable assemblies for the different users

(b) It can be seen from table 3.20-a, 3.20-b, 3.20-c and 3.21-a, 3.21-b, and 3.21-c that the design decisions are same for base 1 and 2 but corresponding LOR decisions are different at these two bases. Thus, the same designed machine may require different LOR at different user/base with different cost parameters such as cost of downtime, transportation cost and spare holding and stock out cost, etc.

(c) Form table 3.19, it can be seen that optimal design at base 3 is most modular. The modular design gives more flexibility in repair and fault diagnosis as LCC obtained is less for the base-3. Thus the integrated approach helps the designer to see the effect of modularity in the fleet system design and its LOR decisions.

(d) *Effect of Slope of Reliability vs. Cost Curve:* A same analysis of reliability vs. cost is conducted for this approach. The details of the analysis are provided in the section 3.7.3. Figure 3.8 provides the trend lines for the different cases of part (111) of the first alternative of assembly-1. The results are summarized in the figure 3.9. The figure 3.9 describes the comparative results of percentage improvement in LCC of fleet maintenance considering the different cases of design cost. It can be seen from fig. 3.9 that even with 50% lower or higher slope the integrated approach by considering the time dependent model gives the better results than the most reliable approach. This further strengthens the findings reported in subsection 3.7.3.

Table 3.21-a: Optimal LOR decisions for different assemblies of the base-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard	
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	$Q(ijk)$
First Assembly (100)									
(110)	1	0	0	0	0	0	0	0	0
(111)	0	1	0	0	0	1	0	0	0
(112)	0	1	0	0	0	1	0	0	0
(113)	0	1	0	0	1	0	0	1	0
(120)	0	1	0	0	0	1	0	0	0
(121)	0	1	0	0	0	1	0	0	0
(122)	0	1	0	0	0	1	0	0	0
(130)	1	0	0	0	0	0	0	0	0
(131)	0	0	1	0	0	0	0	0	3
(132)	0	1	0	0	0	1	0	0	0
(133)	0	1	0	0	0	1	0	0	0
(140)	0	0	1	0	0	0	0	0	3
(141)	0	0	1	0	0	0	0	0	0
(142)	0	0	1	0	0	0	0	0	0
Second Assembly (200)									
(210)	1	0	0	0	0	0	0	0	0
(212)	0	1	0	0	0	1	0	0	0
(213)	0	0	1	0	0	0	0	0	4
(214)	0	1	0	0	0	1	0	0	0
(220)	1	0	0	0	0	0	0	0	0
(221)	0	1	0	0	0	0	0	0	0
(222)	0	0	1	0	0	0	0	0	6
(223)	0	0	1	0	0	0	0	0	5
Third Assembly (300)									
(310)	0	1	0	1	0	0	0	0	0
(311)	0	1	0	0	0	1	0	0	0
(312)	0	1	0	0	0	1	0	0	0
(320)	1	0	0	0	0	0	0	0	0
(321)	0	0	1	0	0	0	0	0	3
(322)	0	1	0	0	0	1	0	0	0
(330)	0	1	0	0	1	0	0	1	0
(331)	0	1	0	0	1	0	0	1	0
(332)	0	1	0	0	1	0	0	1	0
(340)	1	0	0	0	0	0	0	0	0
(341)	0	0	1	0	0	0	0	0	4
(342)	0	1	0	0	1	0	0	1	0

Table 3.21-b : Optimal LOR decisions for different assemblies of the base-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard	
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	$Q(ijk)$
First Assembly (100)									
(110)	1	0	0	0	0	0	0	0	0
(111)	0	0	1	0	0	0	0	0	5
(112)	0	0	1	0	0	0	0	0	4
(113)	0	1	0	0	0	1	0	0	0
(120)	0	1	0	0	1	0	0	1	0
(121)	0	1	0	0	1	0	0	1	0
(122)	0	1	0	0	1	0	0	1	0
(130)	1	0	0	0	0	0	0	0	0
(131)	0	0	1	0	0	0	0	0	3
(132)	0	0	1	0	0	0	0	0	5
(133)	0	1	0	0	0	1	0	0	0
(140)	1	0	0	0	0	0	0	0	0
(141)	0	0	1	0	0	0	0	0	2
(142)	0	1	0	0	1	0	0	1	0
Second Assembly (200)									
(210)	1	0	0	0	0	0	0	0	0
(212)	0	0	1	0	0	0	0	0	5
(213)	0	0	1	0	0	0	0	0	4
(214)	0	1	0	0	0	1	0	0	0
(220)	1	0	0	0	0	0	0	0	0
(221)	0	1	0	0	0	0	0	0	0
(222)	0	1	0	0	0	1	0	0	0
(223)	0	0	1	0	0	0	0	0	5
Third Assembly (300)									
(310)	1	0	0	0	0	0	0	0	0
(311)	0	1	0	0	0	1	0	0	0
(312)	0	0	1	0	0	0	0	0	5
(320)	1	0	0	0	0	0	0	0	0
(321)	0	0	1	0	0	0	0	0	4
(322)	0	0	1	0	0	0	0	0	4
(330)	0	0	1	0	0	0	0	0	7
(331)	0	0	1	0	0	0	0	0	0
(332)	0	0	1	0	0	0	0	0	0
(340)	1	0	0	0	0	0	0	0	0
(341)	0	0	1	0	0	0	0	0	4
(342)	0	0	1	0	0	0	0	0	5

Table 3.21-c: Optimal LOR decisions for different assemblies of the base-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard	
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	$Q(ijk)$
First Assembly (100)									
(110)	1	0	0	0	0	0	0	0	0
(111)	0	0	1	0	0	0	0	0	4
(112)	0	1	0	0	0	1	0	0	0
(120)	1	0	0	0	0	0	0	0	0
(121)	0	0	1	0	0	0	0	0	2
(122)	0	1	0	0	0	1	0	0	0
(130)	1	0	0	0	0	0	0	0	0
(131)	0	0	1	0	0	0	0	0	5
(132)	0	1	0	0	1	0	0	1	0
(140)	0	0	1	0	0	0	0	0	4
(141)	0	0	1	0	0	0	0	0	0
(142)	0	0	1	0	0	0	0	0	0
(150)	0	0	1	0	0	0	0	0	5
(151)	0	0	1	0	0	0	0	0	0
(152)	0	0	1	0	0	0	0	0	0
Second Assembly (200)									
(210)	1	0	0	0	0	0	0	0	0
(211)	0	0	1	0	0	0	0	0	5
(212)	0	0	1	0	0	0	0	0	4
(220)	1	0	0	0	0	0	0	0	0
(221)	0	0	1	0	0	0	0	0	5
(222)	0	1	0	0	0	0	0	0	0
(230)	0	0	1	0	0	0	0	0	5
(231)	0	0	1	0	0	0	0	0	0
(232)	0	0	1	0	0	0	0	0	
Third Assembly (300)									
(310)	1	0	0	0	0	0	0	0	0
(311)	0	0	1	0	0	0	0	0	5
(312)	0	0	1	0	0	0	0	0	5
(320)	0	1	0	1	0	0	0	0	0
(321)	0	1	0	0	1	0	0	1	0
(322)	0	1	0	0	0	1	0	0	0
(330)	0	0	1	0	0	0	0	0	5
(331)	0	0	1	0	0	0	0	0	0
(332)	0	0	1	0	0	0	0	0	0
(340)	0	1	0	0	0	1	0	0	0
(341)	0	1	0	0	0	1	0	0	0
(342)	0	1	0	0	0	1	0	0	0

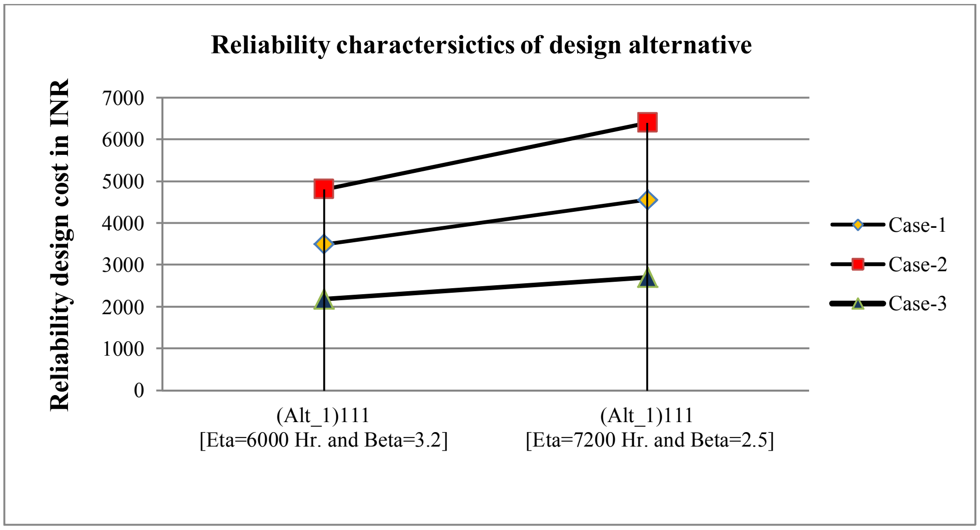

Figure 3.8: Trend lines for different cases of part (111) of the assembly (100) as shown in table 3.8

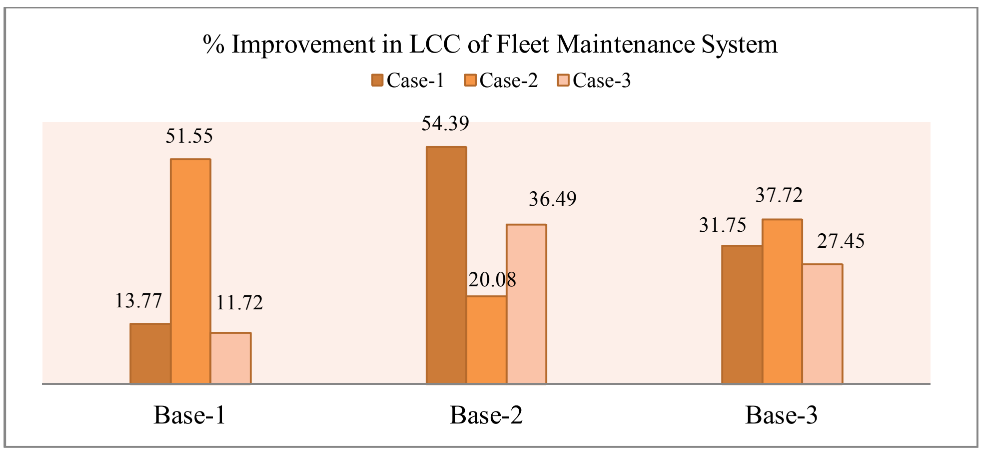

Figure 3.9: % improvement in LCC considering integrated approach for different cases

3.9 Summary

An integrated approach for optimal reliability design and LOR analysis is develop in this chapter. It aims to select an optimal reliability design configuration of the multi-indenture equipment and LOR decisions that minimizing the LCC of the fleet maintenance system. The reliability design configuration is optimized in terms of selection of different design alternatives at assembly, module and part level. Detailed models to estimates the effect of users cost structure on LCC is also presented. The problem and solution methodology are illustrated with the help of numerical example. The results show that the integrated approach gives better LCC performance of fleet maintenance system. It also demonstrates that design and LOR decisions depend on users cost structure. Therefore, the proposed approach helps in providing a user specific and integrated design and LOR decisions solution for fleet maintenance system. The approach is extended to consider the time dependent failure rate of the components in the integrated decisions modeling.

Some thumb rules have also been suggested in this methodology to ease the decision making processes in the absences of sufficient data and time. Though the results are not applied on any real life case, the parameters and problem variables used in this approach are quite generic and representative of any fleet maintenance system. Thus the proposed approaches may be adopted by any fleet user or OEM in optimizing the life cycle cost performance.

Chapter 4*

An Integrated Approach for Optimal Level of Repair and Spare Parts Decisions

4.1 Introduction

The integrated decision provides a better life cycle performance in a fleet maintenance system. This is clearly indicated by the results obtained in the previous chapter. As discussed in the chapter 1, for the effective maintenance planning, the availability of the spare parts plays an important role in making effective LOR decisions. The LOR and spare parts decisions have interdependency but often planned separately in fleet maintenance system. Therefore, the LOR decisions and spare parts stocking decisions are the important decisions and should be decided jointly during the fleet maintenance planning. The spare parts optimization aim at obtaining the optimal number of repair spare inventories of different indentures at different echelons. The joint approaches for LOR and spare part decisions are not adequately explored in the literature. Moreover, some of the works reported in the existing literature considered the assumption of a constant failure rate of the components. This may not be practical while optimizing the spare parts decisions for the components having an increasing failure rates. Thus, the prime objective of this chapter is to develop a joint optimization of the level of repair and spares parts stocking decisions considering the time-dependent failure rate of the components. Following points are considered in this approach:

- Spares of assembly, module and parts are optimized individually at multi-echelon maintenance network i.e. base, depot and OEM.
- Space constraints are considered at various echelons to optimize the spare decisions.

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– The discard decisions will be taken at assembly level or module level or part level on the failure of a machine.

4.2 Problem Description

Let us consider a fleet of "m" identical machines. Each machine is a multi-indenture system as it is made up of assemblies, modules and parts. Let $P_{(ijk)}$ represents the k^{th} part of j^{th} module of i^{th} assembly and $m_{(ij)}$ represents the j^{th} module of i^{th} assembly.
where, $i = 1$ to a; $j = 1$ to b_i; $k = 1$ to c_j
"a" represents the number of assemblies in a machine and b_i denotes the number of modules in i^{th} assembly and c_j denotes the number of parts in j^{th}module. Where b_i and c_j are subjected to system configuration constraints. For example, if a machine is having three assemblies then $a = 3$ (i.e.,$i = 1$ to 3) and assembly 1 is having only two modules, out of which module 1 is having two parts and module 2 has three parts then following system configuration constraints will be applicable:

If $i = 1$, then $b_1 = 2$ (i.e., $j = 1$ to 2) and

for $i = 1$ and $j = 1$ then $c_1 = 2$ (i.e., $k = 1$ to 2) and

for $i = 1$ and $j = 2$ then $c_2 = 3$ (i.e., $k = 1$ to 3)

Let us consider that at every indenture level items are arranged reliability wise in series. Failures of machine occur because of failures at lowest level indenture item i.e. parts failures. It is assumed that the failures of parts are independent. The time to failures of each part follows time dependent failure rate distributions. In the present research, two parameters Weibull distribution is considered. Let η_{ijk} and β_{ijk} be the characteristics life and shape parameter respectively of time to failures distribution of part P_{ijk}.

Whenever a machine fails, the same is restored (maintained) by discarding either assembly or module or part. The discard of any indenture item brings 100 % (as good as new) restoration at that particular indenture level, while it brings lesser restoration at higher indenture levels. For example, discard of a part brings 100 % restoration at that part level and lesser restoration at module level and least restoration at assembly level. Thus, the discard at any indenture level can also be seen as repair at higher indenture levels with reduced degree of restoration. In fleet maintenance system, these maintenance or restoration actions can be made at various repair locations called echelons i.e. base, depot, and OEM (contractor). Thus, fleet maintenance system is a multi-indenture and multi-echelon system. Figure 4.1 shows the pictorial view of a fleet maintenance system.

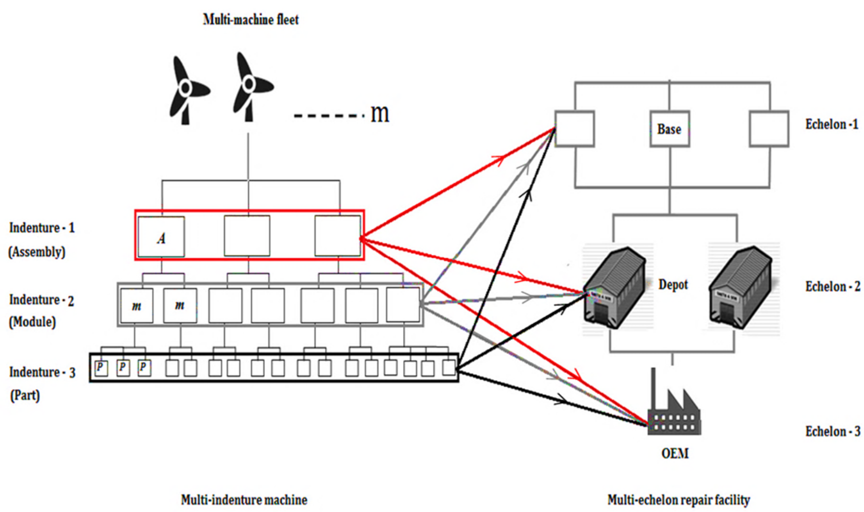

Figure 4.1: Fleet maintenance system

Therefore in this approach, the following two decisions are optimized jointly.

1. Level of repair decisions,
2. Spare parts decisions.

The level of repair decisions aim at identifying optimal level of echelon for maintenance (i.e. base, depot or OEM), optimal level of indenture at which maintenance is performed (i.e. assembly, module or part) and optimal type of maintenance action (i.e. repair, replacement or discard). As mentioned earlier, repair of assembly would mean discard at module or parts level. Similarly, repair of module mean discard at part level. Therefore, in the present research, all the decisions are considered in terms of discard only. The discarded indenture item is replaced by the similar new item from the spare inventory at that echelon where the decision is made. Available infrastructure facilities at each echelon may impose some constraints to possible maintenance decisions. Table 4.1 provides such maintenance decision constraints used in the present research.

Table 4.1: Maintenance decision constraints

Indenture items	Echelon1 (base)	Echelon 2 (Depot)	Echelon 3 (OEM)
Assembly	√	√	x
Module	x	√	√
Part	x	√	√

Table 4.1 suggests that at echelon 1, only possible maintenance decision is the discard of assembly. If assemblies discard decision is not made at echelon 1 then the assembly is transported to echelon 2 for further decision making. At echelon 2 all the three maintenance decisions, i.e., discard of assembly, module or part is possible. Once any decision is made at echelon 2, the new (after discard of assembly decision) or repaired (after discard of the module or part) assembly is transported back to echelon 1 where it is fitted into the machine. If the final decision is not made at echelon 2 then the failed module is removed and transported to echelon 3 for further decision making. Possible decisions at echelon 3 are the discard of module or discard of failed part. Once any decision is made at echelon 3, the new (after discard of module decision) or repaired (after discard of the part) module is transported to echelon 2 where it is fitted into the assembly and then the repaired assembly is transported back to echelon 1 and fitted into the machine.

Spare parts optimization aims at obtaining optimal number of repair spares for assemblies, modules and parts to be stored at various echelons. Traditionally, LOR decisions and spare parts decisions are optimized sequentially, i.e. first level of repair decision is made which is followed by decision of spare parts. However, as discussed earlier, number of repair spares for any indenture required at any echelon depends on the level of repair decisions. It is therefore hypothesized in this research that joint optimization of LOR and number of spare parts may be economical for the fleet maintenance system.

4.3 Problem Formulation

The problem is formulated by minimize the life cycle cost of fleet maintenance, which is expressed as the Present Value(PV_{fm}) of one time investment (non-recurrent cost) for installing fleet maintenance facility and recurrent cost for fleet maintenance activities. Table 4.2 presents the details of various costs in fleet level maintenance planning.

Table 4.2: Elements of life cycle costs in fleet maintenance system

Non-Recurrent cost	Recurrent cost
– Maintenance equipment cost – Maintenance infrastructure cost – Technical documentation cost – Training cost for service crew – Spare holding facility cost	– Failure cost • Cost of consumables • Downtime cost • Transportation cost • Stock-out cost – Spare parts holding cost

These costs depend on a set of decision variables represented by $\{\boldsymbol{I}, \boldsymbol{E}, \boldsymbol{S}\}$. $\{\boldsymbol{I}\}$ represents matrix of decisions denoting the level of indenture (i.e. assembly, module, part) at which the maintenance decisions are performed on failure of machine parts. It can take any value from 1 to 3 with 1 representing discard of assembly, 2 representing discard of corresponding module, and 3 representing the discard of failed part. $\{\boldsymbol{E}\}$ also represents a matrix of decision indicating the level of echelons at which replacement is performed (i.e. base or depot or OEM level) on the failure of machine parts. It can also take any value from 1 to 3 with 1 representing discard at base level, 2 representing discard at depot level and 3 representing discard at OEM level. Thus, the maintenance action constraints represented in table 1 can be written as:

If, $I = 2\ or\ 3$ then, $E > 1$; and if$I = 1$ then $E < 3$

$\{\boldsymbol{S}\}$ denotes the number of spares for various indentures at a given echelon. Thus, $\{\boldsymbol{S}\}$ can be further considered as a matrix of three decision variables $\{\boldsymbol{S}_{(i)_e}, \boldsymbol{S}_{(ij)_e}, \boldsymbol{S}_{(ijk)_e}\}$. Where, $\boldsymbol{S}_{(i)_e}$ represents the number of i^{th} spare assembly at echelon e. $\boldsymbol{S}_{(ij)_e}$ represents the number of j^{th} spare module of i^{th} assembly at echelon e. $\boldsymbol{S}_{(ijk)_e}$ denotes the number of k^{th} spare part of j^{th} module of i^{th} assembly at echelon e. Each of these decision variables can take any integer value from $0\ to\ \infty$. Each echelon generally has the space limitations for keeping the spares for various parts, modules and assemblies. Let V_e be the total space available for keeping the spare inventory at echelon e, then the space constraints at any echelon can be written as:

$$\left\{\sum_{i=1}^{a}\left(\boldsymbol{S}_{(\boldsymbol{i})_{\boldsymbol{e}}} \times v_{(i)}\right) + \sum_{i=1}^{a}\sum_{j=1}^{b_i}\left(\boldsymbol{S}_{(\boldsymbol{ij})_{\boldsymbol{e}}} \times v_{(ij)}\right) + \sum_{i=1}^{a}\sum_{j=1}^{b_i}\sum_{k=1}^{c,}\left(\boldsymbol{S}_{(\boldsymbol{ijk})_{\boldsymbol{e}}} \times v_{(ijk)}\right)\right\} \leq V_e \tag{4.1}$$

for e=1 to 2

$v_{(i)}, v_{(ij)}, v_{(ijk)}$ are the space required for i^{th} assembly, j^{th} module ofi^{th} assembly and k^{th} part of j^{th} module of i^{th} assembly, respectively.

Thus, the problem can be expressed mathematically as

Minimize,

$$\mathbf{PV_{fm}} = f(\boldsymbol{I}, \boldsymbol{E}, \mathbf{S}) \tag{4.2}$$

Subject to,

The system configuration and LOR constraints as discussed in this section 4.2.

In the next section detailed models to calculate LCC of fleet maintenance (i.e. PV_{fm}) is presented.

4.4 Life Cycle Cost Models

The LCC is the sum of all costs incurred during its life span i.e. acquisition and operation cost. In the present work, the LCC of fleet maintenance is the discounted sum of Non Recurrent Cost (NRC) and Annual Average Recurrent Cost (AARC) over the life of the system. It is expressed in terms of Present Value (PV_{fm}) as given in equation (4.3).

$$PV_{fm} = NRC + \sum_{y=1}^{L}\left\{\frac{1}{(1-R)^y} \times (AARC)_y\right\} \tag{4.3}$$

where, L is the expected life of machine and R is the annual discount rate. Elements of recurrent and non-recurrent costs in fleet maintenance are given in table 4.2. Detailed models to calculate these costs are presented in following subsections.

4.4.1 Non-Recurrent Cost Models

Non Recurrent Cost (NRC) is the one time investment made in installing the maintenance facility. It is further divided into two parts i.e. Decision Independent Non-Recurrent Cost (DINRC) and Decision Dependent Non-Recurrent Cost (DDNRC). The Decision Independent Non-Recurrent Cost (DINRC) is sum of the total cost for acquiring and installing the general maintenance equipments and other facilities at each echelon. Some general purpose maintenance equipment and facilities will always be required at each echelon irrespective of fleet maintenance decisions; therefore this cost does not depend on the decisions. The Decision Dependent Non-Recurrent Cost (DDNRC) is the onetime maintenance facility cost, required based on given decisions of level of indenture $\{\boldsymbol{I}\}$ and echelons $\{\boldsymbol{E}\}$ against the failure of part (ijk). Thus, NRC can be written as:

$$\mathrm{NRC} = \sum_{e=1}^{3}(\mathrm{DINRC})_e + \sum_{i=1}^{a}\sum_{j=1}^{b_i}\sum_{k=1}^{c_j}\left[\mathrm{DDNRC}_{(ijk)}\right]_{\{\boldsymbol{I},\boldsymbol{E}\}} \tag{4.4}$$

where $\left[\mathrm{DDNRC}_{(ijk)}\right]_{\{\boldsymbol{I},\boldsymbol{E}\}}$ is the one time investment required based on failure of k^{th} part of j^{th} module of i^{th} assembly based on decision of $\{\boldsymbol{I},\boldsymbol{E}\}$.

4.4.2 Annual Average Recurrent Cost Models

The Annual Average Recurrent Cost(AARC)is the cost that incurs every year throughout the life of the system. It mainly includes annual failure cost and annual spare holding cost. The following subsections presented the detailed models to calculate the failure and spare holding costs.

4.4.2.1 Annual Average Failure Cost Models

The Annual Average Failure Cost (AAFC) is the cost that incurs whenever a machines fails. it includes following costs.

(a) Consumables Cost,

(b) *Downtime Cost,*

(c) *Transportation cost,*

(d) *Stock-out cost.*

These costs depend on the decisions $\{\boldsymbol{I}, \boldsymbol{E}, \boldsymbol{S}\}$ and are calculated as follows:

(a) Annual Average Consumables Cost$(AACC)$

This cost includes the cost of new indenture and other consumables such as oil, grease etc. The equation (4.5) describes the annual average cost of consumables in fleet maintenance.

$$\mathrm{AACC} = \sum_{i=1}^{a} \sum_{j=1}^{b_i} \sum_{k=1}^{c_j} \left\{ \left[\mathrm{C}_{(ijk)}\right]_{\{\boldsymbol{I}\}} \times \left[\mathrm{NF}_{y\,(ijk)}\right]_{\{\boldsymbol{I}\}} \times \mathrm{m} \right\} \tag{4.5}$$

where $\left[C_{(ijk)}\right]_{\{\boldsymbol{I}\}}$ is the cost of consumables against the failures of each part (ijk) based on indenture decisions $\{\boldsymbol{I}\}$ and $\left[\mathrm{NF}_{y\,(ijk)}\right]_{\{\boldsymbol{I}\}}$ is the number of failure of part (ijk) based on decisions $\{\boldsymbol{I}\}$ in y^{th}year. Whereas "m" represents the total number of machine in a fleet. In the present work, $\left[\mathrm{C}_{(ijk)}\right]_{\{\boldsymbol{I}\}}$ is mainly considered to be the cost of new indenture and other consumable cost are considered negligible.

(b) Annual Average Downtime cost $(AADTC)$

The downtime cost is the cost of unavailability of the system during the corrective action on failure of part(ijk). The total downtime is the summation of downtime for repair action and transportation time. The equation (4.6) describes the annual average down time cost against the failure of each part(ijk)in y^{th} year.

$$\mathrm{AADTC} = \sum_{i=1}^{a} \sum_{j=1}^{b_i} \sum_{k=1}^{c_j} \left\{ \left(\left[\mathrm{TTR}_{(ijk)}\right]_{\{\boldsymbol{I}\}} + \left[\mathrm{TTT}_{(ijk)}\right]_{\{\boldsymbol{E}\}} \right) \times \left[\mathrm{NF}_{y\,(ijk)}\right]_{\{\boldsymbol{I}\}} \times \mathrm{m} \times \mathrm{C}_{dt} \right\} \tag{4.6}$$

where, $\left[\mathrm{TTR}_{(ijk)}\right]_{\{\boldsymbol{I}\}}$ denotes to time to repair against the failure of each part (ijk) based on indenture decisions$\{\boldsymbol{I}\}$. Basically time to repair includes the time for removing the failed assembly form the system and reinstalling new or repaired assembly in the system. If assembly is repaired than time to repair also includes the time required for replacing lower level indenture items. Generally, the time required to replace the end indenture (i.e. part) are more than that for the replacement of the first indenture (i.e. assembly). $\left[\mathrm{TTT}_{(\mathrm{ijk})}\right]_{\{\boldsymbol{E}\}}$ represents the total transport time against the failure of each part (ijk) based on decisions $\{\boldsymbol{E}\}$**.** It includes the time required to transport any indenture from base level to any of the higher echelons and send it back to the base level for fitting into the machine. C_{dt} denotes the down time cost per hour.

(c) Annual Average Transportation Cost$(AATC)$

Annual average transportation cost is the annual cost that incurs in transporting a selected indenture from base level to depot or OEM level and sends it back to the base level. Base level is considered as operating site, therefore if the repair decision is made at base level than transportation cost will be zero. The equation (4.7) describes the annual average transportation cost against the failure of each part(ijk).

$$\mathrm{AATC} = \sum_{\mathrm{i}=1}^{\mathrm{a}} \sum_{\mathrm{j}=1}^{\mathrm{b_i}} \sum_{\mathrm{k}=1}^{\mathrm{c_j}} \left\{\left[\mathrm{TC}_{(\mathrm{ijk})}\right]_{\{\boldsymbol{E}\}} \times \left[\mathrm{NF}_{\mathrm{y}\ (\mathrm{ijk})}\right]_{\{\boldsymbol{I}\}} \times \mathrm{m}\right\} \tag{4.7}$$

$\left[\mathrm{TC}_{(\mathrm{ijk})}\right]_{\{\boldsymbol{E}\}}$ represents the total cost of transportation based on decision $\{\boldsymbol{E}\}$ against the failure of part(ijk). Generally it is calculated as some percentage of the cost of the indenture.

(d) Annual Average Stock-out Cost$(AASOC)$

The stock-out cost is the down time cost due to the unavailability of spare parts of a given indenture at given echelons. Whenever the available number of spares for any indenture at any echelon is less than the required number of spare indenture, same is procured from OEM. Thus, the cost of stock-out includes the downtime cost due to the delay in getting the spare inventory from the OEM and transportation cost of transporting the spare inventory from OEM to the required echelon. It is assumed that OEM has infinite number of spare inventory thus the stock-out cost at OEM level will be zero. The annual average stock out cost can be expressed as follows.

$$\mathrm{AASOC} = \sum_{e=1}^{2}\left\{\left[\sum_{i=1}^{a}\left(\mathrm{Q}_{(i)_e} - \boldsymbol{S}_{(\boldsymbol{i})_{\boldsymbol{e}}}\right) + \sum_{i=1}^{a}\sum_{j=1}^{b_i}\left(\mathrm{Q}_{(ij)_e} - \boldsymbol{S}_{(\boldsymbol{ij})_{\boldsymbol{e}}}\right) + \sum_{i=1}^{a}\sum_{j=1}^{b_i}\sum_{k=1}^{c_j}\left(\mathrm{Q}_{(ijk)_e} - \boldsymbol{S}_{(\boldsymbol{ijk})_{\boldsymbol{e}}}\right)\right] \times \left[(\mathrm{T_{Delay}})_e \times \mathrm{C_{dt}} + (\mathrm{TC})_{(e)}\right]\right\} \tag{4.8}$$

where, $\mathrm{Q}_{(i)_e}$, $\mathrm{Q}_{(ij)_e}$ and $\mathrm{Q}_{(ijk)_e}$ respresents the annual quantity of assembly, module and parts respectively, required at echelon e. These quantities can be estimated based on the number of failures of the part (ijk) in y^{th} year $\left(\mathrm{i.e.,NF_{y\,(ijk)}}\right)$ and corresponding decision of $\{\boldsymbol{I}\}$. $\boldsymbol{S}_{(\boldsymbol{i})_{\boldsymbol{e}}}, \boldsymbol{S}_{(\boldsymbol{ij})_{\boldsymbol{e}}}$ ***and*** $\boldsymbol{S}_{(\boldsymbol{ijk})_{\boldsymbol{e}}}$ are the spares decisions for assembly, module and part at echelon e respectively. $\left(\mathrm{T_{Delay}}\right)_e$ is time delay in getting the shortage quantity of required indenture at echelon e form OEM. $(\mathrm{TC})_{(e)}$ is the cost of transporting the shortage quantity of required indenture from OEM to the required echelon e.

Thus, the Annual Average Failure Cost (AAFC) can be written as the summation of equation (4.5), (4.6), (4.7) and (4.8). Mathematically it is represented as;

$$\mathrm{AAFC} = \mathrm{AACC} + \mathrm{AADTC} + \mathrm{AATC} + \mathrm{AASOC} \tag{4.9}$$

4.4.3 Annual Average Spare Holding Cost Model

Annual Average Spare Holding Cost(ASHC) is the cost of carrying the inventory of spare parts of different indentures at different echelons. It includes annualized insurance, physical handling, inventory storage cost such as cost to rent, lease, or finance for storage facility and inventory risk cost (i.e. cost of obsolescence, damage, shrink, deterioration etc.). Carrying cost generally depends on the cost of the indenture. Costly item requires more holding cost than the less costly item. Thus the holding cost varies with assembly, module and part. Also holding cost may vary with echelons. Generally holding the inventory is costlier at base level than at depot level. Similarly holding the inventory at depot level is costlier than holding at OEM level. The annual average spare holding cost is expressed as shown in equation(4.10).

$$\mathrm{AASHC} = \sum_{e=1}^{2}\left\{\sum_{i=1}^{a}\left[\frac{\boldsymbol{S}_{(\boldsymbol{i})_{\boldsymbol{e}}}}{\mathbf{2}} \times \mathrm{h}_{(\mathrm{i})_{\mathrm{e}}}\right] + \sum_{i=1}^{a}\sum_{j=1}^{b_i}\left[\frac{\boldsymbol{S}_{(\boldsymbol{ij})_{\boldsymbol{e}}}}{2} \times \mathrm{h}_{(\mathrm{ij})_{\mathrm{e}}}\right] + \sum_{i=1}^{a}\sum_{j=1}^{b_i}\sum_{K=1}^{C_j}\left[\frac{\boldsymbol{S}_{(\boldsymbol{ijk})_{\boldsymbol{e}}}}{2} \times \mathrm{h}_{(\mathrm{ijk})_{\mathrm{e}}}\right]\right\} + \mathrm{OEM}_{\mathrm{s}} \tag{4.10}$$

where, $\mathrm{h}_{(\mathrm{i})_{\mathrm{e}}}$, $\mathrm{h}_{(\mathrm{ij})_{\mathrm{e}}}$and $\mathrm{h}_{(\mathrm{ijk})_{\mathrm{e}}}$ denotes the holding cost per assembly, module and parts respectively, at echelon e per year. $\mathrm{OEM}_{\mathrm{s}}$ is the annual fixed holding cost of spare inventory at OEM level. $\frac{\boldsymbol{S}_{(\boldsymbol{i})_{\boldsymbol{e}}}}{2}$ is the average quantity of i^{th} spare assembly at echelon e. $\frac{\boldsymbol{S}_{(\boldsymbol{ij})_{\boldsymbol{e}}}}{2}$ is the average quantity of j^{th} spare module of i^{th} assembly at echelon e and $\frac{\boldsymbol{S}_{(\boldsymbol{ijk})_{\boldsymbol{e}}}}{2}$ is the average quantity of k^{th} spare part of j^{th} module of i^{th} assembly at echelon e.

Thus, the annual average recurrent cost can be calculated as the sum of equation (4.9) and (4.10). Mathematically it is represented as;

$$\mathrm{AARC} = \mathrm{AAFC} + \mathrm{AASHC} \tag{4.11}$$

4.5 Numerical Example

In order to illustrate the application of the proposed methodology, let us consider an example of a fleet having 10 machines$(\mathrm{i.e.}\ \mathrm{m} = 10)$. Each machine has one assembly $(\mathrm{i.e.}\ \mathrm{a} = 1)$ and the assembly has three modules $(\mathrm{i.e.}\ \mathrm{b}_1 = 3)$ out of which module 1 has three parts $(\mathrm{i.e.}\ \mathrm{c}_1 = 3)$, module 2 has two parts $(\mathrm{i.e.}\ \mathrm{c}_2 = 2)$ and module 3 has four parts $(\mathrm{i.e.}\ \mathrm{c}_3 = 4)$. The time to failures of parts follow two parameter Weibull distribution with parameters values as shown in table 4.3., Table 4.4 and 4.5 provides the consumable cost and time to repair respectively, against the failures of each part (ijk) based on decision $\{\boldsymbol{I}\}$. The three echelons maintenance facility viz. base (echelon 1), depot (echelon 2) and OEM (echelon 3) is available to support the e machines. Table 4.6 and 4.7 provide the values of the decision independent and decision dependent non-recurrent costs respectively. The transportation cost and holding cost considered in this example is shown in table 4.8 and table 4.9. These costs are generally incurred based on the cost of the components as shown in table 4.8 and 4.9. If the discard decision is made at echelon 1 then no transportation cost is involved. However, if the decision is made at echelon 2 then the transportation of assembly from base to echelon 2 and back to base level will be involved as shown in table 4.8. If the decision is made at echelon 3 then additionally, the cost of transportation of module from echelon 2 to 3 and back to echelon 2 will be required. Holding cost depends on indenture as well as on echelon as shown in table 4.9. However, the holding cost for echelon 3 is considered as fixed as it has infinite capacity to hold the spare inventories.

Table 4.3: Two-parameter Weibull distribution for each part $P_{(ijk)}$

Parameter	P_{111}	P_{112}	P_{113}	P_{121}	P_{122}	P_{131}	P_{132}	P_{133}	P_{134}
β_{ijk} (Scale parameter)	3	2.6	2.5	2.2	2.3	2.6	2	2.7	3
η_{ijk} (Shape parameters, in hrs.)	6000	3500	5000	5000	4000	2500	2000	3000	4000

Table 4.4: Consumable cost $\left[C_{(ijk)}\right]_I$ (in INR)

P_{ijk}	Assembly($I = 1$)	Module($I = 2$)	Part ($I = 3$)
P_{111}	70000	15000	3500
P_{112}	70000	15000	2500
P_{113}	70000	15000	4000
P_{121}	70000	10000	4000
P_{122}	70000	10000	3000
P_{131}	70000	25000	5000
P_{132}	70000	25000	4000
P_{133}	70000	25000	6000
P_{134}	70000	25000	3000

Table 4.5: Time to repair $\left[TTR_{(ijk)}\right]_{\{I\}}$ (in hours)

P_{ijk}	Assembly($I = 1$)	Module($I = 2$)	Part ($I = 3$)
P_{111}	4	6	8
P_{112}	4	6	10
P_{113}	4	6	9
P_{121}	4	7	10
P_{122}	4	7	12
P_{131}	4	10	12
P_{132}	4	10	15
P_{133}	4	10	13
P_{134}	4	10	13

Table 4.6: Decision independent non-recurrent cost (DINRC_e)(in INR)

e_1 (Base)	e_2(Depot)	e_3(OEM)
100000	150000	200000

Table 4.7: Decision dependent non-recurrent cost$[\text{DDNRC}_{(\text{ijk})}]_{\{I,E\}}$(in INR)

P_{ijk}	Assembly $(I = 1)$			Module$(I = 2)$			Part $(I = 3)$		
	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3
P_{111}	10000	6000	-	-	4000	2000	-	2000	1000
P_{112}	10000	6000	-	-	4000	2000	-	2000	1000
P_{113}	10000	6000	-	-	4000	2000	-	2000	1000
P_{121}	10000	6000	-	-	4000	2000	-	2000	1000
P_{122}	10000	6000	-	-	4000	2000	-	2000	1000
P_{131}	10000	6000	-	-	4000	2000	-	2000	1000
P_{132}	10000	6000	-	-	4000	2000	-	2000	1000
P_{133}	10000	6000	-	-	4000	2000	-	2000	1000
P_{134}	10000	6000	-	-	4000	2000	-	2000	1000

Table 4.10 describes the total transportation time spent during the travel between the base level to different echelons and sends it back to the base level. Table 4.11 shows the stock-out delay and transportation cost for getting the spare inventory form echelon 3 to a given indenture in the case of stock-out at that indenture.

Table 4.8: Transportation cost$[\text{TC}_{(\text{ijk})}]_{\{E\}}$(in INR/item)

E_1	E_2	E_3
-	20% of Assembly cost	20% of Assembly + 10 % of module cost

Table 4.9: Holding cost (in INR/item)

Indenture level (I)	h (INR/item/year)		OEM_S (INR/year)
	E_1	E_2	E_3
Assembly level $(I = 1)$	20%	10%	30,000
Module level $(I = 2)$	-	8%	
Part level $(I = 3)$	-	3%	

Table 4.10: Total transportation time $[\text{TTT}_{(\text{ijk})}]_{\{E\}}$(in hours)

Echelons	E_1	E_2	E_3
E_1	-	48	96

Table 4.11: Stock-out delay $(\text{T}_{\text{Delay}})_e$in hours and transportation cost $(\text{TC})_{(e)}$ between different echelons

Echelons	E_1	E_2	E_3
Stock-out delay $(\text{T}_{\text{Delay}})_e$in hours between different echelons			
E_3	108	60	-
Transportation cost $(\text{TC})_{(e)}$ between different echelons			
E_3	15% of indenture cost	5% of indenture cost	-

Let the space available for keeping different indentures at echelon 1 and 2 is $100\ \mathrm{m}^3$ and $200\ \mathrm{m}^3$ respectively. The space required for keeping the individual indentures at each echelon is as follows: for assembly $\mathrm{v}_{(\mathrm{i})} = 30\ m^3$, for the each module $\mathrm{v}_{(\mathrm{ij})} = 8\ m^3$ and for each part $\mathrm{v}_{(\mathrm{ijk})} = 5\ m^3$. The down time cost ($\mathrm{C}_{\mathrm{dt}}$) be 1000 INR per hours and expected life of each machine is $\mathrm{L} = 10$ years and annual discount rate (R) is 5%.

In order to solve this numerical problem, number of failures of the each part of a machine will be required under following three cases.

Case-1 Number of failures if the entire assembly consisting of failed part is replaced,

Case-2 Number of failures if module consisting of the failed part is replaced,

Case-3 Number of failures if part is replaced.

Simulation approach is used to calculate the number of failures under these three cases. BlockSim simulation tool [94] is used for calculating the number of failures. Table 4.12 shows some of the examples of number of failures for each part considering these three cases.

Table 4.12: Expected number of failures for each part (ijk) considering the different indenture decisions $\left(\mathbf{NF}_{\mathbf{1}\ (\mathrm{ijk})}\right)_{I}$

$\mathbf{P}_{\mathbf{ijk}}$	I	$\left(\mathrm{NF}_{1\ (\mathrm{ijk})}\right)_{I}$	I	$\left(\mathrm{NF}_{1\ (\mathrm{ijk})}\right)_{I}$	I	$\left(\mathrm{NF}_{1\ (\mathrm{ijk})}\right)_{I}$	I	$\left(\mathrm{NF}_{1\ (\mathrm{ijk})}\right)_{I}$	I	$\left(\mathrm{NF}_{1\ (\mathrm{ijk})}\right)_{I}$
P_{111}	3	2.79	3	16.336	3	6.382	2	4.548	2	1.994
P_{112}	2	16.698	3	28.342	3	19.482	1	21.54	3	9.152
P_{113}	3	5.95	3	19.472	1	17.124	3	7.244	2	4.7
P_{121}	1	8.502	3	20.044	3	7.454	3	7.474	1	5.872
P_{122}	2	13.584	3	24.886	2	16.12	2	13.52	3	10.482
P_{131}	1	15.558	3	38.63	3	16.902	3	21.534	3	14.726
P_{132}	2	37.436	3	49.612	2	39.698	2	30.522	3	35.224
P_{133}	1	12.298	3	31.944	2	11.25	2	16.404	1	11.032
P_{134}	1	4.378	3	24.932	1	5.734	3	7.732	2	4.022

Now, the problem is subjected to the space constraints, system constraints and echelons specific maintenance constraints discussed in the section 4.2. The size of the solution space increases exponentially with number of: machines in fleet, assemblies in a machine, number of modules in an assembly and number of parts in a module. In the present research with only two decision variables viz. $\{\boldsymbol{I}, \boldsymbol{E}\}$ the solution space become $\mathrm{D}^{\{\text{Total number of parts}\}}$,where $\mathrm{D} = \{\text{number of } \boldsymbol{I} \text{ options} \times \text{number of } \boldsymbol{E} \text{ options}\}$. In presented numerical example, an assembly consists of total nine parts and for each part there will be $\boldsymbol{I} = 1$ to 3, and $\boldsymbol{E} = 1$ to 3 . Then the solution space becomes $(3 \times 3)^{\{9\}} = 387420489$. Solution size further multiplies with third decision variable i.e., repair spare option $\{\boldsymbol{S}\}$. The problem is solved by using RISKOptimizer software [95].

4.6 Results

An improved solution was obtained after "17642" trials as shown in figure 4.2. Table 4.13 describes the optimal decisions of level of repair for each part and optimal spare parts quantity. It also shows the corresponding minimum life cycle cost (PV_{fm}) value. Table 4.13 can be read as follows. Whenever part P_{111} fails, corresponding module (i.e.$\boldsymbol{I} = \mathbf{2}$) will be discarded at OEM level (i.e.$\boldsymbol{E} = \mathbf{3}$); whenever part P_{121} fails, the assembly (i.e.$\boldsymbol{I} = \mathbf{1}$) will be discarded at base level (i.e.$\boldsymbol{E} = \mathbf{1}$), etc. Also, optimal spare parts decisions for part P_{122} at $e = 2$ is 5 (i.e.$\boldsymbol{S_{122}} = \mathbf{5}$) and for part P_{121} and $P_{133}$the optimal number of spares of assemblies at $e = 1$ is3 (i.e.$\boldsymbol{S_1} = \mathbf{3}$). In the same way, decisions corresponding to the failure of other parts can be read from table 4.13. It was also observed that the optimal solution obtained did not change with small variation in the genetic algorithm parameter like population size, crossover probability and mutation rate. In this illustration the value of these parameters are used as follows: the population= 50, crossover probability = 0.75 and mutation rate= 0.1.The sensitivity analysis of the illustrated approach to the down time cost, transportation cost and holding cost is also performed. The analysis is performed with $\pm 10\ \%$ variation in these costs. The results of sensitivity analysis are presented in table 4.14-a and 4.14-b. However it was observed that this approach is not sensitive to down time cost, but it is sensitive to spare holding cost and transportation cost. It is recommended that spare holding cost and transportation cost should be captured as accurately as possible for a particular fleet maintenance system.

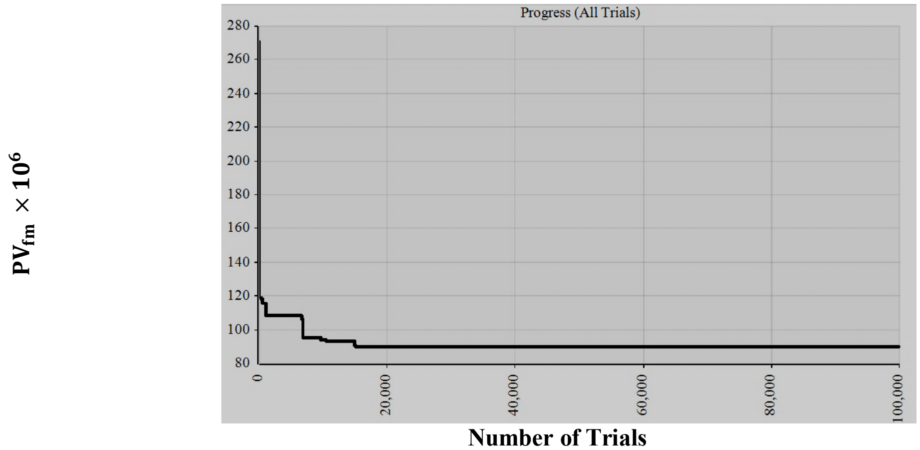

Figure 4.2: Progress of number of trails and reducing fleet maintenance life cycle cost

Table 4.13: Optimal decision of level of repair and spare parts with life cycle cost of Fleet machines

Decision Variables	Optimal Level of Repair Decisions		Annual Required Quantity	Optimal Spare Parts Decisions					
P_{ijk}	***I***	***E***	$(NF_{1\,(ijk)})_I$	$\boldsymbol{S_{ijk}}$	e_1	e_2	$\boldsymbol{S_i/S_{ij}}$	e_1	e_2
P_{111}	**2**	**3**	1.994	$\boldsymbol{S_{111}}$	0	0	S_1	**3**	0
P_{112}	**3**	**3**	9.152	$\boldsymbol{S_{112}}$	0	0	S_{11}	0	0
P_{113}	**2**	**3**	4.7	$\boldsymbol{S_{113}}$	0	0	S_{12}	0	0
P_{121}	**1**	**1**	5.872	$\boldsymbol{S_{121}}$	0	0	S_{13}	0	0
P_{122}	**3**	**2**	10.482	$\boldsymbol{S_{122}}$	0	**5**	Space (V_e) Constraints (in m^3)	**90**	**200**
P_{131}	**3**	**3**	14.726	$\boldsymbol{S_{131}}$	0	0			
P_{132}	**3**	**2**	35.224	$\boldsymbol{S_{132}}$	0	**35**			
P_{133}	**1**	**1**	11.032	$\boldsymbol{S_{133}}$	0	0	Life Cycle Cost PV_{fm} ($\times 10^6$)(in INR)		**89**
P_{134}	**2**	**3**	4.022	$\boldsymbol{S_{134}}$	0	0			

Table 4.14-a: Sensitivity analysis results for level of repair decisions

% Change in Cost	$\{I, E\}$	P_{111}	P_{112}	P_{113}	P_{121}	P_{122}	P_{131}	P_{132}	P_{133}	P_{134}	PV_{fm}	**Sensitive Yes/No**
C_{dt} (+10%)	I	2	3	2	1	3	3	3	1	2	97	**Y**
	E	3	3	3	1	**3**	3	2	1	3		
C_{dt} (Base value)	I	2	3	2	1	3	3	3	1	2	89	-
	E	3	3	3	1	2	3	2	1	3		
C_{dt} (-10%)	I	2	3	2	1	3	3	3	1	2	82	N
	E	3	3	3	1	2	3	2	1	3		
h (+10%)	I	2	**1**	**1**	1	**2**	3	**2**	1	**1**	**97**	**Y**
	E	3	**1**	**1**	1	3	2	**3**	1	**1**		
h (Base value)	I	2	3	2	1	3	3	3	1	2	89	-
	E	3	3	3	1	3	2	2	1	3		
h (-10%)	I	2	3	2	1	3	3	3	1	2	89	N
	E	3	3	3	1	3	2	2	1	3		
TC_{ijk} (+10%)	I	2	3	2	1	3	3	3	1	2	89	N
	E	3	3	3	1	3	2	2	1	3		
TC_{ijk} (Base value)	I	2	3	2	1	3	3	3	1	2	89	-
	E	3	3	3	1	3	2	2	1	3		
TC_{ijk} (-10%)	I	2	**1**	**1**	1	**2**	3	**2**	1	**1**	**96**	**Y**
	E	3	**1**	**1**	1	3	2	**3**	1	**1**		

Table 4.14-b: Sensitivity analysis results of spare part decisions

% Change in Cost	e	S_1	S_{11}	S_{111}	S_{112}	S_{113}	S_{12}	S_{121}	S_{122}	S_{13}	S_{131}	S_{132}	S_{133}	S_{134}	Sensitive Yes/No
C_{dt} (+10%)	e_1	3	-	-	-	-	-	-	-	-	-	-	-	-	**Y**
	e_2	0	0	0	0	0	0	0	**0**	0	0	**36**	0	0	
C_{dt} (Base value)	e_1	3	-	-	-	-	-	-	-	-	-	-	-	-	-
	e_2	0	0	0	0	0	0	0	5	0	0	35	0	0	
C_{dt} (-10%)	e_1	3	-	-	-	-	-	-	-	-	-	-	-	-	N
	e_2	0	0	0	0	0	0	0	5	0	0	35	0	0	
h (+10%)	e_1	3	-	-	-	-	-	-	-	-	-	-	-	-	**Y**
	e_2	0	0	0	0	0	0	0	0	0	**15**	0	0	0	
h (Base value)	e_1	3	-	-	-	-	-	-	-	-	-	-	-	-	-
	e_2	0	0	0	0	0	0	0	5	0	0	35	0	0	
h (-10%)	e_1	3	-	-	-	-	-	-	-	-	-	-	-	-	**Y**
	e_2	0	0	0	0	0	0	0	0	0	**14**	**26**	0	0	
TC_{ijk} (+10%)	e_1	3	-	-	-	-	-	-	-	-	-	-	-	-	**Y**
	e_2	0	0	0	0	0	0	0	0	0	**14**	**26**	0	0	
TC_{ijk} (Base value)	e_1	3	-	-	-	-	-	-	-	-	-	-	-	-	-
	e_2	0	0	0	0	0	0	0	5	0	0	35	0	0	
TC_{ijk} (-10%)	e_1	3	-	-	-	-	-	-	-	-	-	-	-	-	**Y**
	e_2	0	0	0	0	0	0	0	0	0	**15**	0	0	0	

4.6.1 Case Analysis

An analysis is conducted considering the different users in a fleet having different number of machines and their down time costs. Table 4.15 shows the different cases used of the analysis. Thus, the problem for joint optimization has been solved for the different users in a fleet. The obtained results are provided in the table- 4.16-a, b, c and d. Form the results, it can be seen that the integrated decision of level of repair and spare parts depends on the user's cost structure. The user's cost profile plays an important role to decide these decisions.

Table 4.15: Case analysis

Users	Number of machine at base	Down time cost INR/hr.
	m	C_{dt}
User-1	10	3000
User-2	10	6000
User-3	20	3000
User-4	20	6000

Table 4.16-a: Integrated results for user-1

Decision Variables	Optimal Level of Repair Decisions		Annual Required Quantity	Optimal Spare Parts Decisions					
P_{ijk}	$\boldsymbol{I}$	$\boldsymbol{E}$	$(NF_{1\,(ijk)})_I$	$\boldsymbol{S_{ijk}}$	e_1	e_2	$\boldsymbol{S_i/S_{ij}}$	e_1	e_2
P_{111}	**2**	**2**	1.094	$\boldsymbol{S_{111}}$	0	0	$\boldsymbol{S_1}$	**3**	**6**
P_{112}	**3**	**2**	6.384	$\boldsymbol{S_{112}}$	0	0	$\boldsymbol{S_{11}}$	0	0
P_{113}	**2**	**2**	3.116	$\boldsymbol{S_{113}}$	0	0	$\boldsymbol{S_{12}}$	0	0
P_{121}	**1**	**1**	4.578	$\boldsymbol{S_{121}}$	0	0	$\boldsymbol{S_{13}}$	0	0
P_{122}	**1**	**1**	6.28	$\boldsymbol{S_{122}}$	0	0	Space (V_e) Constraints (in m^3)	**90**	**180**
P_{131}	**1**	**1**	15.9	$\boldsymbol{S_{131}}$	0	0			
P_{132}	**1**	**2**	31.918	$\boldsymbol{S_{132}}$	0	0			
P_{133}	**1**	**1**	9.524	$\boldsymbol{S_{133}}$	0	0	Life Cycle Cost PV_{fm} ($\times 10^6$)(in INR)		**297**
P_{134}	**2**	**2**	3.38	$\boldsymbol{S_{134}}$	0	0			

Table 4.16-b: Integrated results for user-2

Decision Variables	Optimal Level of Repair Decisions		Annual Required Quantity	Optimal Spare Parts Decisions					
P_{ijk}	$\boldsymbol{I}$	$\boldsymbol{E}$	$(NF_{1\,(ijk)})_I$	$\boldsymbol{S_{ijk}}$	e_1	e_2	$\boldsymbol{S_i/S_{ij}}$	e_1	e_2
P_{111}	**3**	**2**	1.122	$\boldsymbol{S_{111}}$	0	0	$\boldsymbol{S_1}$	**3**	**6**
P_{112}	**1**	**1**	7.252	$\boldsymbol{S_{112}}$	0	0	$\boldsymbol{S_{11}}$	0	0
P_{113}	**3**	**2**	3.1	$\boldsymbol{S_{113}}$	0	**4**	$\boldsymbol{S_{12}}$	0	0
P_{121}	**1**	**2**	4.388	$\boldsymbol{S_{121}}$	0	0	$\boldsymbol{S_{13}}$	0	0
P_{122}	**1**	**1**	6.53	$\boldsymbol{S_{122}}$	0	0	Space (V_e) Constraints (in m^3)	**90**	**200**
P_{131}	**2**	**2**	14.116	$\boldsymbol{S_{131}}$	0	0			
P_{132}	**1**	**1**	33.89	$\boldsymbol{S_{132}}$	0	0			
P_{133}	**1**	**1**	10.18	$\boldsymbol{S_{133}}$	0	0	Life Cycle Cost PV_{fm} ($\times 10^6$)(in INR)		**510**
P_{134}	**3**	**2**	3.572	$\boldsymbol{S_{134}}$	0	0			

Table 4.16-c: Integrated results for user-3

Decision Variables	Optimal Level of Repair Decisions		Annual Required Quantity	Optimal Spare Parts Decisions					
P_{ijk}	$\boldsymbol{I}$	$\boldsymbol{E}$	$(NF_{1\,(ijk)})_I$	$\boldsymbol{S_{ijk}}$	e_1	e_2	$\boldsymbol{S_i/S_{ij}}$	e_1	e_2
P_{111}	**3**	**2**	1.844	$\boldsymbol{S_{111}}$	0	0	$\boldsymbol{S_1}$	**3**	0
P_{112}	**1**	**1**	12.58	$\boldsymbol{S_{112}}$	0	0	$\boldsymbol{S_{11}}$	0	0
P_{113}	**2**	**2**	5.46	$\boldsymbol{S_{113}}$	0	0	$\boldsymbol{S_{12}}$	0	0
P_{121}	**1**	**1**	7.924	$\boldsymbol{S_{121}}$	0	0	$\boldsymbol{S_{13}}$	0	0
P_{122}	**1**	**1**	11.268	$\boldsymbol{S_{122}}$	0	0	Space (V_e) Constraints (in m^3)	**90**	**0**
P_{131}	**1**	**1**	28.276	$\boldsymbol{S_{131}}$	0	0			
P_{132}	**1**	**1**	58.688	$\boldsymbol{S_{132}}$	0	0			
P_{133}	**1**	**1**	35.612	$\boldsymbol{S_{133}}$	0	0	Life Cycle Cost PV_{fm} ($\times 10^6$)(in INR)		**543**
P_{134}	**2**	**2**	5.996	$\boldsymbol{S_{134}}$	0	0			

Table 4.16-d: Integrated results for user-4

Decision Variables	Optimal Level of Repair Decisions		Annual Required Quantity	Optimal Spare Parts Decisions					
P_{ijk}	I	E	$\left(NF_{1\,(ijk)}\right)_I$	S_{ijk}	e_1	e_2	S_i/S_{ij}	e_1	e_2
P_{111}	**2**	**2**	2.188	S_{111}	0	0	S_1	**3**	0
P_{112}	**3**	**2**	12.768	S_{112}	0	0	S_{11}	0	0
P_{113}	**2**	**2**	6.232	S_{113}	0	0	S_{12}	0	0
P_{121}	**1**	**1**	9.156	S_{121}	0	0	S_{13}	0	0
P_{122}	**1**	**1**	12.56	S_{122}	0	0	Space (V_e) Constraints (in m^3)	**90**	**0**
P_{131}	**1**	**1**	31.8	S_{131}	0	0			
P_{132}	**1**	**1**	63.836	S_{132}	0	0			
P_{133}	**1**	**1**	19.048	S_{133}	0	0	Life Cycle Cost PV_{fm} ($\times 10^6$)(in INR)		**997**
P_{134}	**2**	**2**	6.76	S_{134}	0	0			

4.7 Summary

An integrated approach for level of repair and spare parts has been developed in this chapter. It simultaneously optimizes decision of location of maintenance, level of indenture for maintenance, degree of maintenance (repair/discard) and level of repair spares inventory at different echelons. Results shows that integrated decisions are depended on the user's profile such as costs and number of machine etc. Another important addition to the body of knowledge is the use of time dependent failure rate model for different part failure in a machine. This will further help in considering effect of Preventive Maintenance (PM) and restoration factor in LOR analysis. The same is discussed in the next chapter. The approach presented in this paper is robust against the small variation in model parameters. It is expected that application of proposed approach to real world problem will used to significant saving to the industries.

Chapter 5*

An Integrated Strategy for Preventive Maintenance and Level of Repair Decisions

5.1 Introduction

LOR analysis is done to optimize the repair decisions for fleet system. Most of these systems are industrial system. Industries also perform preventive maintenance to reduce failure rate of components and increase the life of such system. However, the current research on LOR analysis makes an assumption of constant failure rate, which does not allow the design to consider the effect of preventive maintenance. Moreover, as discussed in chapter 1, the preventive maintenance and LOR decisions are interdependent and optimizing LOR without considering preventive maintenance may not lead to optimal LCC performance. Hence a approach is needed that consider time dependent failure rate and joint optimization LOR and preventive maintenance. The same is addressed in this research.

5.2 Problem Description

Let us consider a fleet of m identical machines. Each machine is made up of multiple assembly, module and parts as shown in figure 5.1. If a machine fails at the base, the corrective action for the same is made based on the LOR decisions. Figure 5.2 shows the flow chart of this decision making process considered in this research work for LOR analysis. The figure 5.2 can be read as follows. On the failure of a machine the enclosed failed assembly is removed from the machine and is send to the base level maintenance facility. At base level maintenance facility, failed module is removed and decision on "repair", "replace" or "move of the module to depot" is made. Each of these will further lead to different repair

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options as indicated in figure 5.2. For example, the “repair decision of a failed module” will follow the process highlighted in bold in figure 5.2. It says that the repair decision of module leads to further decision options on discard of the part at base or move the part to depot. If part is moved to depot the part can be either discarded at depot itself or can be moved to OEM level maintenance facility for subsequent discard there. Similarly, other decision branches i.e. “module move to depot level” and “module discarded at base level” can be read from the figure 5.2.

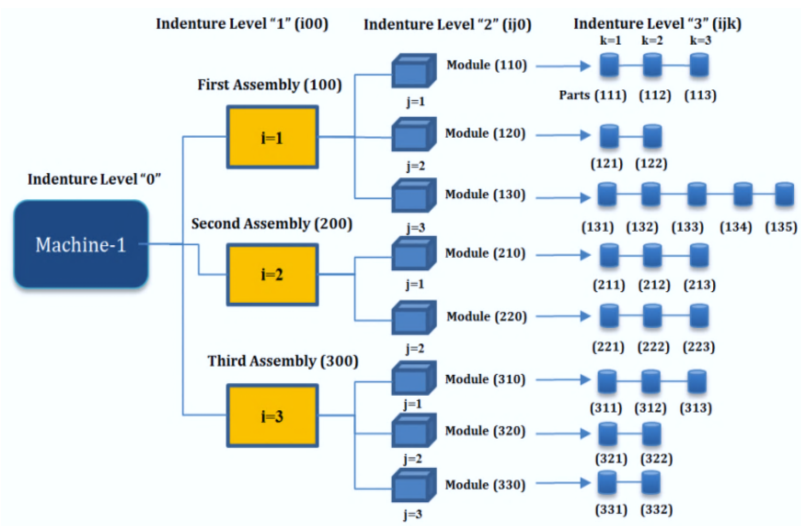

Figure 5.1: Pictorial view of multi-indenture items for a machine

Apart for this, preventive maintenance is generally done to reduce the failure rate and increase the useful life of the machine components. Each PM activity requires time and cost which could otherwise be used for production. On the other hand, ignoring PM may lead to unexpected failures resulting into excessive down time costs. Therefore, PM optimization is done to obtain the optimum interval for preventive maintenance that minimizes the life cycle cost or cost of maintenance. For modular systems like multi-indenture systems, it is often preferable to perform PM at module level.

Therefore an integrated strategy is required that minimizes the LCC of the fleet maintenance while selecting the following decisions;

- Optimal LOR decisions;
- Optimal decisions for PM schedule,
- Number of spare at base level for the modules and parts.

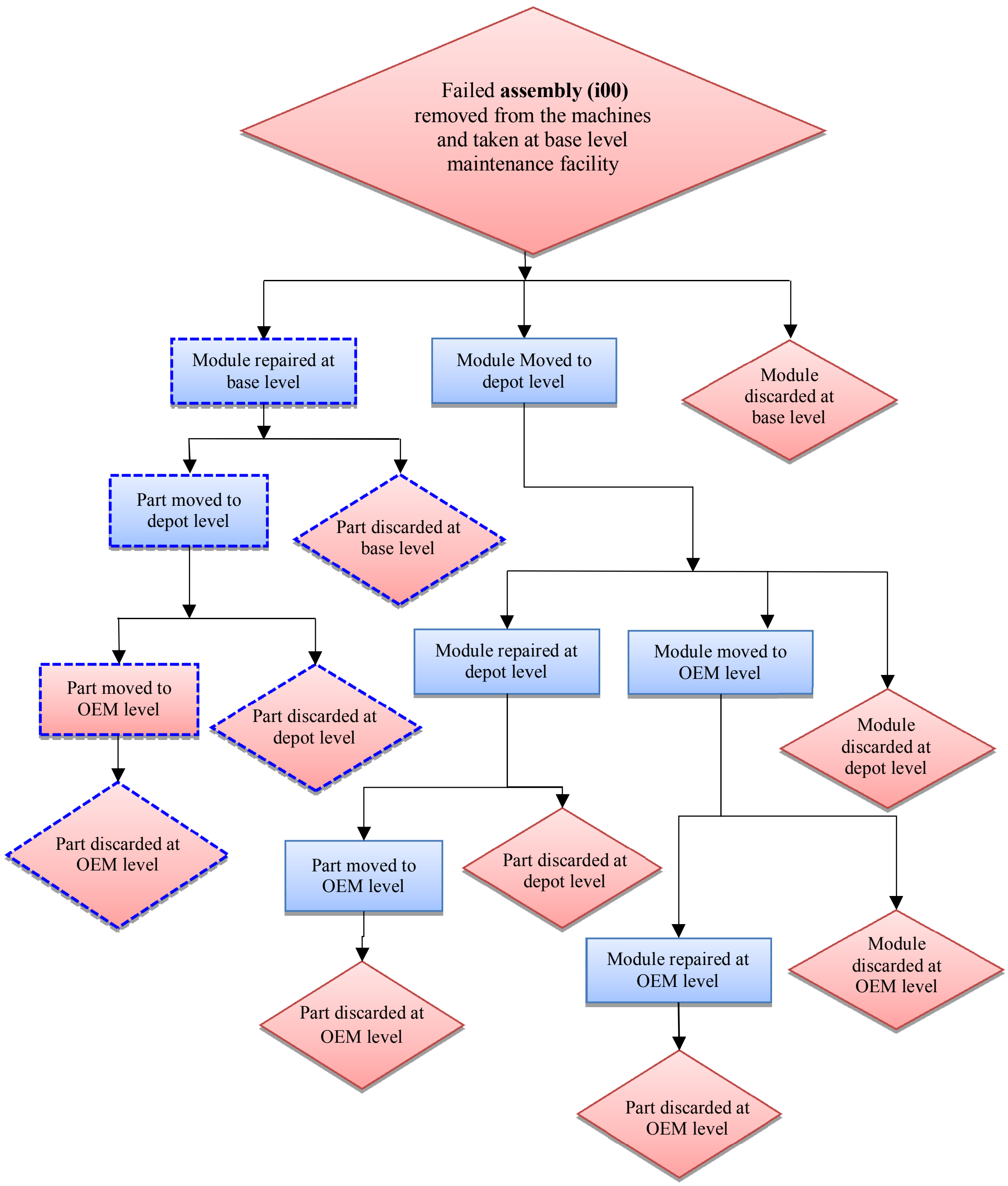

Figure 5.2: Flow chart for the decision process considered during LOR analysis

5.3 Problem Formulation

As mentioned in section 5.2, our objective is to identify the optimal decisions for PM schedule and LOR of the machine that minimizes LCC. The LCC is measured in the form of Present Value (PV). Thus the problem of integrated decisions of PM schedule and LOR discussed above can be formulated as:

Minimize

$$\text{PV} = \text{f}\left[\boldsymbol{t_{pm}(ijk)}, \boldsymbol{L_{r,e}(ijk)}, \textbf{model parameters}\right] \quad (5.1)$$

where, $\boldsymbol{t_{pm}(ijk)}$ represents matrix of decision of PM schedule for enclosed $\mathrm{k^{th}}$ part of $\mathrm{j^{th}}$ module of $\mathrm{i^{th}}$ assembly. In this research work, the fixed calendar time based PM policy is considered, where PM varies from $\boldsymbol{t_{pm}}$ = 500 hr. to 8760 hr. During each preventive action, all parts (ijk) of a module will be restored with some Restoration Factors (RF). In this research, different cases for RF such as 20%, 30%, 40%, 50%, 60%, 70% and 80% are used to evaluate the integrated strategy.

$\boldsymbol{L_{r,e}(ijk)}$ denotes to LOR decision matrix for enclosed $\mathrm{k^{th}}$ part of $\mathrm{j^{th}}$ module of $\mathrm{i^{th}}$ assembly, where"$\mathbf{r}$" denotes to the repair action decisions; $\mathrm{r} = 1$ denoting to "repair decision", $\mathrm{r} = 2$ denoting to "move decision" and $\mathrm{r} = 3$ denoting to "discard decision". These repair actions are performed at different echelons in fleet structure represented by"$\mathbf{e}$"; $\mathrm{e} = 1$ denotes to "base level" (echelon 1),$\mathrm{e} = 2$ denotes to "depot level" (echelon 2) and $\mathrm{e} = 3$ denotes to "OEM level" (echelon 3). In the optimization model these LOR decision is considered as follows;

$$\boldsymbol{L_{r,e}(ijk)} = \begin{cases} 1, & \text{repair action "r" at echelon "e" is selected for indenture item (ijk);} \\ 0, & \text{otherwise;} \end{cases}$$

Q(ijk) represents the number of spare of the modules and parts stock at base level. The quantity of the spares is estimated with predefined service level considering the Poisson approximation method. The number of spare depends on the number of corrective action for the particular modules and parts. The corrective actions are affected by different PM schedules. Additionally the selection of LOR decisions (i.e. discard and repair) also affects the corrective action as discard at module gives the higher restoration than the repair.

LOR decision constraints represent the repair actions that are not feasible at particular echelon. In multi-echelon maintenance system, base is generally the operating site of the machine and some specific advanced inspection facility and equipment may not be available at base. Therefore, some maintenance constraints are considered for some of the modules and its enclosed parts at base level in this problem. For example, Modules (120), (210), (310) and their enclosed parts cannot be discarded at base due to lack of required technical facility. Table 5.1 shows the details of the LOR constraints considered in this research work.

Table 5.1: Possible LOR decisions for different modules of a machines

<table>
<tr><th>First Indenture level</th><th>Second Indenture level</th><th>Base (e=1)</th><th>Depot (e=2)</th><th>OEM (e=3)</th></tr>
<tr><td>Assembly (100)</td><td>Module (110)
Module (120)
Module (130)</td><td>Repair, Move, Discard
Repair , Move,
Repair, Move, Discard</td><td rowspan="3">Repair, Move, Discard</td><td rowspan="3">Repair, Discard</td></tr>
<tr><td>Assembly (200)</td><td>Module (210)
Module (220)</td><td>Repair, Move,
Repair, Move, Discard</td></tr>
<tr><td>Assembly (300)</td><td>Module (310)
Module (320)
Module (330)</td><td>Repair , Move,
Repair, Move, Discard
Repair, Move, Discard</td></tr>
<tr><td>Third Indenture level</td><td>parts (ijk)</td><td>Move, Discard</td><td>Move, Discard</td><td>Discard</td></tr>
</table>

5.4 Life Cycle Cost Models

The LCC is one of the key parameters considered in evaluating the cost-effectiveness of any system (Blanchard, 1992). LCC may be classified in many different ways, depending on the type of system and purpose of the analysis. In present work, the effect of integrated decision of PM schedule and LOR on LCC of the machines in a fleet is studied. For this purpose, LCC is divided into two categories, i.e. Non-Recurrent Cost (NRC) and Annual Average Recurrent Cost (AARC). Details of the continents of the each cost are discussed earlier in the section [3.4.1 and 3.4.2] of the Chapter 3.

5.4.1 Non Recurrent Cost Models

Non recurrent cost is the one-time investment made in installing the maintenance facility. NRC is mainly classified in two costs i.e. Decisions Independent Non Recurrent Cost (DINRC) and Decisions Dependent Non Recurrent Cost (DDNRC) as discussed in the section [3.4.1] of the chapter 3. However, the DINRC is not affects the decisions of PM and LOR therefore it is excluded in this analysis. Therefore, the DDNRC can be calculated as follows;

$$\text{DDNRC} = \sum_{\text{ijk}} \sum_{r=1}^{3} \sum_{e=1}^{3} [\text{C}_{\text{mf}}]_{\text{r,e}}(\text{ijk}) \cdot [\boldsymbol{L_{r,e}(ijk)}] \qquad (5.2)$$

5.4.2 Annual Average Recurrent Cost Models

Annual average recurrent cost is the cost that incurs every year throughout the life of the machines based on decisions of "PM schedule" and "LOR". Generally the PM action is performed at operating site (i.e. base) of the machine and AACC and AADTC are the costs which incur during preventive maintenance. Whereas the AADTC, AATC, AACC, AASHC and AASOC are the costs associated with LOR analysis.

AADTC Model

In this approach, as two maintenance actions i.e. PM and LOR are performed on the machines. Therefore down time of the machines are estimated based on time consumed during each maintenance action. It mainly depends on time to repair of the particular indenture item (ijk) of the machine. As it is considered that preventive actions are perform at module level, therefore down time is estimated at module level only. Similarly, on failure of a machine, down time is incurred based on the LOR decisions. During the LOR analysis, the down time of an indenture item (ijk) is estimated based on Total Mean Time to Repair (TMTTR). Therefore, the total mean time to repair for an indenture item (ijk) is the summation of $\text{MTTR}_1(\text{i00})$ and $\text{MTTR}_2(\text{ijk})$ as shown below.

$$\text{TMTTR(ijk)} = \text{MTTR}_1(\text{i00}) + \text{MTTR}_2(\text{ijk}) \qquad (5.3)$$

The details for the calculation of $\text{MTTR}_1(\text{i00})$ and $\text{MTTR}_2(\text{ijk})$ is provided in the equation [3.23] of the Chapter 3. Therefore, the AADTC is estimated by the equation 5.4.

$$\mathrm{AADTC} = \sum_{\mathrm{ij0}} \left\{ [\mathrm{TTRPM(ij0)}] \times \mathrm{NPM(ij0)}_{\boldsymbol{t_{pm}(ijk)}} \times \mathrm{m} \times \mathrm{C_{dt}} \right\} + \sum_{\mathrm{ijk}} \left\{ \mathrm{TMTTR(ijk)} \times \left[\mathrm{nof(ijk)}_{\boldsymbol{t_{pm}(ijk)}} \right]_{\mathrm{y}} \times \mathrm{m} \times \mathrm{C_{dt}} \right\} \tag{5.4}$$

AACC Model

The annual average consumable cost is the cost incurred during the different maintenance actions performed on the machines. Each maintenance action performed on the fleet machines requires consumables to repair its indenture items. During the "preventive schedule" of a module, it requires consumables to restore its enclosed parts. On the other hand, whenever a machine fails, the failed indenture item consumes the consumable based on given LOR decisions. Therefore, the annual average consumable cost is the summation of consumable cost incurs during the PM action and LOR analysis. Thus, it can be calculated as;

$$\mathrm{AACC} = \sum_{\mathrm{ijk}} \mathrm{CC(ijk)_{PM}} \times \mathrm{NPM(ijk)}_{\boldsymbol{t_{pm}(ijk)}} \times \mathrm{m} + \sum_{\mathrm{ijk}} \sum_{\mathrm{r=1}}^{3} \sum_{\mathrm{e=1}}^{3} \left(\mathrm{CC_{r,e}(ijk)} \times \left[\mathrm{nof(ijk)}_{\boldsymbol{t_{pm}(ijk)}} \right]_{\mathrm{y}} \times \mathrm{m} \right) \cdot \left[\boldsymbol{L_{r,e}(ijk)} \right] \tag{5.5}$$

During the LOR analysis, the consumable cost incurs based on selected repair action "r" at echelon "e" for the indenture item (ijk). For example, if "repair" decision is made on the "module" then the cost of consumable includes the cost of grease, seals and other minor repair spares used to repair the module. Similarly "discards" decision on the module or part, consumes the cost of new module or part. The cost of packing, documentation etc. is consumed during the "move" decision selected on the module or part.

AATC Model

Whenever, a "move" decision is made for the failed item at base and depot. Then the failed item is send to the next maintenance echelon. This incurs the cost of transportation between base to depot and depot to OEM. Thus, AATC is estimated as follows;

$$\mathrm{AATC} = \sum_{\mathrm{ijk}} \left(\mathrm{TC(ijk)}_{\mathrm{b-D}} \times \left[\mathrm{nof(ijk)}_{\boldsymbol{t_{pm}(ijk)}} \right]_{\mathrm{y}} \times \mathrm{m} \right) \cdot \boldsymbol{L_{2,1}(ijk)} + \sum_{\mathrm{ijk}} \left(\mathrm{TC(ijk)}_{\mathrm{D-OEM}} \times \left[\mathrm{nof(ijk)}_{\boldsymbol{t_{pm}(ijk)}} \right]_{\mathrm{y}} \times \mathrm{m} \right) \cdot \boldsymbol{L_{2,2}(ijk)} \tag{5.6}$$

AASHC and AASOC Model

A fixed holding cost per year is considered at depot and OEM and which is not affected by the LOR decisions therefore it is not included in the present work. Whereas, the base level maintenance facility maintains spare parts with a predefined service level (SL), for the modules or parts that are discarded at base. Therefore, to estimates the recommended spare quantity with a predefined SL, Poisson cumulative probability based algorithm is used in the current problem. The details of that algorithm are discussed in section [3.4.2.2.2] of the chapter 3.

Therefore the AARC is the summation of all the above discussed costs i.e.AACC, AADTC, AATC, AASHC and AASOC. Whereas NRC is the summation of DINRC and DDNRC. The AARC and NRC are estimated by the given equation 5.7 and 5.8.

$$\mathrm{AARC} = \mathrm{AADTC} + \mathrm{AATC} + \mathrm{AACC} + \mathrm{AASHC} + \mathrm{AASOC} \tag{5.7}$$

$$\mathrm{NRC} = \mathrm{DINRC} + \mathrm{DDNRC} \tag{5.8}$$

Therefore, LCC of fleet maintenance system is the discounted sum of Non-recurrent Cost (NRC) and Annual Average Recurrent Cost (AARC) over the life of the system. Then Present Value of fleet maintenance LCC is estimated as follows;

$$\mathrm{PV} = \mathrm{NRC} + \sum_{\mathrm{y=1}}^{\mathrm{L}} \left\{ \frac{1}{(1-\mathrm{R})^{\mathrm{y}}} \times \mathrm{AARC} \right\} \tag{5.9}$$

5.5 Numerical Illustration

Let us consider a fleet of 30 identical machines (i.e. m=30). Let each machine be made up of multiple indentures of assemblies, modules and parts. In the current problem, each machine is considered to be made up of three assemblies (i.e., i=1 to 3). Figure 5.1 shows the pictorial view of the multi indenture system considered in this work. Let each machine be operated 8760 hours per year at the base. Table 5.2 shows reliability parameters and costs for each of the parts considered in this work.

Table 5.2: Weibull distribution parameters and cost of the parts enclosed in different assembly for a machine

First Assembly i.e. (100)					Second Assembly i.e. (200)					Third Assembly i.e. (300)				
Modules (ij0)	Part (ijk)	η_{ijk} (in Hr.)	β_{ijk}	Cost (in `)	Modules (ij0)	Part (ijk)	η_{ijk} (in Hr.)	β_{ijk}	Cost (in `)	Modules (ij0)	Part (ijk)	η_{ijk} (in Hr.)	β_{ijk}	Cost (in `)
110	111	6000	3.2	3500	210	211	3000	3	5000	310	311	2500	2.4	4373
	112	3500	2.6	2500		212	3500	3.2	5650		312	3850	2	4665
	113	5000	3.1	4000		213	4500	3	7500		313	3260	2.2	5000
120	121	5000	2.2	4000	220	221	2500	2.2	4550	320	321	7600	4	3000
	122	4000	2.3	3000		222	2200	2.1	2500		322	6100	2.5	3500
130	131	2500	2.6	5000		223	3600	3	2500	330	331	2000	2.83	3500
	132	2000	2	4000							332	2670	3	4500
	133	3000	2.7	6000										
	134	4000	3	3000										
	135	5000	2.5	6500										

Let there be three echelons maintenance network of “Base (e=1)” or operating site, “Depot (e=2)” or central maintenance facility and “OEM (e=3)” or Original Equipment Manufacturer. Table 5.3 provides the details of the DDNRC for the different assemblies of a machine respectively. Table 5.4 provides the time to repair for different modules, consumed during PM action. Whereas, on the failure of an assembly, the time to repair of each assembly and enclosed indenture items follow the normal distribution. Table 5.5 provides the normal distribution parameters (μ, σ) of different time to repair for each assembly and its enclosed indenture items at different echelons. It also provides the transportation delay time used in this research work. The cost of down time of the machine is considered as 1000 INR /hours. The transportation cost is calculated as some percentage of cost of indenture items as described in table 5.6. The transportation cost given in table 5.6 includes “to and fro” cost between two echelons. The costs of consumable during the PM are considered as some percentage of the indenture cost. In the present work 1% of module and 3% of part cost is considered as PM consumable cost. Whereas the consumable costs for respective LOR decisions for modules and parts of different assemblies are mentioned in table 5.7. Let the life of each machine at the base be $L = 10$ years and discounting factor for money be 5% which remains constant throughout the life of machine.

Table 5.3: Decision dependent non-recurrent cost for machine indenture items (ijk) (in INR)

Assemblies (i00)	Indenture level (ijk)	Base (echelon-1)			Depot (echelon-2)			OEM (echelon-3)	
		Repair	Move	Discard	Repair	Move	Discard	Repair	Discard
		$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$
Assembly (100)	(110)	1500	0	375	1100	0	275	825	137.5
	(111)	-	0	100	-	0	100	-	50
	(112)	-	0	100	-	0	100	-	50
	(113)	-	0	100	-	0	100	-	50
	(120)	1000	0	NA	800	0	200	600	100
	(121)	-	0		-	0	75	-	37.5
	(122)	-	0		-	0	75	-	37.5
	(130)	1100	0	275	1200	0	300	900	150
	(131)	-	0	100	-	0	100	-	50
	(132)	-	0	100	-	0	100	-	50
	(133)	-	0	100	-	0	100	-	50
	(134)	-	0	100	-	0	100	-	50
	(135)	-	0	100	-	0	100	-	50
Assembly (200)	(210)	1200	0	NA	1050	0	262.5	787.5	131.25
	(211)	-	0		-	0	100	-	50
	(212)	-	0		-	0	100	-	50
	(213)	-	0		-	0	100	-	50
	(220)	1050	0	262.5	950	0	237.5	712.5	118.75
	(221)	-	0	100	-	0	120	-	60
	(222)	-	0	100	-	0	120	-	60
	(223)	-	0	100	-	0	120	-	60
Assembly (300)	(310)	1500	0	NA	1200	0	300	900	150
	(311)	-	0		-	0	100	-	50
	(312)	-	0		-	0	100	-	50
	(313)	-	0		-	0	100	-	50
	(320)	700	0	175	500	0	125	375	62.5
	(321)	-	0	100	-	0	75	-	37.5
	(322)	-	0	100	-	0	75	-	37.5
	(330)	850	0	212.5	650	0	162.5	487.5	81.25
	(331)	-	0	100	-	0	80	-	40
	(332)	-	0	100	-	0	80	-	40

Table 5.4: Time to repair for the different modules (ij0) of a machine during the PM action

Module (ij0)	(110)	(120)	(130)	(210)	(220)	(310)	(320)	(330)
TTRPM(ij0) in hr.	10	6	8	8	8	8	6	6

Table 5.5: Normal Distribution Parameters (μ, σ) for TTR_1 of different assemblies and for TTR_2 of each indenture items (ijk) of different assemblies at different echelon and transportation delay between different echelons (in Hr.)

Assembly(100)				Assembly(200)				Assembly(300)			
$TTR_1(100)$	(2, 0.8)			$TTR_1(200)$	(3, 0.6)			$TTR_1(300)$	(4, 0.4)		
(ijk)	$(TTR_2)_b$	$(TTR_2)_D$	$(TTR_2)_{OEM}$	(ijk)	$(TTR_2)_b$	$(TTR_2)_D$	$(TTR_2)_{OEM}$	(ijk)	$(TTR_2)_b$	$(TTR_2)_D$	$(TTR_2)_{OEM}$
(110)	(8,0.8)	(5,0.5)	(3,0.3)	(210)	NA	(5,0.5)	(3,0.3)	(310)	NA	(5,0.5)	(3,0.3)
(111)	(12,1)	(9,1)	(6,0.6)	(211)		(9,1)	(6,0.6)	(311)		(9,1)	(6,0.6)
(112)	(15,1)	(11,1)	(8,0.8)	(212)		(11,1)	(8,0.8)	(312)		(11,1)	(8,0.8)
(113)	(16,1)	(12,1)	(9,0.9)	(213)		(12,1)	(9,0.9)	(313)		(12,1)	(9,0.9)
(120)	NA	(4,0.4)	(2,0.2)	(220)	(8,0.8)	(5,0.5)	(3,0.3)	(320)	(6,0.6)	(4,0.4)	(2,0.2)
(121)		(9,1)	(6,0.6)	(221)	(12,1)	(9,1)	(6,0.6)	(321)	(11,1)	(9,1)	(6,0.6)
(122)		(9,1)	(6,0.6)	(222)	(15,1)	(11,1)	(8,0.8)	(322)	(11,1)	(9,1)	(6,0.6)
(130)	(10,1)	(8,0.8)	(6,1)	(223)	(16,1)	(12,1)	(9,0.9)	(330)	(8,0.8)	(4,0.4)	(8,0.8)
(131)	(18,2)	(15,1)	(10,2)	Transportation delay (in hours) between the different echelons				(331)	(11,2)	(9,1)	(6,0.6)
(132)	(16,2)	(11,2)	(9,0.9)					(332)	(11,2)	(9,1)	(6,0.6)
(133)	(17,2)	(14,3)	(10,1)	$[T_{Delay}]_{b-D}$		$[T_{Delay}]_{d-OEM}$					
(134)	(21,3)	(18,3)	(10,2)	75 Hr.		96 Hr.					
(135)	(14,2)	(10,2)	(7,0.7)								

Table 5.6: Cost of transportation for an indenture items (ijk) between different echelons

Indenture level (ijk)	Transportation cost between base to depot	Transportation cost between depot to OEM
	$TC(ijk)_{b-D}$	$TC(ijk)_{D-OEM}$
Module (ij0)	18 %	20%
Parts (ijk)	8%	10%

Table 5.7: Consumable cost for different assemblies based on repair action "r" at echelon "e"(in INR)

Assemblies (i00)	Indenture items (ij0)/(ijk)	Base (echelon-1)			Depot (echelon-2)			OEM (echelon-3)	
		Repair	Move	Discard	Repair	Move	Discard	Repair	Discard
		$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$
Assembly (100)	(110)	200	50	11000	200	50	11000	200	11000
	(111)	-	50	3500	-	50	3500	-	3500
	(112)	-	50	2500	-	50	2500	-	2500
	(113)	-	50	4000	-	50	4000	-	4000
	(120)	150	50	NA	150	50	7700	150	7700
	(121)	-	50		-	50	4000	-	4000
	(122)	-	50		-	50	3000	-	3000
	(130)	350	50	26950	350	50	26950	350	26950
	(131)	-	50	5000	-	50	5000	-	5000
	(132)	-	50	4000	-	50	4000	-	4000
	(133)	-	50	6000	-	50	6000	-	6000
	(134)	-	50	3000	-	50	3000	-	3000
	(135)	-	50	6500	-	50	6500	-	6500
Assembly (200)	(210)	200	50	NA	200	50	19965	200	19965
	(211)	-	50		-	50	5000	-	5000
	(212)	-	50		-	50	5650	-	5650
	(213)	-	50		-	50	7500	-	7500
	(220)	200	50	10505	200	50	10505	200	10505
	(221)	-	50	4550	-	50	4550	-	4550
	(222)	-	50	2500	-	50	2500	-	2500
	(223)	-	50	2500	-	50	2500	-	2500
Assembly (300)	(310)	200	50	NA	200	50	15441.8	200	15441.8
	(311)	-	50		-	50	4373	-	4373
	(312)	-	50		-	50	4665	-	4665
	(313)	-	50		-	50	5000	-	5000
	(320)	150	50	7150	150	50	7150	150	7150
	(321)	-	50	3000	-	50	3000	-	3000
	(322)	-	50	3500	-	50	3500	-	3500
	(330)	150	50	8800	150	50	8800	150	8800
	(331)	-	50	3500	-	50	3500	-	3500
	(332)	-	50	4500	-	50	4500	-	4500

5.6 Solution Methods

This section discusses the complexities of solving such problems followed by the results for the current problem. Basically the optimization complexities are depending on number decision variables in the optimization model. In the proposed optimization model, "PM schedule" and "LOR" are considered as two types of decisions variables. The optimization complexities further depend on size of the solution space. The size of the solution space will be decided based on the size of the decision variables in an optimization model. In the proposed optimization model, the size of LOR decisions for a machine depends on number of enclosed indenture items (ijk) and the possible maintenance actions at each echelon. For example, first assembly of the machine has 13 number of enclosed indenture items (i.e. 3 modules + 10 parts of corresponding modules), second assembly of the machine has 8 number of enclosed indenture items (i.e. 2 modules + 6 parts of corresponding modules) whereas third assembly of the machine has 10 indenture items as shown in figure 5.1. Similarly the number of repair actions available at base, depot and OEM for each indenture item are 8 (i.e., 3 at base + 3 at depot + 2 at OEM). Therefore the total number of "LOR decision" would be $\left[\text{Total number of LOR decisions}^{(\text{Number of indenture item in a assembly})}\right]$ i.e. 8^{13} for first assembly, 8^{8} for second assembly and 8^{10} for third assembly. Moreover the "PM schedule" decisions for modules of the machine will further multiplied in the LOR decisions. Each module of the assemblies has 28 possible PM decisions (i.e. from 500 hr. to 8760 hr. with the step size of 600 hr.) for the possible of "PM schedule". As the first, second and third assembly has number of modules 3, 2 and 3 respectively. Therefore total number of PM schedule decisions would be $\left[\text{Total number of PM schedule decisions}^{(\text{Number of module in a assembly})}\right]$ i.e. for first assembly it is 28^{3}, for second and third assembly it is 28^{2} and 28^{3} respectively. Now the total size of LOR and PM schedule decisions for an assembly would be estimates as;

$$\begin{aligned}&\text{Total size of LOR and PM schedule decisions}\\ &\qquad = \left[\text{Total number of LOR decisions}^{(\text{Number of indenture item in a assembly})}\right]\\ &\qquad \times \left[\text{Total number of PM schedule decisions}^{(\text{Number of module in a assembly})}\right]\end{aligned}$$

Therefore the total size of LOR and PM schedule decisions for first assembly is $8^{13} \times 28^{3}$. Similarly for second and third assembly, it is $8^{8} \times 28^{2}$ and $8^{10} \times 28^{3}$ respectively. Now total solution space size is equal to $8^{13} \times 28^{3} + 8^{8} \times 28^{2} + 8^{10} \times 28^{3} \approx 12.09 \times 10^{16}$. The complexities further increase due to the presence of many stochastic variables in the problem.

To solve this integrated problem, the number of failures of the machine will be required for different "PM schedule" under following cases;

Case-1: Numbers of failures of parts (ijk), if the individual part of the module is discard;

Case-2: Numbers of failures of a module (ij0), if the module consisting of the all enclosed part is discarded.

Table 5.8 provides a sample of the number of failures simulated for Case-1 and Case-2 under some of the PM schedules for assembly-1 of the machine.

Table 5.8: Number of failures of different parts for assembly-1considering different PM schedules

Modules (ij0)	Parts (ijk)	No PM		500 hr.		3200 hr.		5000 hr.	
		Case-1	Case-2	Case-1	Case-2	Case-1	Case-2	Case-1	Case-2
(110)	(111)	1.2136	2.8428	0.0102	0.2176	0.3456	2.1382	0.6628	2.5154
	(112)	2.3994		0.1838		1.6254		2.042	
	(113)	1.532		0.0256		0.635		1.0506	
(120)	(121)	1.601	2.664	0.184	0.4374	0.978	2.0938	1.2444	2.3952
	(122)	2.0882		0.2548		1.3976		1.7444	
(130)	(131)	3.5412	7.2172	0.3508	1.912	2.7278	6.3684	3.1358	6.774
	(132)	4.5832		1.2564		3.9012		4.2238	
	(133)	2.8624		0.184		1.9896		2.469	
	(134)	2.007		0.05		1.03		1.608	
	(135)	1.5806		0.0742		0.7486		1.111	

5.7 Optimization Results and Discussions

The problem for integrated LOR and PM is solved for the different cases of degree of restoration for PM. The obtained results of LCC associated to different cases of restoration factors are described in table 5.9. Figure 5.3 shows the percentage improvement of LCC considering the "integrated strategy" over "dis-integrated strategy" for the different cases of degree of restoration. It is concluded that "integrated strategy" helps in reducing more LCC of the fleet maintenance system as compared to the "dis-integrated strategy". This means the integration of the PM and LOR analysis is beneficial to achieve an economic LCC performance for the fleet users. However, there is no specific trend in percentage of improvement with respect to restoration factors.

Table 5.9: LCC achieved considering the different cases of restoration factor

Descriptions	Different Cases of Restoration Factor (RF)						
	20%RF	30%RF	40%RF	50%RF	60%RF	70%RF	80%RF
LCC (PV_{fm}) x 10^7 in INR (In" integrated straty")	35.94	34.02	29.29	32.70	32.59	29.28	30.97
Total CM Cost (x10^6) in INR (In "integ. Straty")	24.9	24.72	21.05	21.66	21.34	19.17	20.37
Total PM Cost (x10^6) in INR (In "integ. Straty")	22.11	19.17	16.8	20.33	20.87	17.51	19.77

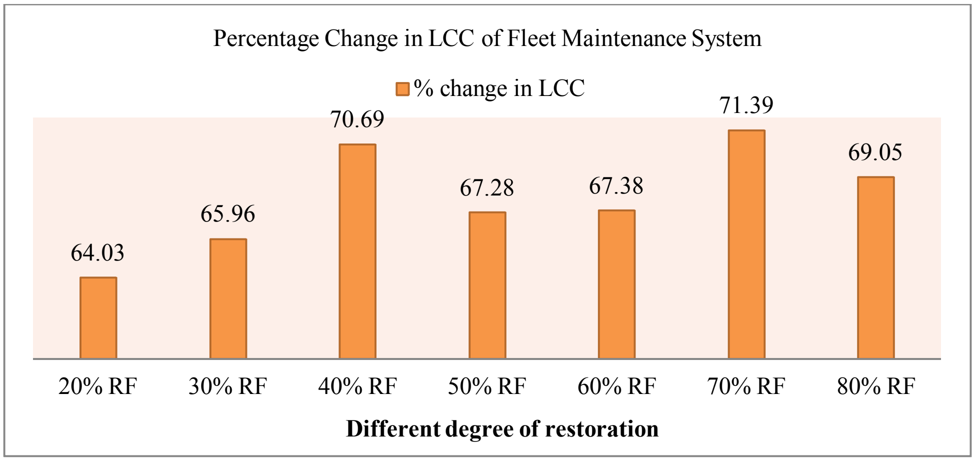

Figure 5.3: % improvement of LCC considering the integrated strategy over dis-integrated strategy

The obtained optimal "PM schedule" for different modules of the machine for all the cases of restoration is summarized in table 5.10. It can be seen from table 5.10 that the optimal PM schedule for module (110) is 2300 hr. in 20% RF, 2600 hr. in 30% RF and 1700 hr. in 40% RF, 50%RF, 60% RF, 70% RF and 2000 hr. in 80% RF. Thus, each of the module, we have achieved the different optimal "PM Schedules" by considering the different cases of restorations during PM actions. Therefore, the restoration factor may change the optimal PM schedule and hence needed to be considered while optimizing the LOR decisions.

Table 5.10: Optimum "PM Schedule" (in Hours) for different enclosed modules of assemblies

Modules	Parts	Different Cases of Restoration Factor (RF)						
(ij0)	(ijk)	20%	30%	40%	50%	60%	70%	80%
Module (110)	(111)	**2300**	**2600**	**1700**	**1700**	**1700**	**1700**	**2000**
	(112)	**2300**	**2600**	**1700**	**1700**	**1700**	**1700**	**2000**
	(113)	**2300**	**2600**	**1700**	**1700**	**1700**	**1700**	**2000**
Module (120)	(121)	800	800	500	500	800	800	500
	(122)	800	800	500	500	800	800	500
Module (130)	(131)	**500**	**1100**	**1700**	**800**	**500**	**1400**	**800**
	(132)	**500**	**1100**	**1700**	**800**	**500**	**1400**	**800**
	(133)	**500**	**1100**	**1700**	**800**	**500**	**1400**	**800**
	(134)	**500**	**1100**	**1700**	**800**	**500**	**1400**	**800**
	(135)	**500**	**1100**	**1700**	**800**	**500**	**1400**	**800**
Module (210)	(211)	800	800	800	800	800	800	800
	(212)	800	800	800	800	800	800	800
	(213)	800	800	800	800	800	800	800
Module (220)	(221)	800	800	2000	800	800	800	800
	(222)	800	800	2000	800	800	800	800
	(223)	800	800	2000	800	800	800	800
Module (310)	(311)	500	500	500	500	500	500	500
	(312)	500	500	500	500	500	500	500
	(313)	500	500	500	500	500	500	500
Module (320)	(321)	1100	500	1100	1100	1100	1400	1400
	(322)	1100	500	1100	1100	1100	1400	1400
Module (330)	(331)	2000	2000	2000	2000	2000	2000	2000
	(332)	2000	2000	2000	2000	2000	2000	2000

The optimal results of LOR decision for the case of 20% and 30% restoration (i.e. 20%RF and 20%RF) are described in table 5.11.

Table 5.11: Optimal LOR decisions for different assembly of a machine for **20%RF** and **30%RF**

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
(110)	**1**	0	0	0	0	0	0	0	2000	-
(111)	0	0	**1**	0	0	0	0	0	2000	**1**
(112)	0	0	**1**	0	0	0	0	0	2000	**3**
(113)	0	0	**1**	0	0	0	0	0	2000	**1**
(120)	**1**	0	NA	0	0	0	0	0	800	NA
(121)	0	**1**		0	**1**	0	0	**1**	800	
(122)	0	**1**		0	0	**1**	0	0	800	
(130)	**1**	0	0	0	0	0	0	0	**500**	-
(131)	0	0	**1**	0	0	0	0	0	**500**	**1**
(132)	0	**1**	0	0	0	**1**	0	0	**500**	-
(133)	0	**1**	0	0	0	**1**	0	0	**500**	-
(134)	0	0	**1**	0	0	0	0	0	**500**	**1**
(135)	0	0	**1**	0	0	0	0	0	**500**	**1**
(210)	**1**	0	NA	0	0	0	0	0	800	NA
(211)	0	**1**		0	**1**	0	0	**1**	800	
(212)	0	**1**		0	0	**1**	0	0	800	
(213)	0	**1**		0	0	**1**	0	0	800	
(220)	**1**	0	0	0	0	0	0	0	500	-
(221)	0	**1**	0	0	0	**1**	0	0	500	-
(222)	0	**1**	0	0	0	**1**	0	0	500	-
(223)	0	0	**1**	0	0	0	0	0	500	**1**
(310)	**1**	0	NA	0	0	0	0	0	500	NA
(311)	0	**1**		0	0	**1**	0	0	500	
(312)	0	**1**		0	0	**1**	0	0	500	
(313)	0	**1**		0	**1**	0	0	**1**	500	
(320)	0	0	**1**	0	0	0	0	0	1100	**4**
(321)	0	0	**1**	0	0	0	0	0	1100	-
(322)	0	0	**1**	0	0	0	0	0	1100	-
(330)	**1**	0	0	0	0	0	0	0	2000	-
(331)	0	0	**1**	0	0	0	0	0	2000	**1**
(332)	0	**1**	0	0	0	**1**	0	0	2000	-
Optimal LOR decisions for different assembly of a machine **30%RF**										
(110)	**1**	0	0	0	0	0	0	0	2600	-
(111)	0	0	**1**	0	0	0	0	0	2600	**1**
(112)	0	0	**1**	0	0	0	0	0	2600	**3**
(113)	0	0	**1**	0	0	0	0	0	2600	**1**
(120)	**1**	0	NA	0	0	0	0	0	800	NA
(121)	0	**1**		0	0	**1**	0	0	800	
(122)	0	**1**		0	0	**1**	0	0	800	
(130)	**1**	0	0	0	0	0	0	0	**1100**	-
(131)	0	0	**1**	0	0	0	0	0	**1100**	-
(132)	0	**1**	0	0	0	**1**	0	0	**1100**	-
(133)	0	**1**	0	0	0	**1**	0	0	**1100**	-
(134)	0	0	**1**	0	0	0	0	0	**1100**	**1**
(135)	0	**1**	0	0	**1**	0	0	**1**	**1100**	-
(210)	**1**	0	NA	0	0	0	0	0	800	NA
(211)	0	**1**		0	0	**1**	0	0	800	
(212)	0	**1**		0	0	**1**	0	0	800	
(213)	0	**1**		0	**1**	0	0	**1**	800	
(220)	**1**	0	0	0	0	0	0	0	800	-
(221)	0	**1**	0	0	0	**1**	0	0	800	-
(222)	0	0	**1**	0	0	0	0	0	800	**4**
(223)	0	0	**1**	0	0	0	0	0	800	**1**
(310)	**1**	0	NA	0	0	0	0	0	500	NA
(311)	0	**1**		0	**1**	0	0	**1**	500	
(312)	0	**1**		0	0	**1**	0	0	500	
(313)	0	**1**		0	0	**1**	0	0	500	
(320)	**1**	0	0	0	0	0	0	0	500	-
(321)	0	**1**	**1**	0	0	0	0	0	500	-
(322)	0	0	0	0	0	**1**	0	0	500	**1**
(330)	**1**	0	0	0	0	0	0	0	2000	-
(331)	0	0	**1**	0	0	0	0	0	2000	**1**
(332)	0	**1**	0	0	0	**1**	0	0	2000	-

The obtained optimal LOR decisions for the case of 20%RF can be read as follows; whenever the assembly (100) of the machines fails and if its enclosed module (130) found failed then it will go for “repair decision” at “base level” by “discarding” the enclosed parts (131), (134) and (135) at “base level” and by “discarding” the enclosed parts (132) and (133) at “depot level” i.e. as highlighted in table 5.11. The recommended spares with 95 % service level for the indenture items at base level are also describes in table 5.11. For example, in the case of 20%RF, the recommended spare i.e. $Q(ijk)$ with 95 % service level for part (111) is 1, for part (112), it is 3 and for part (113), it is 1. Table 5.12 to 5.14 shows the integrated results of LOR and PM decisions considering other cases of restoration i.e. 40%RF, 50%RF, 60%RF, 70%RF and 80%RF respectively. The optimal results of LOR decisions considering the “dis-integrated strategy” are described in the table 5.15. The “PM schedule” and “LOR decisions” are interrelated to each other. Applying the different restoration on enclosed parts of each module, it not only affects the PM schedule but also affects the LOR decisions. For example, in most of the restoration cases the module (130) is obtained different optimal decisions of PM schedule and LOR. Table 5.16 highlights the interdependency between PM schedule and LOR decision obtained for the module (130) considering the different cases of restoration. Thus, the proposed approach considering the time dependent failure rate of the parts plays an important role to achieve the better system performance as it helps in considering the effect of preventive maintenance while optimize the LOR decisions.

Table 5.12: Optimal LOR decisions for different assembly of a machine **40%RF** and **50%RF**

(ijk)	Base (e=1) Repair	Base (e=1) Move	Base (e=1) Discard	Depot (e=2) Repair	Depot (e=2) Move	Depot (e=2) Discard	OEM (e=3) Repair	OEM (e=3) Discard	Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
(110)	1	0	0	0	0	0	0	0	1700	-
(111)	0	0	1	0	0	0	0	0	1700	1
(112)	0	0	1	0	0	0	0	0	1700	2
(113)	0	1	0	0	0	1	0	0	1700	-
(120)	1	0		0	0	0	0	0	500	
(121)	0	1	NA	0	1	0	0	1	500	NA
(122)	0	1		0	0	1	0	0	500	
(130)	1	0	0	0	0	0	0	0	**1700**	-
(131)	0	0	1	0	0	0	0	0	**1700**	5
(132)	0	1	0	0	0	1	0	0	**1700**	-
(133)	0	0	1	0	0	0	0	0	**1700**	1
(134)	0	0	1	0	0	0	0	0	**1700**	1
(135)	0	1	0	0	0	1	0	0	**1700**	-
(210)	1	0		0	0	0	0	0	800	
(211)	0	1	NA	0	0	1	0	0	800	NA
(212)	0	1		0	1	0	0	1	800	
(213)	0	1		0	0	1	0	0	800	
(220)	0	0	1	0	0	0	0	0	2000	7
(221)	0	0	1	0	0	0	0	0	2000	-
(222)	0	0	1	0	0	0	0	0	2000	-
(223)	0	0	1	0	0	0	0	0	2000	-
(310)	1	0		0	0	0	0	0	500	
(311)	0	1	NA	0	0	1	0	0	500	NA
(312)	0	1		0	0	1	0	0	500	
(313)	0	1		0	0	1	0	0	500	
(320)	0	0	1	0	0	0	0	0	1100	-
(321)	0	0	1	0	0	0	0	0	1100	-
(322)	0	0	1	0	0	0	0	0	1100	-
(330)	1	0	0	0	0	0	0	0	2000	-
(331)	0	1	0	0	1	0	0	1	2000	-
(332)	0	0	1	0	0	0	0	0	2000	1
Optimal LOR decisions for different assembly of a machine **50%RF**										
(110)	1	0	0	0	0	0	0	0	1700	-
(111)	0	0	1	0	0	0	0	0	1700	1
(112)	0	0	1	0	0	0	0	0	1700	2
(113)	0	1	0	0	0	1	0	0	1700	-
(120)	1	0		0	0	0	0	0	500	
(121)	0	1	NA	0	1	0	0	1	500	NA
(122)	0	1		0	0	1	0	0	500	
(130)	1	0	0	0	0	0	0	0	**800**	-
(131)	0	0	1	0	0	0	0	0	**800**	5
(132)	0	1	0	0	0	1	0	0	**800**	-
(133)	0	0	1	0	0	0	0	0	**800**	1
(134)	0	0	1	0	0	0	0	0	**800**	1
(135)	0	1	0	0	1	0	0	1	**800**	-
(210)	1	0		0	0	0	0	0	800	
(211)	0	1	NA	0	0	1	0	0	800	NA
(212)	0	1		0	0	1	0	0	800	
(213)	0	1		0	0	1	0	0	800	
(220)	1	0	0	0	0	0	0	0	800	-
(221)	0	1	0	0	0	1	0	0	800	-
(222)	0	0	1	0	0	0	0	0	800	3
(223)	0	0	1	0	0	0	0	0	800	1
(310)	1	0		0	0	0	0	0	500	
(311)	0	1	NA	0	0	1	0	0	500	NA
(312)	0	1		0	1	0	0	1	500	
(313)	0	1		0	0	1	0	0	500	
(320)	1	0	0	0	0	0	0	0	1100	-
(321)	0	0	1	0	0	0	0	0	1100	3
(322)	0	0	1	0	0	0	0	0	1100	2
(330)	1	0	0	0	0	0	0	0	2000	-
(331)	0	1	0	0	1	0	0	1	2000	-
(332)	0	0	1	0	0	0	0	0	2000	1

Table 5.13: Optimal LOR decisions for different assembly of a machine **60%RF** and **70%RF**

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
(110)	**1**	0	0	0	0	0	0	0	1700	-
(111)	0	0	**1**	0	0	0	0	0	1700	**1**
(112)	0	0	**1**	0	0	0	0	0	1700	**2**
(113)	0	**1**	0	0	0	**1**	0	0	1700	-
(120)	**1**	0		0	0	0	0	0	800	
(121)	0	**1**	NA	0	**1**	0	0	**1**	800	NA
(122)	0	**1**		0	0	**1**	0	0	800	
(130)	**1**	0	0	0	0	0	0	0	**500**	-
(131)	0	**1**	0	0	0	**1**	0	0	**500**	-
(132)	0	**1**	0	0	0	**1**	0	0	**500**	-
(133)	0	**1**	0	0	**1**	0	0	**1**	**500**	-
(134)	0	0	**1**	0	0	0	0	0	**500**	**1**
(135)	0	0	**1**	0	0	0	0	0	**500**	**1**
(210)	**1**	0		0	0	0	0	0	800	
(211)	0	**1**	NA	0	0	**1**	0	0	800	NA
(212)	0	**1**		0	0	**1**	0	0	800	
(213)	0	**1**		0	0	**1**	0	0	800	
(220)	**1**	0	0	0	0	0	0	0	800	-
(221)	0	**1**	0	0	0	**1**	0	0	800	-
(222)	0	0	**1**	0	0	0	0	0	800	**3**
(223)	0	0	**1**	0	0	0	0	0	800	**1**
(310)	**1**	0		0	0	0	0	0	500	
(311)	0	**1**	NA	0	0	**1**	0	0	500	NA
(312)	0	**1**		0	**1**	0	0	**1**	500	
(313)	0	**1**		0	**1**	0	0	**1**	500	
(320)	0	0	**1**	0	0	0	0	0	1100	**4**
(321)	0	0	**1**	0	0	0	0	0	1100	-
(322)	0	0	**1**	0	0	0	0	0	1100	-
(330)	0	**1**	0	**1**	0	0	0	0	2000	**1**
(331)	0	**1**	0	0	**1**	0	0	**1**	2000	-
(332)	0	**1**	0	0	0	**1**	0	0	2000	-
Optimal LOR Decisions for Different Assembly of a Machine **70%RF**										
(110)	**1**	0	0	0	0	0	0	0	1700	-
(111)	0	0	**1**	0	0	0	0	0	1700	**1**
(112)	0	0	**1**	0	0	0	0	0	1700	**2**
(113)	0	**1**	0	0	0	**1**	0	0	1700	-
(120)	**1**	0		0	0	0	0	0	500	
(121)	0	**1**	NA	0	0	**1**	0	0	500	NA
(122)	0	**1**		0	0	**1**	0	0	500	
(130)	**1**	0	0	0	0	0	0	0	**1400**	-
(131)	0	0	**1**	0	0	0	0	0	**1400**	**5**
(132)	0	**1**	0	0	0	**1**	0	0	**1400**	-
(133)	0	0	**1**	0	0	0	0	0	**1400**	**1**
(134)	0	0	**1**	0	0	0	0	0	**1400**	**1**
(135)	0	0	**1**	0	0	0	0	0	**1400**	**2**
(210)	**1**	0		0	0	0	0	0	1100	
(211)	0	**1**	NA	0	0	**1**	0	0	1100	
(212)	0	**1**		0	0	**1**	0	0	1100	NA
(213)	0	**1**		0	0	**1**	0	0	1100	
(220)	**1**	0	0	0	0	0	0	0	800	-
(221)	0	**1**	0	0	0	**1**	0	0	800	-
(222)	0	0	**1**	0	0	0	0	0	800	**3**
(223)	0	0	**1**	0	0	0	0	0	800	**1**
(310)	**1**	0		0	0	0	0	0	500	
(311)	0	**1**	NA	0	0	**1**	0	0	500	
(312)	0	**1**		0	0	**1**	0	0	500	NA
(313)	0	**1**		0	**1**	0	0	**1**	500	
(320)	0	0	**1**	0	0	0	0	0	1100	**4**
(321)	0	0	**1**	0	0	0	0	0	1100	-
(322)	0	0	**1**	0	0	0	0	0	1100	-
(330)	**1**	0	0	0	0	0	0	0	2000	-
(331)	0	**1**	0	0	**1**	0	0	**1**	2000	-
(332)	0	0	**1**	0	0	0	0	0	2000	**1**

Table 5.14: Optimal LOR decisions for different assembly of a machine **80%RF**

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
(110)	**1**	0	0	0	0	0	0	0	2000	-
(111)	0	0	**1**	0	0	0	0	0	2000	**1**
(112)	0	0	**1**	0	0	0	0	0	2000	**2**
(113)	0	**1**	0	0	0	**1**	0	0	2000	-
(120)	**1**	0	NA	0	0	0	0	0	500	NA
(121)	0	**1**		0	**1**	0	0	**1**	500	
(122)	0	**1**		0	0	**1**	0	0	500	
(130)	**1**	0	0	0	0	0	0	0	**800**	-
(131)	0	0	**1**	0	0	0	0	0	**800**	**5**
(132)	0	**1**	0	0	0	**1**	0	0	**800**	-
(133)	0	0	**1**	0	0	0	0	0	**800**	**1**
(134)	0	0	**1**	0	0	0	0	0	**800**	**1**
(135)	0	**1**	0	0	**1**	0	0	**1**	**800**	-
(210)	**1**	0	NA	0	0	0	0	0	800	NA
(211)	0	**1**		0	0	**1**	0	0	800	
(212)	0	**1**		0	0	**1**	0	0	800	
(213)	0	**1**		0	**1**	0	0	**1**	800	
(220)	**1**	0	0	0	0	0	0	0	800	-
(221)	0	**1**	0	0	0	**1**	0	0	800	-
(222)	0	0	**1**	0	0	0	0	0	800	**3**
(223)	0	0	**1**	0	0	0	0	0	800	**1**
(310)	**1**	0	NA	0	0	0	0	0	500	NA
(311)	0	**1**		0	0	**1**	0	0	500	
(312)	0	**1**		0	**1**	0	0	**1**	500	
(313)	0	**1**		0	0	**1**	0	0	500	
(320)	0	0	**1**	0	0	0	0	0	1400	**5**
(321)	0	0	**1**	0	0	0	0	0	1400	-
(322)	0	0	**1**	0	0	0	0	0	1400	-
(330)	**1**	0	0	0	0	0	0	0	2000	-
(331)	0	**1**	0	0	0	**1**	0	0	2000	-
(332)	0	0	**1**	0	0	0	0	0	2000	**1**

Table 5.15: Optimal LOR decisions for different assembly of a machine in **dis-integrated strategy**

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard	
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	Q(ijk)
(110)	**1**	0	0	0	0	0	0	0	-
(111)	0	0	**1**	0	0	0	0	0	**3**
(112)	0	0	**1**	0	0	0	0	0	**5**
(113)	0	**1**	0	0	0	**1**	0	0	-
(120)	**1**	0	NA	0	0	0	0	0	NA
(121)	0	**1**		0	0	**1**	0	0	
(122)	0	**1**		0	**1**	0	0	**1**	
(130)	**1**	0	0	0	0	0	0	0	-
(131)	0	0	**1**	0	0	0	0	0	**6**
(132)	0	0	**1**	0	0	0	0	0	**8**
(133)	0	**1**	0	0	0	**1**	0	0	-
(134)	0	**1**	0	0	0	**1**	0	0	-
(135)	0	**1**	0	0	0	**1**	0	0	-
(210)	**1**	0	NA	0	0	0	0	0	NA
(211)	0	**1**		0	**1**	0	0	**1**	
(212)	0	**1**		0	0	**1**	0	0	
(213)	0	**1**		0	0	**1**	0	0	
(220)	**1**	0	0	0	0	0	0	0	-
(221)	0	0	**1**	0	0	0	0	0	**6**
(222)	0	0	**1**	0	0	0	0	0	**7**
(223)	0	**1**	0	0	**1**	0	0	1	-
(310)	**1**	0	NA	0	0	0	0	0	NA
(311)	0	**1**		0	0	**1**	0	0	
(312)	0	**1**		0	**1**	0	0	**1**	
(313)	0	**1**		0	**1**	0	0	**1**	
(320)	0	**1**	0	**1**	0	0	0	0	-
(321)	0	**1**	0	0	**1**	0	0	**1**	-
(322)	0	**1**	0	0	0	**1**	0	0	-
(330)	0	0	**1**	0	0	0	0	0	**4**
(331)	0	0	**1**	0	0	0	0	0	-
(332)	0	0	**1**	0	0	0	0	0	-

Table 5.16: Effect of degree of restoration on LOR and PM schedule for the module (130)

Different Restoration Case	(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)
		Repair	Move	Discard	Repair	Move	Discard	Repair	Discard	
		$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	
20%RF	(130)	**1**	0	0	0	0	0	0	0	500
	(131)	0	0	**1**	0	0	0	0	0	500
	(132)	0	**1**	0	0	0	**1**	0	0	500
	(133)	0	**1**	0	0	0	**1**	0	0	500
	(134)	0	0	**1**	0	0	0	0	0	500
	(135)	0	0	**1**	0	0	0	0	0	500
30% RF	(130)	**1**	0	0	0	0	0	0	0	1100
	(131)	0	0	**1**	0	0	0	0	0	1100
	(132)	0	**1**	0	0	0	**1**	0	0	1100
	(133)	0	**1**	0	0	0	**1**	0	0	1100
	(134)	0	0	**1**	0	0	0	0	0	1100
	(135)	0	**1**	0	0	**1**	0	0	**1**	1100
40% RF	(130)	**1**	0	0	0	0	0	0	0	1700
	(131)	0	0	**1**	0	0	0	0	0	1700
	(132)	0	**1**	0	0	0	**1**	0	0	1700
	(133)	0	0	**1**	0	0	0	0	0	1700
	(134)	0	0	**1**	0	0	0	0	0	1700
	(135)	0	**1**	0	0	0	**1**	0	0	1700
50% RF	(130)	**1**	0	0	0	0	0	0	0	800
	(131)	0	0	**1**	0	0	0	0	0	800
	(132)	0	**1**	0	0	0	**1**	0	0	800
	(133)	0	0	**1**	0	0	0	0	0	800
	(134)	0	0	**1**	0	0	0	0	0	800
	(135)	0	**1**	0	0	**1**	0	0	**1**	800
60% RF	(130)	**1**	0	0	0	0	0	0	0	500
	(131)	0	**1**	0	0	0	**1**	0	0	500
	(132)	0	**1**	0	0	0	**1**	0	0	500
	(133)	0	**1**	0	0	**1**	0	0	**1**	500
	(134)	0	0	**1**	0	0	0	0	0	500
	(135)	0	0	**1**	0	0	0	0	0	500
70% RF	(130)	**1**	0	0	0	0	0	0	0	1400
	(131)	0	0	**1**	0	0	0	0	0	1400
	(132)	0	**1**	0	0	0	**1**	0	0	1400
	(133)	0	0	**1**	0	0	0	0	0	1400
	(134)	0	0	**1**	0	0	0	0	0	1400
	(135)	0	0	**1**	0	0	0	0	0	1400
80% RF	(130)	**1**	0	0	0	0	0	0	0	800
	(131)	0	0	**1**	0	0	0	0	0	800
	(132)	0	**1**	0	0	0	**1**	0	0	800
	(133)	0	0	**1**	0	0	0	0	0	800
	(134)	0	0	**1**	0	0	0	0	0	800
	(135)	0	**1**	0	0	**1**	0	0	**1**	800

5.8 Summary

In this chapter, we have presented an integrated strategy that finds optimal solution for integrated preventive maintenance schedule and level of repair analysis. Such strategy for the LOR optimization is scarcely reported in literature. The results clearly indicate that the proposed integrated PM and LOR strategy leads to better LCC performance compare to without integrated strategy. Additionally the degree of restoration also affects the PM schedule as well as

LOR decisions of the fleet machines. In this chapter, an important addition to the body of knowledge is the use of time dependent failure rate model for different part failure in a machine. It is expected that application of the developed strategy will lead to significant saving to the industries.

Chapter 6*

A Novel Approach for Machine Tool Maintenance Modelling Under Fleet System Architecture

6.1 Introduction

Maintenance of machine tools is one of the major activities in manufacturing industries. Inefficient maintenance planning affects production quality, quantity and process variability. As a result, inadequate production cost and customer dissatisfaction. Despite of the maintenance criticality in the production equipment only few manufacturing industries work with strategic maintenance planning. One of the reason for this may be the existing methods and concepts for maintenance development are quite resource demanding. Machine tool is the equipment, which is used by most of the manufacturing industries such automobile, electronics etc. for their production and operation purpose. These machine tool users are sharing the risk of failures with the machine tool manufacturers by engaging into long term maintenance or availability contracts. This has created new business avenue for machine tool manufacturers for "Servicizing" their traditionally product focused business. Most of the machine tool manufacturers provide the maintenance services for their machines through third party contractor. Alternatively, some of the machine tool manufacturers group together to installed their central maintenance facility to support the maintenance requirement of the group members. The fleet system architecture may be considered as a good alternative for machine tool maintenance. A multi echelon maintenance network of base, central depot and OEM can therefore be used to model the maintenance of machine tools.

However, machine tools fleet deviate significantly from conventionally analyzed fleet maintenance system. As mentioned in the chapter 1, fleet

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maintenance modelling is generally used for equipment like aircraft, wind turbine, etc., and is dealt with LOR analysis. Conventionally, LOR analysis gives more emphasis on maintenance modelling of identical equipment/machines. Usually, these machines are operated at single base and maintained by single OEM under multi-echelons maintenance networks of base, depot and OEM. Apart from this, fleet systems are made up of various indenture levels, which are considered for LOR analysis. The machine tool also forms a complex system consisting of various subsystems/components. The gear boxes, slides and slide ways, drives, spindles, work holding devices, tool magazines and changers, pallet systems are example of some of the sub-assemblies in machine tool system (Rao, 2007). LOR analysis for multi-indenture systems considers constant failure rate to model the time to failures of the indenture items. Conversely, most of the machine tool components follow time dependent failure rate models (Lad and Kulkarni, 2012; Cassady and Kutanoglu, 2003, 2005; Ahmad and Kamaruddin, 2012). Moreover, an assumption of the constant failure rate does not allow considering the Preventive Maintenance (PM) at the time of LOR optimization. PM is an important part for any machine tool user to meet quality and delivery performance. These deviations from conventional fleet maintenance system need to be addressed while modelling the maintenance for machine tools considering fleet system architecture. Table 6.1 shows a comparison of conventional fleet maintenance system with machine tools maintenance scenarios.

Table 6.1: Comparison of conventional fleet maintenances system with the machine tools maintenance scenarios

Assumptions in conventional LOR analysis	Machine tools maintenance scenarios
Constant failure rate assumption	A time dependent failure rates distribution is more common
Preventive maintenance is not considered	Machine tools are maintained preventively
Fleet of identical machines	Different types of machines at the shop floor of one user (base)
Generally single OEM	Machines are purchased from multiple OEMs
Generally single base	Machines operating at different users (multiple base)
Modular system	Not all the subsystem are modular

Machine tools fleets generally consist of multiple bases (different users' shop floor) with each user having wide variety of machine tools form different OEMs. Usually in LOR analysis, most of the maintenance actions are considered either at depot or OEM level maintenance facilities. At base level maintenance facility, only limited maintenance actions are considered. For example, Saranga and Kumar (2006) highlighted the maintenance constraints scenario at multi–echelon maintenance locations for multi-indenture system. In this works, at base level, only the discard and replacement action is considered for the assembly. However, in case of machine tools, each of the users (bases) generally have dedicated maintenance department, responsible for corrective and preventive maintenances apart from the maintenance support received from central maintenance facility and OEMs.

Despite the dis-similarity mentioned in the table 6.1, there are motivations to look into the machine tool maintenance modelling from LOR point of view. In fleet maintenance system, LOR analysis is an important decision making process to optimize the maintenance decisions as discussed in the previous chapters. It plays an important role in improving the life cycle performance of the machine tool users and helps to optimize manufacturer's profit from the maintenance contracts. A LOR and PM decision contributes greatly in the life cycle performance of the machine tool users. However, the maintenance decisions are affected by user's cost structure and their shop floor operation policies. The effect of user's cost structure and their shop floor policies on maintenance decisions have been extensively investigated in the literature. Lad and Kulkarni (2012) studied the effect of user's cost structure on the maintenance decisions in detail. They also classified the failure cost of the machine tool based on the failure consequences, which is usually seen in the machine tool system. Gurel and Akturk (2007) modelled the preventive maintenance cost as a function of the production rate and other user-specific parameters such as work material, hardness of the cutting tool, etc. The LOR and PM decisions may differ from user to user depending on their shop floor level requirements and user's costs structure. Moreover, the PM schedule will also affect LOR decisions as concluded the Chapter 5.

Therefore, a novel approach is required for machine tool users to customize their integrated decision of LOR and PM schedule by considering the user's costs structure and shop floor level requirements. Moreover, this approach may be useful for machine tool manufacturers to decide the profitable maintenance decisions and avoid the economic challenge in the maintenance contracts. The next section provides the detailed discussion on machine tool failure.

6.2 Machine Tool Failure

In this research work, the failures of a machine tool are modeled in terms of its consequences. These consequences carry the users' view of failure under the mutually agreed operating conditions between the users and the manufacturers. It is assumed that whenever a machine tool fails, it leads to one of the following three consequences (Lad and Kulkarni, 2012).

- Failure Consequence 1 (FC1): brings the machine instantly to breakdown state and detected immediately.
- Failure Consequence 2 (FC2): the machine is running, but at slower speed.
- Failure Consequence 3 (FC3): machine is running but producing more rejection than the normal rejection rate.

The FC1 is immediately detected whereas FC2 and FC3 are detected after a time lag by the users. However between the event of occurrence and detection of FC2 and FC3, the machine tool runs at a reduced performance level. Figure 6.1 shows the different failure consequences on a time-performance curve.

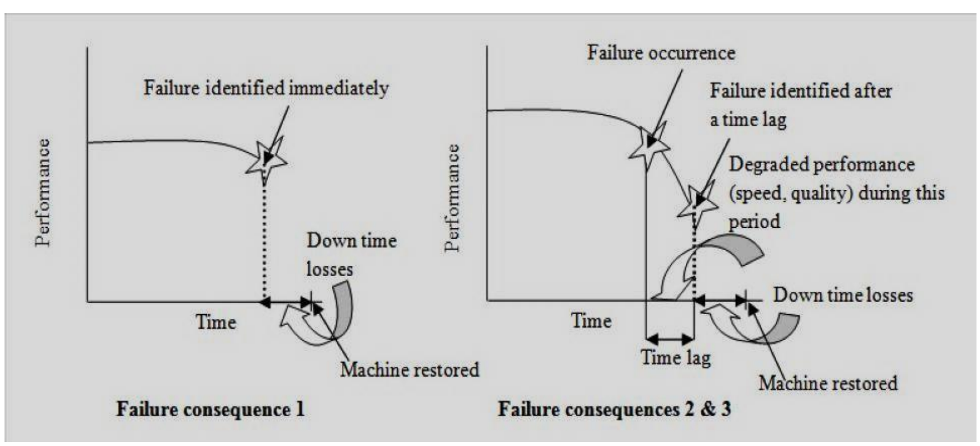


Figure-6.1: Failure consequences on a time-performance curve (Lad and Kulkarni, 2013)

These failure consequences are not only affects the availability but also affects the production rate, quality rate and failure costs of the machine tool. For example, in CNC grinding machine if tail stock does not move properly (due to malfunction of quill) then the production rate of the machine tool is affected. Similarly, the quality rate of the machine tool is affected because of appearing chatter marks and ovality on the job (due to malfunction of wheel and ball screw respectively). Such malfunction of any part of the machine tool by which production and quality performance is affected comes under the FC2 and FC3 respectively. It is clearly indicated that a strong relation exists between the machine tool failure and availability, production rate, quality rate and failure cost. The same needs to be consider while modeling the machine tool maintenance.

6.3 Problem Description

Let us consider a three-echelon machine tool fleet maintenance system. Let echelon-1 be “Base” (user shop floor), echelon-2 be “Central Depot” (or third party depot) and echelon-3 be “OEM” (manufacturer site). Let there be “b” (b=1, 2….B) such users situated at different geographical locations in a fleet structure as shown in figure 6.2-a. Let " $(\mathrm{m_n})_\mathrm{b}$" be the numbers of "$n^{th}$" machine tools operated at base “b”. Further, consider that each machine tool be made up of modular and non-modular indenture levels i.e. assemblies, modules and parts. Let n^{th} machine’s indenture levels are represented by an order triplet i.e."$(\mathrm{ijk})_{\mathrm{m_n}}$". Where $(\mathrm{i00})_{\mathrm{m_n}}$denotes the enclosed $\mathrm{i^{th}}$ assembly at the first indenture level of $\mathrm{n^{th}}$ machine tool, $(\mathrm{ij0})_{\mathrm{m_n}}$ denotes the enclosed $\mathrm{j^{th}}$ module of $\mathrm{i^{th}}$ assembly at the second indenture level of $\mathrm{n^{th}}$ machine tool and $(\mathrm{ijk})_{\mathrm{m_n}}$ denotes the enclosed $\mathrm{k^{th}}$ part of $\mathrm{j^{th}}$ module of $\mathrm{i^{th}}$ assembly of the third indenture level of $\mathrm{n^{th}}$ machine tool. The physical configuration of the machine tool mainly varies in terms of number of the modular and non-modular sub-assemblies and parts enclosed in that machine. Figure 6.2-b shows the pictorial example of the modular and non-modular indentures levels for the machine.

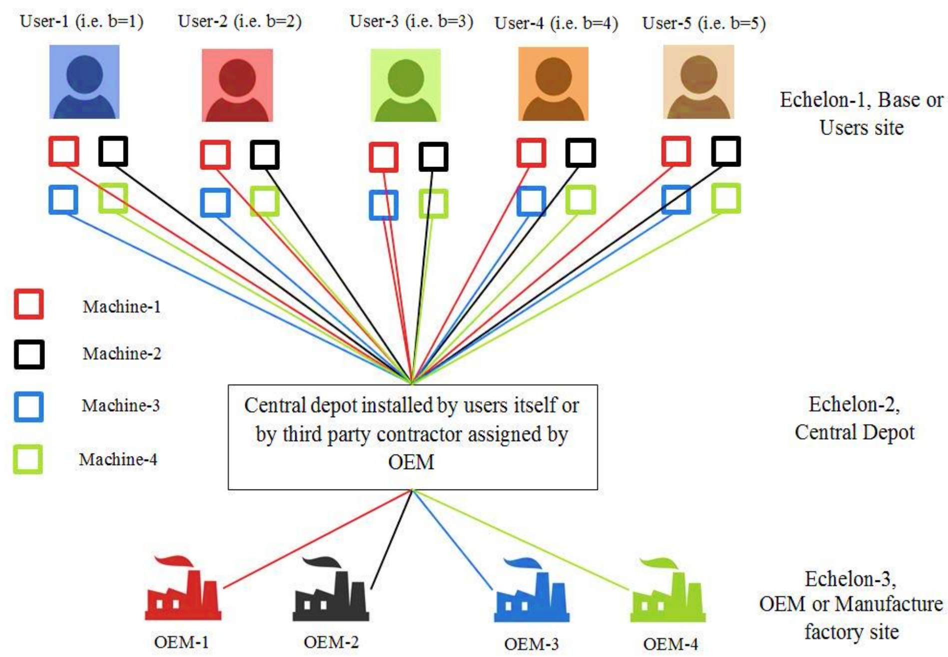


Figure-6.2-a: Pictorial representation of machine tool fleet maintenance architecture

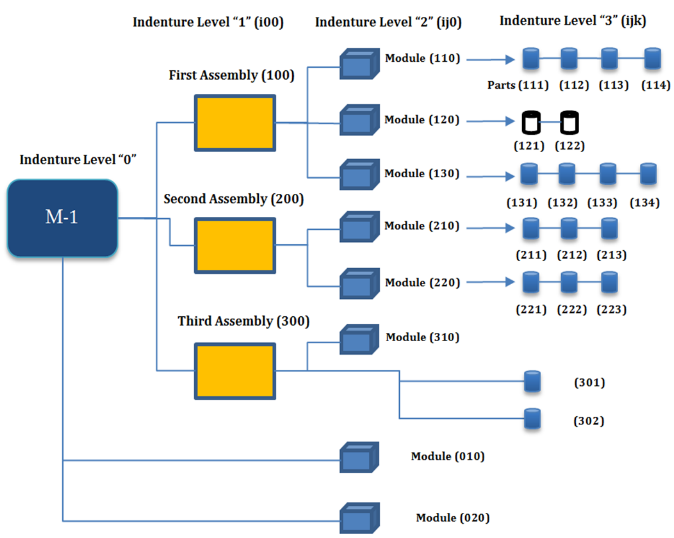


Figure-6.2-b: Physical configuration of machine tool with modular and non-modular items

Let us assume that the machine tool and its enclosed indenture items are arranged reliability wise in series. Failure of "n^{th}" machine tool occurs because of failure of the lowest indenture item, i.e. $\text{part}(ijk)_{m_n}$. To model the time to failures of the each part of the machine tool, a two parameter Weibull distribution is used. Let the shape and scale parameters of the distribution for part(ijk) be β_{ijk} and η_{ijk} respectively. The failure of the each enclosed parts of the machine tool is independent to each other. The machine tool failure results into three Failure Consequences i.e. FC1, FC2 and FC3 as discussed in previous section. The failure consequences FC1, FC2 and FC3 in the machines are independent to each other. Whenever the machine leads to the one of the failure consequence, LOR analysis is used to find out the optimal corrective action as discussed in the section 5.2 of the previous chapter. The aim of LOR analysis is to minimize the life cycle cost of the user "b" for a given multi-indenture machine tool design and maintenance repair network. Table 6.2 also indicates the constraints of maintenance action considered for indenture levels at different maintenance locations.

Besides of that, each part in the machine tool has different time to failure. As discussed earlier that the time to failure of the parts follows a Weibull probability distribution. When $\beta > 1$, the hazard function is an increasing function and it may be practical and important to take Preventive Maintenance (PM) for the parts in order to reduce the increasing risk of machine failure. Preventive maintenance optimization is therefore done to make an optimal balance between cost of failure and cost of preventive maintenance.

Table 6.2: Possible repair actions considered at multi-echelon maintenance facility

Modular and non-modular indenture items	Base (e = 1)			Depot (e = 2)			OEM (e = 3)	
	Repair (r = 1)	Move (r = 2)	Discard (r = 3)	Repair (r = 1)	Move (r = 2)	Discard (r = 3)	Repair (r = 1)	Discard (r = 3)
Modular indenture items (ijk)								
Modules (ijk)	√	√	√	√	√	√	√	√
Parts (ijk)	x	√	√	x	√	√	x	√
Non-modular indenture items (ijk)								
Modules (ij0),	√	√	x	√	√	x	√	x
Parts (ijk)	√	√	x	√	√	x	√	x

6.3.1 Integrated Strategy for Machine Tool User

Chapter 5 discusses integrated strategy to investigate the importance of the PM in the LOR optimization. However, in this chapter, the same is used to investigate the effect of user's cost structure and the shop floor and quality control policies on integrated PM and LOR decisions. Thus, an integrated approach is solved for dedicated to machine tool user that minimizes the LCC in a machine tool fleet maintenance system, while selecting the following decisions;

- Optimal LOR decisions for machine tools;

– Optimal preventive interval for the individual modules of the machine tools.

6.4 Problem Formulation

The problem of machine tool fleet maintenance system is formulated as follows;

Minimize

$$(\mathbf{LCC_{PV}})_{\mathbf{b}} = f(\boldsymbol{L_{r,e}}(\boldsymbol{ijk})_{\boldsymbol{m_n}}, \boldsymbol{t_{pm}}(\boldsymbol{ijk})_{\boldsymbol{m_n}}, \textbf{user's shop floor and quality control parameters})$$

Subject to,

LOR decisions constraints (discussed in table 6.2)

Machine tool physical constraints

Where, $(\mathbf{LCC_{PV}})_{\mathbf{b}}$ is the life-cycle cost contribution of machine tool to the user "**b**" in a machine tool fleet maintenance system. It is measured in terms of the present value of the LCC. It can be calculated as;

$$(\mathbf{LCC_{PV}})_{\mathbf{b}} = \mathrm{NRC_b} + \sum_{y=1}^{L}\left\{\left(\frac{1}{(1-\mathrm{R})^{y}}\right) \times [\mathrm{AAFC_b} + \mathrm{AAPMC_b}]\right\} \tag{6.1}$$

$\mathrm{NRC_b}$ is the non-recurrent cost incurs one-time investment required for the maintenance inspection and repair facilities at multi-echelon maintenance locations. $\mathrm{AAFC_b}$ is the annual average cost of failures that incurs whenever a machine tool fails at user "b". Annual Average Preventive Maintenance Cost ($\mathrm{AAPMC_b}$) mainly includes consumable cost and downtime cost which incurs during the preventive maintenance repair action by the user "b". All these costs are depends on decision variable of LOR and PM Interval. The detailed models related $\mathrm{AAFC_b}$ and $\mathrm{AAPMC_b}$ are describes in the section 6.5.2 and 6.5.3 respectively.

6.4.1 LOR Decision Variable

The LOR decision variable for enclosed modular and non-modular items i.e. $\mathrm{k^{th}}$ part of $\mathrm{j^{th}}$ module of $\mathrm{i^{th}}$ assembly of n^{th} machine denotes by $\boldsymbol{L_{r,e}(ijk)_{m_n}}$. In the optimization model these LOR decision is considered as follows;

$$\boldsymbol{L_{r,e}(ijk)_{m_n}} = \begin{cases} 1, & \text{repair action "}\mathbf{r}\text{" at echelon "}\mathbf{e}\text{" is selected for indenture item (ijk)of } n^{th} \text{ machine;} \\ 0, & \text{otherwise;} \end{cases}$$

Where"$\mathbf{r}$" denotes to the repair action decisions: $\mathbf{r} = 1$ denoting to "repair decision", $\mathbf{r} = 2$ denoting to "move decision" and $\mathbf{r} = 3$ denoting to "discard decision". These repair actions are performed at different echelons in fleet structure represented by "$\mathbf{e}$"; $\mathbf{e} = 1$ denotes to "base level" (echelon 1),$\mathbf{e} = 2$ denotes to "depot level" (echelon 2) and $\mathbf{e} = 3$ denotes to "OEM level" (echelon 3).

6.4.2 PM Decisions Variable:

The decision of PM interval for enclosed $\mathrm{k^{th}}$ part of $\mathrm{j^{th}}$ module of $\mathrm{i^{th}}$ assembly of n^{th} machine denotes by $\boldsymbol{t_{pm}(ijk)_{m_n}}$**.** In this research work, the fixed calendar time based PM policy is considered. We assume that PM restores the machine in between "as bad as old" to "as good as new" condition, which implies that the PM is imperfect. During each preventive action, all parts (ijk) of a module will be restored with some restoration factors. The different cases of restoration such PM-I with 25% restoration, PM-II with 50% restoration and PM-III with 75% restoration are considered to evaluate the integrated strategy for user "b" in the fleet.

6.4.3 User Specific Costs Parameters

Effect of user's cost structure on the LOR and PM decisions is one of the important considerations of the current problem. Moreover, different users have different quality control chart parameters for their machine tools. The following costs and quality control parameters are identified which are as follows;

1. *Cost of lost production per job;*
2. *Cost of rejection per job;*
3. *Cost of transportation between user and central depot;*

4. *Frequency of the sampling for the quality control;*
5. *Sample size.*

However, all these costs and quality control parameters are also differing from machine to machine operated at user's site in the fleet maintenance system. In fleet maintenance system, the cost of failure for the each machine and each user are evolved in different way. Therefore, it may impact on the decisions of LOR and PM interval in the machine tool fleet maintenance system. The next section describes the development of integrated life cycle cost models for the user "b".

6.5 LCC Models for Machine Tool

The LCC is divided into three terms i.e. Non-Recurrent Cost (NRC), Annual Average Failure Cost (AAFC) and Annual Average Preventive Maintenance Cost (AAPMC). The Non-Recurrent Cost (NRC) includes one-time investment cost required to install the facilities for maintenance inspection and repair action at multi-echelon maintenance locations i.e. base, central depot and OEM, based on selected LOR decisions. The AAFC is the cost of failure incurs due to failure of the machine tools throughout a year. The Annual Average Preventive Maintenance Cost (AAPMC) is the cost incurred annually based on the selected PM Interval decisions for each machine tool. All these costs are then used to calculate the life-cycle cost contribution of the machine tools operated at the site of user 'b" as shown in equation (6.1). The development of detailed LCC model for the user "b" is described below and considers the following conditions and notations.

- The failure Cost per corrective action for a part (ijk) of n^{th} machine is $\mathrm{FC(ijk)}_{\mathrm{m_n}}$.
- The consumable cost incurs during the preventive repair action for a part (ijk) of n^{th} machine is $\mathrm{CCPM}_{\mathrm{m_n}}\mathrm{(ijk)}$;
- The total time to repair consumes during the preventive repair for a module (ij0) of n^{th} machine is $\mathrm{TTRPM(ij0)}$;
- The time to repair consumes during the preventive repair action $\mathrm{TTRPM(ijk)}$;
- The cost of lost production per job for n^{th} machine is $\left[\mathrm{C_{lp}}\right]_{\mathrm{m_n}}$;

- The cost of rejection per job for n^{th} machine is $[\mathrm{C_{rej.}}]_{\mathrm{m_n}}$;
- The n^{th} machine is required to operate at the designed production rate $\mathrm{DPR_{m_n}}$ (jobs/hour);
- The non-recurrent cost for a part (ijk) of n^{th} machine is $\mathrm{C_{mf}(ijk)_{m_n}}$;
- The consumable cost for a part (ijk) of n^{th} machine is $\mathrm{CC(ijk)_{m_n}}$;
- The downtime cost for a part (ijk) of n^{th} machine is $\mathrm{DTC(ijk)_{m_n}}$;
- The transportation cost for a part (ijk) of n^{th} machine is $\mathrm{TC(ijk)_{m_n}}$;
- The spare holding cost for a part (ijk) of n^{th} machine is $\mathrm{SHC(ijk)_{m_n}}$;
- The stock-out cost for a part (ijk) of n^{th} machine is $\mathrm{SOC(ijk)_{m_n}}$;
- The process is centered with upper and lower control limits at $\pm 3\sigma$;
- The sample size and the time between samples for the control chart are $\mathrm{S_{m_n}}$ and ts_{m_n}, respectively.

6.5.1 Non-Recurrent Cost Model

The NRC is the cost of maintenance facility required for various parts of n^{th} machine. Basically it will depend on selected LOR decisions. The detail of the non-recurrent cost is discussed earlier in the previous chapter 5. This cost is considered only once considering the LOR decisions for the user "b". Thus, the non-recurrent cost for the machines operated at user "b" can be express as follows;

$$\mathrm{NRC_b} = \sum_{\mathrm{n=1}}^{\mathrm{N}} \sum_{\mathrm{ijk}} \mathrm{C_{mf}(ijk)_{m_n}} \tag{6.2}$$

6.5.2 Annual Average Failure Cost Model

In this research work, Annual Average Failure Cost (AAFC) is estimated based on the three failure consequences (Lad and Kulkarni, 2012). Therefore, the AAFC is classified into following three cost categories;

1. Cost of Failure Consequence 1 (FC1)
2. Cost of Failure Consequence 2 (FC2)
3. Cost of Failure Consequence 3 (FC3)

6.5.2.1 Cost of Failure Consequences 1 (FC1)

The cost of failure consequence 1 for n^{th} machine at the site of user "b" mainly includes consumable cost, down time cost, transportation cost, spare holding and stock-out cost. The chapter 5 discussed the detailed life cycle cost models. These costs are estimated based on the selected LOR decisions for a part (ijk) of n^{th} machine. Thus, the cost of failure for a part (ijk) of n^{th} machine when failure leads to FC1 can be written as follows:

$$\begin{aligned} \mathrm{C_{FC1}(ijk)_{m_n}} = {} & \mathrm{CC}_{\mathbf{r,e}}(\mathrm{ijk})_{\mathrm{m_n}} + \mathrm{DTC}_{\mathbf{r,e}}(\mathrm{ijk})_{\mathrm{m_n}} + \mathrm{TC}_{\mathbf{r,e}}(\mathrm{ijk})_{\mathrm{m_n}} + \\ & \mathrm{SHC}_{\mathbf{r,e}}(\mathrm{ijk})_{\mathrm{m_n}} + \mathrm{SOC}_{\mathbf{r,e}}(\mathrm{ijk})_{\mathrm{m_n}} \cdot \boldsymbol{L_{r,e}(ijk)_{m_n}} \end{aligned} \tag{6.3}$$

6.5.2.2 Cost of Failure Consequences 2 (FC2)

The cost of failure consequence 2 is incurred whenever the part in the machine tool leads to Failure Consequences 2 (FC2). It includes the cost of production lost due to the reduced production rate and the cost of maintenance for the corrective action i.e. cost of failure consequences 1. Thus the cost of failure for a part (ijk) of n^{th} machine when the failure leads to FC2 can be estimates as follows:

$$\mathrm{C_{FC2}(ijk)_{m_n}} = \mathrm{DPR_{m_n}} \times \mathrm{RPR_{m_n}} \times \mathrm{t_{FC2_{m_n}}} \times \left[\mathrm{C_{lp}}\right]_{\mathrm{m_n}} + \mathrm{C_{FC1}(ijk)_{m_n}} \tag{6.4}$$

where $\mathrm{DPR_{m_n}}$, $\mathrm{RPR_{m_n}}$ and $\left[\mathrm{C_{lp}}\right]_{\mathrm{m_n}}$ denotes to the design production rate, reduced production rate and cost of lost production respectively. Whenever a failure of a part (ijk) of n^{th} machine leads to Failure Consequence 2 (FC2), it reduces the production rate of n^{th} machine by $\mathrm{RPR_{m_n}}$ and the same is detected after $\mathrm{t_{FC2_{m_n}}}$ hours.

6.5.2.3 Cost of Failure Consequences 3 (FC3)

The cost of failure consequence 3 is incurred whenever the part in the machine tool leads to Failure Consequences 3 FC3. It includes the cost of rejection due to the increasing rejection rate and the cost of maintenance for the corrective action i.e. cost of failure consequences 1. Thus the cost of failure for a part (ijk) of n^{th} machine when the failure leads to FC3 can be estimates by the equation 6.5.

$$\mathrm{C_{FC3}(ijk)_{m_n} = DPR_{m_n} \times IRR_{m_n} \times t_{FC3\,m_n} \times \left[C_{rej.}\right]_{m_n} + C_{FC1}(ijk)_{m_n}} \qquad (6.5)$$

Where, $\mathrm{IRR_{m_n}}$ and $\mathrm{t_{FC3\,m_n}}$ denotes the increasing rejection rate and time to detect the failure consequences 3 for n^{th} machine. Whenever a failure of a part (ijk) of n^{th} machine leads to Failure Consequence 3 (FC3), it shifts the process mean by $\delta_{m_n} \times \sigma$. It can be calculated as follows;

Let it is assumed that the users are monitored the machine process by an quality-control chart with upper and lower control limits at $\pm 3\sigma$, the β' (type II) error for n^{th} machine can be expressed as (Montgomery, 2004 and Panagiotidou and Tagaras, 2006).

$$\begin{aligned}\beta'_{\mathrm{m_n}} = \varphi\left[3 - \delta_{\mathrm{m_n}} \times \sqrt{\mathrm{S}}\right] \\ - \varphi\left[-3 - \delta_{\mathrm{m_n}} \times \sqrt{\mathrm{S}_{\mathrm{m_n}}}\right]\end{aligned} \qquad (6.6)$$

the number of samples taken from the n^{th} machine before the shift is detected, i.e. the average run length, is calculated by the equation 6.7 and 6.8.

$$\left(ARL_{\beta'}\right)_{\mathrm{m_n}} = \frac{1}{1-\beta'} \qquad (6.7)$$

$$\mathrm{t_{FC3\,m_n}} = \frac{1}{1-\beta'} \times ts_{m_n} \qquad (6.8)$$

Similarly, the increases in rejection from the n^{th} machine due to FC3 can be estimated as;

$$\mathrm{IRR_{m_n}} = 1 - \left\{\varphi\left[3 - \delta_{\mathrm{m_n}}\right] - \varphi\left[3 + \delta_{\mathrm{m_n}}\right]\right\} \qquad (6.9)$$

Let the each part (ijk) of n^{th} machine has probability of three failure consequences i.e. $\mathrm{P_{FC1}(ijk)_{m_n}}$, $\mathrm{P_{FC2}(ijk)_{m_n}}$ and $\mathrm{P_{FC3}(ijk)_{m_n}}$. Thus, the cost of failure per corrective action for a part (ijk) of n^{th} machine will be calculated as follows;

$$\begin{aligned}\mathrm{FC(ijk)_{m_n}} = \mathrm{C_{FC1}(ijk)_{m_n} \times P_{FC1}(ijk)_{m_n} + C_{FC2}(ijk)_{m_n} \times P_{FC2}(ijk)_{m_n}} \\ + \mathrm{C_{FC3}(ijk)_{m_n} \times P_{FC3}(ijk)_{m_n}}\end{aligned} \qquad (6.10)$$

$FC(ijk)_{m_n}$ is basically the summation of failure cost of C_{FC1}, C_{FC2} and C_{FC3} when the failure leads to FC1, FC2 and FC3 respectively;

Now, the Annual Average Failure Cost (AAFC) for part (ijk) of n^{th} machine can be expressed as follows;

$$\begin{aligned} AAFC(ijk)_{m_n} = \; & C_{FC1}(ijk)_{m_n} \cdot \left([nof(ijk)]_{m_n} \times m_n \times P_{FC1}(ijk)_{m_n}\right) \\ & + C_{FC2}(ijk)_{m_n} \cdot \left([nof(ijk)]_{m_n} \times m_n \times P_{FC2}(ijk)_{m_n}\right) \\ & + C_{FC3}(ijk)_{m_n} \cdot \left([nof(ijk)]_{m_n} \times m_n \times P_{FC3}(ijk)_{m_n}\right) \end{aligned} \tag{6.11}$$

Similarly, Annual Average Failure Cost (AAFC) considering the all the machines operated at user "b" will be estimated by the equation 6.12.

$$AAFC_b = \sum_{n=1}^{N} \sum_{ijk} AAFC(ijk)_{m_n} \tag{6.12}$$

6.5.3 Annual Average Preventive Maintenance Cost Model

The annual average preventive maintenance cost is the cost incurred during the scheduled preventive maintenance intervals of different modules of the machines throughout the year. This cost mainly includes the cost of consumable and down time cost. Thus, annual AAPMC for the user "b" will be estimated as follows;

$$\begin{aligned} AAPMC_b = & \sum_{N=1}^{n} \sum_{ijk} \left(CCPM_{m_n}(ijk)\right) \times [nof(ijk)]_{m_n} \times m_n \\ & + \sum_{ij0} \Big\{[TTRPM(ij0)]_{m_n} \times [nof(ij0)]_{m_n} \times m_n \\ & \times \left[C_{lp}\right]_{m_n} \Big\} \end{aligned} \tag{6.13}$$

6.6 Numerical Illustrations and Solution Methods

To illustrates the integrated approach for the machine tool users, a numerical problem is presented considering five machine tool users (i.e. b=1 to 5) in a machine tool fleet maintenance system. Let each user "b" requires the four non-identical machine tools such as $m_{1,} m_{2,} m_3$ and m_4 "b". Table 6.3 provides the details of number of machine requires at each base "b". Figure 6.3-a, b, c, d shows the detailed multi-indenture structure of the each machine. Each machine considered is expected to operate for 8760 hours.

Table 6.3: Details of the machine operated at the site of user "b"

Number of users in the fleet (i.e. base "b")	$(m_1)_b$	$(m_2)_b$	$(m_3)_b$	$(m_4)_b$	Number of the N machine available at each user
1	15	15	10	10	50
2	10	10	5	5	30
3	5	5	10	10	30
4	10	10	10	10	40
5	5	5	5	5	20

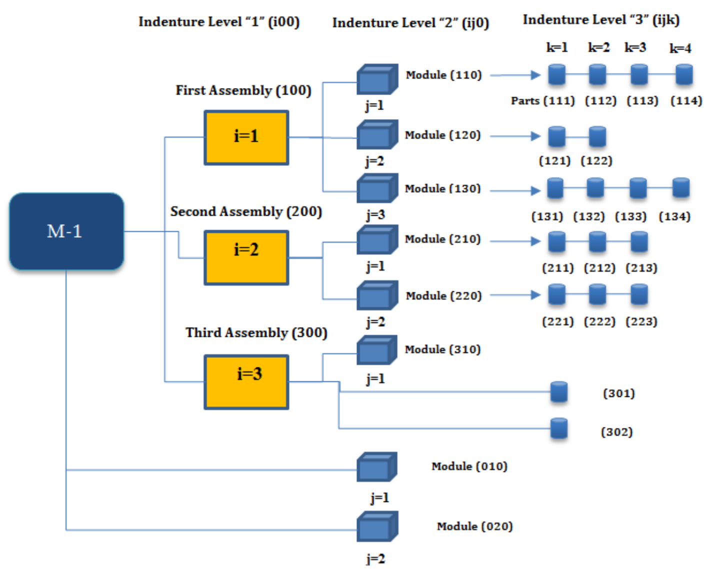


Figure 6.3-a: multi-indenture items of the machine -1 (m_1)

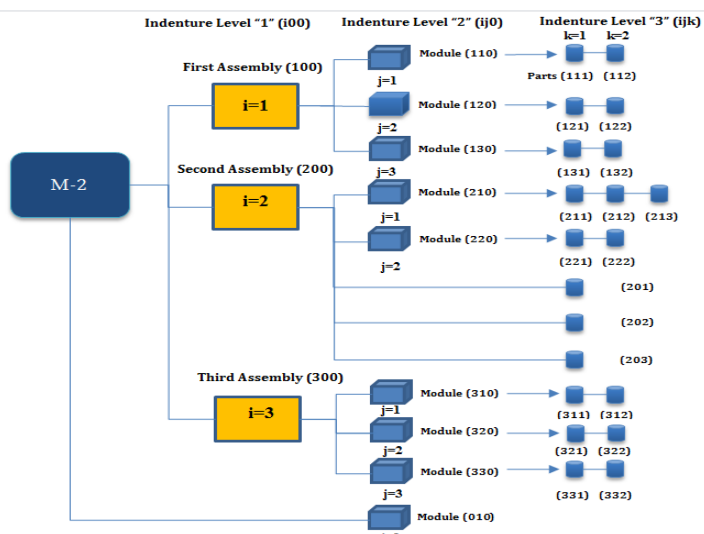


Figure 6.3-b: multi-indenture items of the machine -2 (m_2)

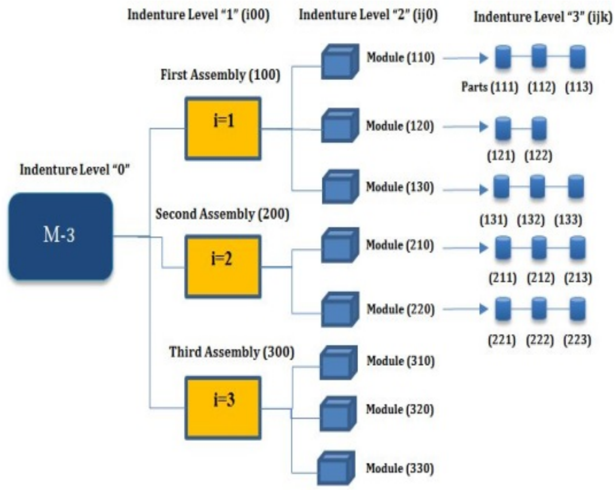


Figure 6.3-c: multi-indenture items of the machine -3 (m_3)

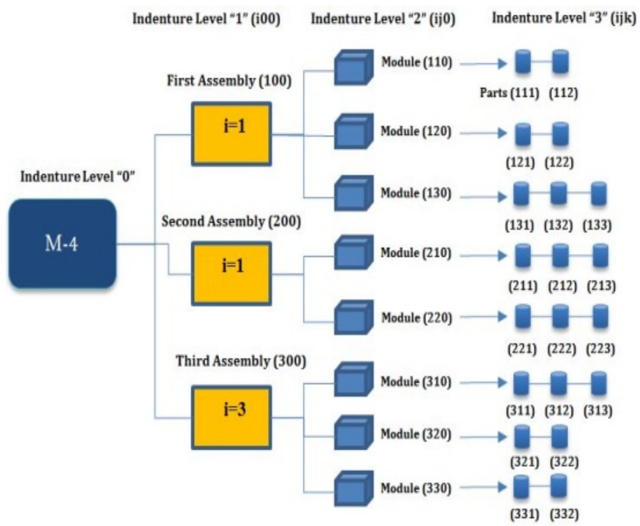


Figure 6.3-d: multi-indenture items of the machine-4 (m_4)

The time to failure of the each part of the different machines follows a two parameter distribution with values for the scale parameters η and shape parameters β as shown in the table 6.4 and 6.5. It also provides the cost and probability of different failure consequences of enclosed parts of the different machines.

Table 6.4: Reliability, cost parameters and probability of failure consequences for each of the indenture items of machine-1 and machine-2

Machine - 1 (i.e. m_1)							
Non-modular and Modular items $(ijk)_{m_1}$		η_{ijk} (in hr.)	β_{ijk}	Cost (INR)	Probability of FC		
					P_{FC1}	P_{FC2}	P_{FC3}
*Module (010)		6500	2	14000	0.5	0.2	0.3
*Module (020)		6000	2	16000	0.5	0	0.5
*Module (310)		7700	2	9000	0.6	0.4	0
*Part (301)		6840	3.5	10000	0.5	0.5	0
*Part (302)		5500	2	12000	0.4	0.3	0.3
Module (110)	111	4000	3.2	3500	0.5	0	0.5
	112	3500	2.6	2500	0.5	0.1	0.4
	113	4500	3.1	4000	0.6	0.1	0.3
	114	5000	2.2	5500	0.6	0.2	0.2
Module (120)	121	4000	2.3	3000	0.6	0.2	0.2
	122	2500	2.6	5000	0.6	0.2	0.2
Module (130)	131	2000	2	4000	0.7	0.3	0
	132	3000	2.7	6000	0.7	0.3	0
	133	4000	3	3000	0.5	0	0.5
	134	2500	2.4	4373	0.5	0	0.5
Module (210)	211	3850	2	4665	0.6	0.2	0.2
	212	3260	2.2	5000	0.5	0.5	0
	213	4200	3.2	5500	0.6	0.3	0.1
Module (210)	221	2580	2	6500	0.5	0.2	0.3
	222	3900	2.8	3000	0.5	0	0.5
	223	6500	2	15000	0.7	0.3	0

Machine - 2 (i.e. m_2)							
Non-modular and Modular items $(ijk)_{m_2}$		η_{ijk} (in hr.)	β_{ijk}	Cost (INR)	Probability of FC		
					P_{FC1}	P_{FC2}	P_{FC3}
*Module (010)		5500	3	17000	0.5	0	0.5
*Part (201)		3260	2.7	9500	0.6	0.4	0
*Part (202)		4200	2.3	11500	0.5	0.5	0
*Part (203)		2580	2.5	13500	0.7	0.3	0
Module (110)	111	3500	3	5000	0.6	0.3	0.1
	112	4200	3.2	5650	0.7	0.3	0
Module (120)	121	2800	2.3	6500	0.5	0.2	0.3
	122	5000	2.2	4000	0.4	0.4	0.2
Module (130)	131	4000	2.3	3000	0.4	0.3	0.3
	132	2500	2.4	4373	0.7	0.3	0
Module (210)	211	2000	3	4665	0.6	0	0.4
	212	3000	2.2	5000	0.5	0.5	0
	213	4000	3	3000	0.7	0.3	0
Module (220)	221	2500	2.2	3500	0.5	0	0.5
	222	3850	2.1	4550	0.5	0	0.5
Module (310)	311	3900	2.8	3500	0.6	0.2	0.2
	312	6500	3	3200	0.5	0	0.5
Module (320)	321	7700	1.3	9000	0.5	0.2	0.3
	322	6840	2	4555	0.7	0.3	0
Module (330)	331	5500	1.3	5500	0.6	0.1	0.3
	332	6500	2	6000	0.4	0.3	0.3

Table 6.5: Reliability, cost parameters and probability of failure consequences for each of the indenture items of machine-3 and machine-4

Machine - 3 (i.e. m_3)							
Non-modular and Modular items $(ijk)_{m_3}$		η_{ijk} (in hr.)	β_{ijk}	Cost (in INR)	Probability of FC		
					P_{FC1}	P_{FC2}	P_{FC3}
*Module (330)		7200	1.8	12000	0.5	0	0.5
*Module (310)		6600	2	14000	0.4	0.2	0.4
*Module (320)		6550	1.6	15000	0.7	0.3	0
Module (110)	111	3000	3	5800	0.6	0.2	0.2
	112	4800	2.9	5640	0.6	0.4	0
	113	4000	2.8	6200	0.6	0	0.4
Module (120)	121	5000	2.2	4000	0.7	0.1	0.2
	122	4000	2.3	3000	0.7	0.1	0.2
Module (130)	131	3900	2	5000	0.5	0	0.5
	132	4500	2.8	5400	0.5	0.5	0
	133	4000	3	4800	0.6	0	0.4
Module (210)	211	3700	3.2	2500	0.8	0.1	0.1
	212	3400	3	2500	0.7	0.2	0.1
	213	4200	2.8	1500	0.9	0	0.1
Module (220)	221	4200	2.2	6000	0.9	0.1	0
	222	5200	2	6200	0.9	0	0.1
	223	3500	3	3500	0.9	0.1	0

Machine - 4 (i.e. m_4)							
Modular items $(ijk)_{m_4}$		η_{ijk} (in hr.)	β_{ijk}	Cost (in INR)	Probability of FC		
					P_{FC1}	P_{FC2}	P_{FC3}
Module (110)	111	4860	2.5	5550	0.6	0.2	0.2
	112	3880	3	2000	0.6	0	0.2
	113	5500	2	1500	0.6	0	0.2
Module (120)	121	5000	2.2	4000	0.7	0.3	0
	122	4000	2.3	3000	0.6	0	0.4
Module (130)	131	3500	3.2	5650	0.5	0	0.7
	132	4500	3	7500	0.6	0.3	0.5
	133	2500	2.2	4550	0.7	0.2	0.1
Module (210)	211	3458	2	5000	0.6	0.5	0.1
	212	7738	2	6500	0.6	0.2	0.2
	213	6840	3.2	5500	0.6	0.4	0
Module (220)	221	3750	2.8	5200	0.6	0.4	0
	222	4250	2.2	5340	0.7	0	0.3
	223	2800	1.5	2560	0.6	0	0.4
Module (310)	311	5000	3.1	4000	0.7	0.1	0.2
	312	5000	2.2	4000	0.7	0.3	0
	313	4000	2.3	3000	0.7	0.2	0.1
Module (320)	321	4860	2.5	5550	0.5	0	0.5
	322	3880	3	2000	0.7	0.1	0.3
Module (330)	331	5500	1.8	6500	0.6	0.2	0.2
	332	6000	1.5	7500	0.6	0.2	0.2

* indicates the non-modular items of the machines

In machine tool fleet systems, each user is situated at dispersed location form the depot. Let the transportation delay time between different users and depot level is 75 hr., 100 hr. and 150 hr. for User-1, User-2 and User-3 respectively as shown in table 6.6. Similarly, it also provides the delay time between the depot and OEM's of different machines. It is considered during the estimation of the down time based on the LOR decisions selected at depot or OEM level. The cost of consumables during the LOR decisions and PM action for the modules and parts are provided in the table 6.6.

Table 6.6: Details of relevant cost and shop floor parameters used in the numerical example

Description of the parameters	Details				
Consumable cost based on selected LOR decisions	CC_{m_n} in INR				
If repair decision is selected at module level	15 % of the cost of module and part item				
If move decision is selected at module level	2 % of the cost of module item				
If discard decision is selected at module and part level	Cost of module and part item				
If move decision is selected at part level	1 % of the cost of part item				
Consumable cost considered during the PM action	$CCPM_{m_n}$ in INR				
Module (ij0)	1 % of the cost of module item				
Parts (ijk)	3 % of the cost of part item				
Spare holding cost (% of the item cost) considered at base level	SHC in INR				
Module (ij0) and Parts (ijk)	50% of the cost of item				
Transportation delay between different users and central depot	Delay time (in hr.)				
User-1	75				
User-2	100				
User-3	150				
User-4	180				
User-5	200				
Transportation delay between central depot and different OEM of their machine	Delay time (in hr.)				
OEM-1	96				
OEM-2	120				
OEM-3	75				
OEM-4	150				
Transportation cost (% of the item cost) between different users and central depot TC_{m_n} in INR	User- 1	User-2	User-3	User-4	User-5
Module (ij0)	18%	20%	25%	30%	35%
Parts (ijk)	8%	10%	15%	20%	25%
Transportation cost (% of the item cost) between central depot and different OEM (TC_{m_n}) in INR	OEM-1	OEM-2	OEM-3	OEM-4	
Module (ij0)	20%	25%	15%	30%	
Parts (ijk)	10%	15%	5%	20%	

Table 6.6: Continue…….

Description of the parameters	Details			
Magnitude of the process shift because of the FC3 of n^{th} machine for the users, δ_{m_n}	m_1	m_2	m_3	m_4
User-1, 2, 3, 4 and 5	1.2	0.9	0.8	1
Time to detect the FC2 of n^{th} machine for the users, $t_{FC2_{m_n}}$(in hr.)	m_1	m_2	m_3	m_4
User-1, 2, 3, 4 and 5	4	3	5	7
Time between samples for the control chart of n^{th} machine for different users, ts_{m_n}(in hr.)	m_1	m_2	m_3	m_4
User-1	4	5	6	6
User-2	4	6	5	7
User-3	6	8	7	5
User-4	3	8	3	5
User-5	4	5	7	6
Sample size of n^{th} machine for different users, S_{m_n} (in hr.)	m_1	m_2	m_3	m_4
User-1	6	5	4	5
User-2	8	5	6	7
User-3	8	7	4	4
User-4	7	6	8	5
User-5	5	8	5	7
Cost of lost production per job of n^{th} machine for different users $[C_{lp}]_{m_n}$ (in INR /hr.)	m_1	m_2	m_3	m_4
User-1	500	800	500	300
User-2	2000	2600	2500	3000
User-3	4000	4800	4500	4600
User-4	7300	7000	6500	6000
User-5	10000	12000	15000	9000
Cost of rejection per job of n^{th} machine for different users $[C_{rej.}]_{m_n}$ (in INR /hr.)	m_1	m_2	m_3	m_4
User-1	1000	6000	5000	4000
User-2	4000	3000	6000	5000
User-3	6000	4000	1000	3000
User-4	5000	1000	4000	6000
User-5	2000	5000	3000	1000
Reduced production rate of n^{th} machine when the failure leads to FC2 for the users RPR_{m_n}	m_1	m_2	m_3	m_4
User-1, 2, 3, 4 and 5	30 %	40 %	60 %	50 %
Designed production rate of n^{th} machine for the users DPR_{m_n} (jobs/hours)	m_1	m_2	m_3	m_4
User-1, 2, 3, 4 and 5	45	60	55	75

Other cost parameter like transportation, spare holding for the enclosed module and part can be seen form the table 6.6. Each user has used Quality Control (QC) chart to monitor the machine process producing a jobs. The details of the shop floor and quality control policy used by the different users are provided in the table 6.6. Let the process is centered with upper and lower control limits at $\pm 3\sigma$. Whenever the machines i.e. $m_{1,}m_{2,}m_3$ and m_4 failure that are lead to FC3, it shift the process mean by $1.2 \times \sigma, 0.9 \times \sigma, 0.8 \times \sigma$ and $1 \times \sigma$ respectively. The time to detect the process shift of the n^{th} machine is estimated by the equation [6.8]. Table 6.6 shows the different user's cost structure and quality control parameters such cost of lost production, cost of rejection, time between samples for the control chart and sample size of the n^{th} machine. Let the machines i.e. $m_{1,}m_{2,}m_3$ and m_4 failure that are lead to FC2 reduced the production rate by 30%, 40%, 60% and 50% respectively. The reduction in production rate on the machines $m_{1,}m_{2,}m_3$ and m_4 is detected by the users after 4 hr., 3 hr., 5 hr. and 7 hr. respectively. It is assumed that the effective life of the each machine tool on the shop floor is 10 years and discounting factor for money be 5% which remains constant throughout the life of the machine.

To solve this problem, the complexities are increases with increasing number of machine and number of enclosed modular and non-modular indenture items in the machine. For a given failure characteristics of parts of the different machines, expected number of corrective actions in y^{th} year for the different PM cases such as PM-I, PM-II and PM-II is obtained from simulation as a function of PM interval and restoration factors for a given η and β during selected planning horizon.

6.7 Results and Discussions

The problem of integrated LOR and PM schedule is solved for each machine tool users. Table 6.7 summarizes the results of LCC achieved by the integrated approach for each machine tool users. The percentage reduction in LCC considering "integrated approach" over dis-integrated approach is shown in figure 6.4.

Table 6.7: LCC achieved considering the different cases of preventive maintenance

Integrated Approach									
Descriptions of LCC	LCC_{PV} x 10^6 in INR			Total CM Cost (x10^6) in INR			Total PM Cost (x10^6) in INR		
Different Users	PM-I	PM-II	PM-III	PM-I	PM-II	PM-III	PM-I	PM-II	PM-III
User-1	178.32	141.97	148.91	18.21	13.41	13.89	4.87	5.21	5.34
User-2	291.28	343.69	351.93	23.37	30.25	31.10	14.67	13.88	14.26
User-3	689.64	517.08	484.45	62.69	38.58	47.14	27.01	28.32	26.80
User-4	1011.48	1155.11	918.86	93.08	113.20	81.79	38.05	36.45	36.09
User-5	1160.71	1205.49	1315.53	96.44	100.08	114.39	52.86	56.70	55.20

According to the figure 6.4, we have obtained the significant percentage reduction in LCC considering the different cases of PM i.e. PM-I, PM-II and PM-III. For example, 3.40 %, 10.04 % and 12.19 % reduction in LCC achieved for the user-1 with integrated approach over dis-integrated approach for PM-I, PM-II and PM-III cases respectively. Similarly, we can see the percentage reduction for the other users from figure 6.4.

A sample of results for the optimal LOR decisions and PM schedules for the user-1 of their machines are described in table 6.8. The optimal LOR decisions of the machine-1 can be read as follows; whenever the assembly (100) of the machine-1 fails and if its enclosed module (110) found failed then it will go for the "repair" at base level by discarding the enclosed parts (111), (112), (113) and (114) at base level. Similarly, if its enclosed module (130) found failed then it will go for "repair" at "base level" by "discarding" the enclosed parts (131) at base level, part (133), (134) and (135) at "Depot level" and part (132) at OEM level as highlighted in table 6.8. Similar the LOR decisions of the modules for others machines can be seen form the table 6.8. Whereas, the non-modular items of the machine-1 i.e. modules (010), (020), (310) and parts (301) and (302) will be repaired at base level. Additionally, the table 6.8 provides the improved solutions of the PM schedules achieved for the modules of the different assemblies. According to the table 6.8, the optimal PM interval for the non-modular items of the machine-1 i.e. (010), (020), and (310) are at 900 hour whereas for the items (301) and (302) are at 1500 and 600 hours respectively. However, for the modular items i.e. module (110), (120) and (130), the PM interval are at 600 hours. While for the module (210) and (220), it is at 300 hours.

In similar manner, the optimal LOR decisions and PM intervals for other machines are presented in table 6.8.

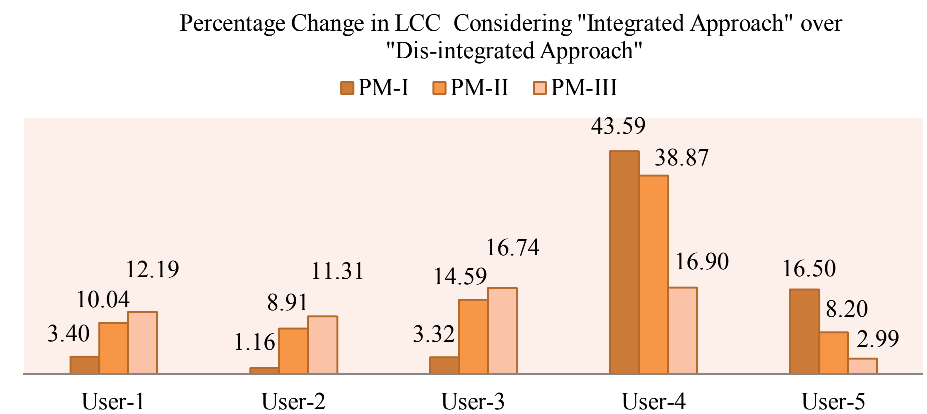


Figure 6.4: % change in LCC considering different PM strategy of different users

The recommended spares with 95 % service level for the indenture items of the different machine at base level (i.e. site of the user-1) are also describes in table 6.8. For example, as the part (111), (112), (113), (114) (121), (122), (131), (211) and (212) are discarded at base level as an optimal LOR decisions. Therefore the recommended spare i.e. Q (ijk) with 95 % service level for the parts (111), (112), (113), (114), (121, (211) and (212) is 1. Whereas, the recommended spares for the part (122) and (131) are 6 and 2 respectively.

The numerical example discussed in the section 6.6 is also solved by dis-integrated approach for the different users. Table 6.9 provides the sample results of optimal LOR decisions and PM schedules considering dis-integrated approach. We have achieved significant change in LOR decisions and PM schedules considering the all preventive maintenance strategies. The results discussed in tables 6.8 and 6.9 are the sample results of integrated and dis-integrated approach. The series of table presented in APPENDIX-A and B describes the detail results of integrated and dis-integrated approach considering different PM strategies for the different machine tool users in a fleet. Figure 6.4 shows the percentage improvement in LCC for the different users considering integrated approach over dis-integrated approach. It shows the effectiveness of preventive maintenance approaches applied to the different users in the fleet.

Table 6.8: Optimal LOR decisions and PM intervals for user-1 with PM-I

Machine-1										
(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	1	0	0	0	0	0	0	0	900	0
020	1	0	0	0	0	0	0	0	900	0
310	1	0	0	0	0	0	0	0	900	0
301	1	0	0	0	0	0	0	0	1500	0
302	1	0	0	0	0	0	0	0	600	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	1
112	0	0	1	0	0	0	0	0	600	1
113	0	0	1	0	0	0	0	0	600	1
114	0	0	1	0	0	0	0	0	600	1
120	1	0	0	0	0	0	0	0	600	0
121	0	0	1	0	0	0	0	0	600	1
122	0	0	1	0	0	0	0	0	600	6
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	2
132	0	1	0	0	1	0	0	1	300	0
133	0	1	0	0	0	1	0	0	300	0
134	0	1	0	0	0	1	0	0	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	0	1	0	0	0	0	0	300	1
212	0	0	1	0	0	0	0	0	300	1
213	0	1	0	0	0	1	0	0	300	0
220	0	1	0	1	0	0	0	0	300	0
221	0	1	0	0	1	0	0	1	300	0
222	0	1	0	0	1	0	0	1	300	0
223	0	1	0	0	0	1	0	0	300	0
Machine-2										
(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	1	0	0	0	0	0	0	0	300	0
201	1	0	0	0	0	0	0	0	3000	0
202	1	0	0	0	0	0	0	0	3900	0
203	1	0	0	0	0	0	0	0	2400	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	1
112	0	0	1	0	0	0	0	0	600	1
120	1	0	0	0	0	0	0	0	300	0
121	0	0	1	0	0	0	0	0	300	1
122	0	0	1	0	0	0	0	0	300	1
130	1	0	0	0	0	0	0	0	300	0
131	0	1	0	0	0	1	0	0	300	0
132	0	1	0	0	0	1	0	0	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	0	1	0	0	0	0	0	300	1
212	0	1	0	0	0	1	0	0	300	0
213	0	0	1	0	0	0	0	0	300	1
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	2
222	0	1	0	0	1	0	0	1	300	0
310	1	0	0	0	0	0	0	0	300	0
311	0	0	1	0	0	0	0	0	300	1
312	0	0	1	0	0	0	0	0	300	1
320	1	0	0	0	0	0	0	0	600	0
321	0	0	1	0	0	0	0	0	600	2
322	0	1	0	0	1	0	0	1	600	0
330	1	0	0	0	0	0	0	0	300	0
331	0	1	0	0	1	0	0	1	300	0
332	0	1	0	0	0	1	0	0	300	0

Table 6.8: Cont.….

Machine-3										
(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	1	0	0	0	0	0	0	0	300	0
310	1	0	0	0	0	0	0	0	6300	0
320	1	0	0	0	0	0	0	0	6300	0
110	1	0	0	0	0	0	0	0	300	0
111	0	1	0	0	0	1	0	0	300	0
112	0	0	1	0	0	0	0	0	300	1
113	0	1	0	0	0	1	0	0	300	0
120	0	0	1	0	0	0	0	0	300	1
121	0	0	1	0	0	0	0	0	300	0
122	0	0	1	0	0	0	0	0	300	0
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	0	1	0	0	0	0	0	300	1
133	0	0	1	0	0	0	0	0	300	1
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	0	1	0	0	300	0
212	0	1	0	0	0	1	0	0	300	0
213	0	1	0	0	0	1	0	0	300	0
220	1	0	0	0	0	0	0	0	600	0
221	0	0	1	0	0	0	0	0	600	1
222	0	0	1	0	0	0	0	0	600	1
223	0	0	1	0	0	0	0	0	600	1

Machine-4										
(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	0	1	0	1	0	0	0	0	300	0
111	0	1	0	0	0	1	0	0	300	0
112	0	1	0	0	1	0	0	1	300	0
113	0	1	0	0	1	0	0	1	300	0
120	0	0	1	0	0	0	0	0	300	1
121	0	0	1	0	0	0	0	0	300	0
122	0	0	1	0	0	0	0	0	300	0
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	0	1	0	0	0	0	0	300	1
133	0	1	0	0	0	1	0	0	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	1	0	0	1	300	0
212	0	0	1	0	0	0	0	0	300	1
213	0	1	0	0	0	1	0	0	300	0
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	1
222	0	0	1	0	0	0	0	0	300	1
223	0	1	0	0	1	0	0	1	300	0
310	1	0	0	0	0	0	0	0	300	0
311	0	0	1	0	0	0	0	0	300	1
312	0	0	1	0	0	0	0	0	300	1
313	0	1	0	0	1	0	0	1	300	0
320	1	0	0	0	0	0	0	0	300	0
321	0	1	0	0	1	0	0	1	300	0
322	0	0	1	0	0	0	0	0	300	1
330	1	0	0	0	0	0	0	0	300	0
331	0	0	1	0	0	0	0	0	300	1
332	0	0	1	0	0	0	0	0	300	1

Table 6.9: Optimal LOR and PM interval decisions considering dis-integrated approach

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimal PM Schedules with Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
010	1	0	0	0	0	0	0	0	6300	1500	300
020	1	0	0	0	0	0	0	0	1500	1500	5100
310	1	0	0	0	0	0	0	0	1800	5700	900
301	1	0	0	0	0	0	0	0	2700	3000	900
302	1	0	0	0	0	0	0	0	600	600	900
110	1	0	0	0	0	0	0	0	600	300	900
111	0	0	1	0	0	0	0	0	600	300	900
112	0	0	1	0	0	0	0	0	600	300	900
113	0	0	1	0	0	0	0	0	600	300	900
114	0	0	1	0	0	0	0	0	600	300	900
120	1	0	0	0	0	0	0	0	300	2100	600
121	0	0	1	0	0	0	0	0	300	2100	600
122	0	0	1	0	0	0	0	0	300	2100	600
130	1	0	0	0	0	0	0	0	300	300	300
131	0	0	1	0	0	0	0	0	300	300	300
132	0	0	1	0	0	0	0	0	300	300	300
133	0	0	1	0	0	0	0	0	300	300	300
134	0	0	1	0	0	0	0	0	300	300	300
210	1	0	0	0	0	0	0	0	600	300	300
211	0	0	1	0	0	0	0	0	600	300	300
212	0	0	1	0	0	0	0	0	600	300	300
213	0	0	1	0	0	0	0	0	600	300	300
220	1	0	0	0	0	0	0	0	300	300	300
221	0	1	0	0	0	1	0	0	300	300	300
222	0	1	0	0	0	1	0	0	300	300	300
223	0	1	0	0	0	1	0	0	300	300	300

6.7.1 Observations

(1) *Integrated approach vs. dis-integrated approach:* Based on the observations, it can be seen that as compare to dis-integrated approach, the integrated approach significantly reduces the LCC of the different users. Therefore, the percentage improvement in LCC considering the integrated approach shows the importance of the integration of the LOR and PM.

(2) *PM effectiveness in integrated approach:* By applying the different PM strategy in the integrated approach, User-4 achieved more percentage reduction in LCC compare to others users shown in figure 6.4. It can be seen form figure 6.4 that User -1, User-2, User-3 have the similar trends of PM effectiveness in the integrated approach. Similarly, User-4 and User-5 have similar trends of PM effectiveness in the integrated approach. It can also be seen form figure 6.4 that the PM-III strategy is more valuable for the User-1, User -2 and User-3 compare to PM-I and PM-II. While, the PM-I strategy is more effective for User-4 and User-5. This different trend

clearly shows the importance of the preventive maintenance in machine tool fleet maintenance planning. Actually, this dissimilarity in PM effectiveness for the machine tool users may be due to their shop floor and quality control policies. Table 6.6 shows the cost data and quality control parameters used by the different users. Where, User-1 has lesser cost of lost production per job (i.e. 500, 800, 500 and 300 INR/hr.), lesser cost of rejection per job (i.e. 1000, 6000, 5000 and 4000 INR/hr.) of their machines. On the other hand, User-4 has higher cost of lost production (i.e. 7300, 7000, 6500 and 6000 INR/hr.), higher cost of rejection (i.e. 5000, 1000, 4000 and 6000 INR/hr.) of their machines. Similarly, it can be seen for the quality control parameters i.e. sampling frequency and sample size for the User-1 and User-4. Thus, it can be concluded that machine tool users with low cost of lost production and rejection per job of their machines may go for the PM-III strategy. Whereas, users with high cost of lost production and rejection per job may go for the PM-I strategy.

(3) *Effect of user's cost structure on integrated decisions*: We have achieved the different LOR and PM decisions to the different users for their machine tools. This may be due to the different user's cost structure and also maintenance support cost of machine tool fleet maintenance system. Table 6.10 shows the effect on the LOR decisions for the machine-4 indenture items i.e. module (110) and module (310) considering different users cost structure. The results discussed above are specific for the user's cost structure i.e. cost of lost production and rejection per job and quality control parameter i.e. sample size and sampling frequency considered in the previous example. In order to generalize the performance of the proposed integrated approach over dis-integrated approach, a comprehensive analysis is performed considering the different cases of user's cost structure and quality control policy. These different cases are created by varying the cost of lost production per job, cost of rejection per job, sample size and sampling frequency of the different machines. These different cases are varied with high and low values of these parameters for

the different machines used by different users. Table 6.11 provides the values of the parameters considered in the integrated model. The detailed discussions of the effect of shop floor and quality control parameters are as follows;

(a) *Effect of cost of lost production and cost of rejection per job:* To identify the impact of cost of lost production and cost of rejection, different cases of these costs are considered. Each user has four different cases considering high and low values of these cost parameters for their machines such as if particular user (i.e. user-1) has high cost of lost production and low cost of rejection per job of their machine. The different cases are provided a what-if analysis to take a decisions making on the LOR and PM decisions. Figure 6.5 shows the effect of the cost of lost production and cost of rejection per job on the LCC of the different users in machine tool fleet maintenance system. After the simulating the different scenarios for the different users, it is found out that for the user-1, we have obtained the maximum percentage improvement i.e. 59.22% in LCC for the case of “Low” cost of production lost and “Low” cost of rejection per job. However, in the case of “High” cost of lost production and “Low” cost of rejection per job, we have achieved minimum percentage improvement i.e. 3.63% in LCC for the user-1. Similarly, we can see the maximum and minimum percentage improvement for the other users as highlighted in the figure 6.5. Therefore, these costs have significant impact on the LCC. The proposed integrated approach shows 3.63 to 63 % improvement compare to dis-integrated approach. Hence, it recommended that the cost of lost production and rejection must be considered while optimizing the LOR and PM decisions in a machine tool fleet maintenance system. Additionally, this demonstrates that the integrated approach always provide lesser LCC compare to dis-integrated approach for various combination constructed for these costs.

(b) *Effect of sample size and sampling frequency:* To analyze the effect of quality parameters, values of quality control parameters i.e. sample size and time between two samples have been varied for the case of maximum and minimum percentage improvement obtained in LCC of the cost of lost production and cost of rejection per job as shown in figure 6.5. Each user has four cases i.e. high and low values of each parameters i.e. sample size and time between sampling. Each case with maximum and minimum improvement is evaluated by integrated as well as dis-integrated approach. Figure 6.6-a, b, c, d and e illustrates the effect of quality control policies on the LCC of the different users. It is clearly indicated for the figure 6.6-a, b, c, d and e that quality control parameter of the machines has a significant impact on the LCC and also on the LOR and PM decisions for the different users. Results shows that integrated approach always provide reduced LCC compared to dis-integrated approach. From figure 6.6-a, it can be seen that for the user-1, we have achieved the maximum percentage improvement i.e. 32 % in the LCC for the case of "Max-High-High" and minimum percentage improvement i.e. 3.25 % in the LCC for the case of "Min-High-High". More improvement in LCC has been observed for "Low" values of sample size and "Low" values of the sampling frequency for most of the users. It is also be seen that the integrated approach shows 0.18 % to 32 % improvements in LCC compared to dis-integrated approach. Therefore, machine tool users should explicitly consider the cost of rejection of their machines for the shop floor planning.

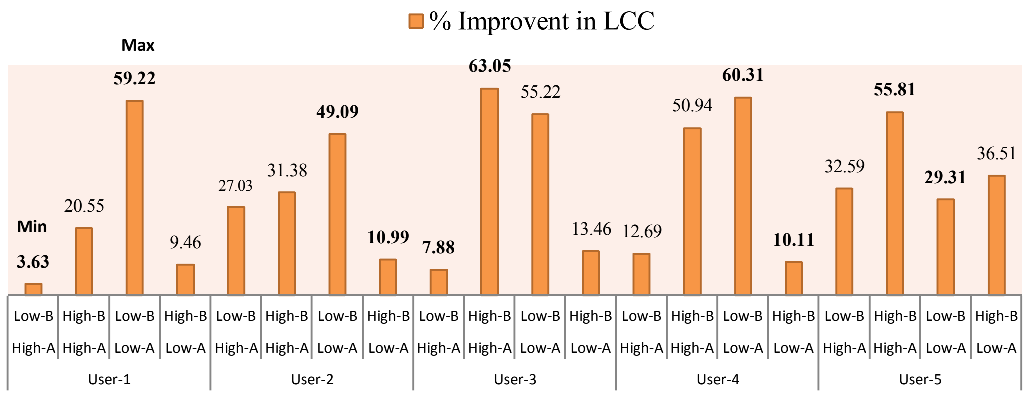
Table 6.12 describes the highest percentage improvement achieved in LCC considering particular scenario for different users.

Table 6.10: Effect of User's Cost Structure on LOR Decisions

Users	User's cost structure		(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)	
				Repair	Move	Discard	Repair	Move	Discard	Repair	Discard
				$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$
User-1	$[C_{lp}]_{m_n}$	300	**Machine-4 with module (110) and module(310)**								
			110	0	1	0	1	0	0	0	0
	$[C_{rej.}]_{m_n}$	4000	111	0	1	0	0	0	1	0	0
			112	0	1	0	0	1	0	0	1
	$[S]_{m_n}$	5	113	0	1	0	0	1	0	0	1
			310	1	0	0	0	0	0	0	0
	$[ts]_{m_n}$	6	311	0	0	1	0	0	0	0	0
			312	0	0	1	0	0	0	0	0
	Delay time between base to depot	75	313	0	1	0	0	1	0	0	1
User-2	$[C_{lp}]_{m_n}$	3000	**Machine-4 with module (110) and module(310)**								
			110	1	0	0	0	0	0	0	0
	$[C_{rej.}]_{m_n}$	5000	111	0	1	0	0	0	1	0	0
			112	0	1	0	0	1	0	0	1
	$[S]_{m_n}$	7	113	0	1	0	0	0	1	0	0
			310	1	0	0	0	0	0	0	0
	$[ts]_{m_n}$	7	311	0	0	1	0	0	0	0	0
			312	0	0	1	0	0	0	0	0
	Delay time between base to depot	100	313	0	0	1	0	0	0	0	0
User-3	$[C_{lp}]_{m_n}$	4600	**Machine-4 with module (110) and module(310)**								
			110	1	0	0	0	0	0	0	0
	$[C_{rej.}]_{m_n}$	3000	111	0	1	0	0	1	0	0	1
			112	0	1	0	0	0	1	0	0
	$[S]_{m_n}$	4	113	0	1	0	0	0	1	0	0
			310	1	0	0	0	0	0	0	0
	$[ts]_{m_n}$	5	311	0	0	1	0	0	0	0	0
			312	0	1	0	0	0	1	0	0
	Delay time between base to depot	150	313	0	0	1	0	0	0	0	0
User-4	$[C_{lp}]_{m_n}$	6000	**Machine-4 with module (110) and module(310)**								
			110	1	0	0	0	0	0	0	0
	$[C_{rej.}]_{m_n}$	6000	111	0	1	0	0	1	0	0	1
			112	0	1	0	0	1	0	0	1
	$[S]_{m_n}$	5	113	0	1	0	0	0	1	0	0
			310	1	0	0	0	0	0	0	0
	$[ts]_{m_n}$	5	311	0	0	1	0	0	0	0	0
			312	0	0	1	0	0	0	0	0
	Delay time between base to depot	180	313	0	1	0	0	0	1	0	0
User-5	$[C_{lp}]_{m_n}$	9000	**Machine-4 with module (110) and module(310)**								
			110	1	0	0	0	0	0	0	0
	$[C_{rej.}]_{m_n}$	1000	111	0	1	0	0	0	1	0	0
			112	0	1	0	0	1	0	0	1
	$[S]_{m_n}$	7	113	0	1	0	0	0	1	0	0
			310	0	0	1	0	0	0	0	0
	$[ts]_{m_n}$	6	311	0	0	1	0	0	0	0	0
			312	0	0	1	0	0	0	0	0
	Delay time between base to depot	200	313	0	0	1	0	0	0	0	0

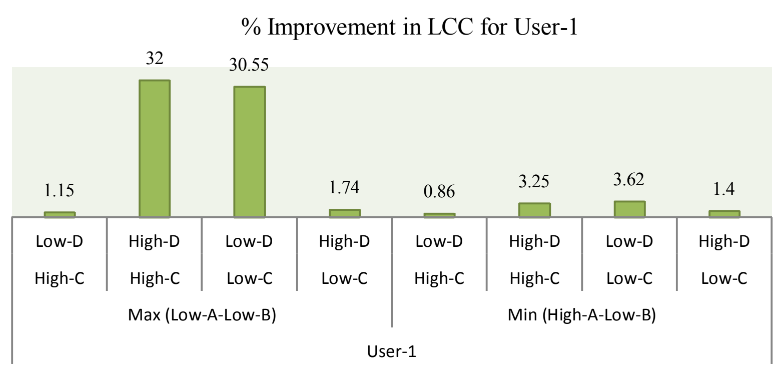
Table 6.11: Values of the different shop floor and quality control parameters

Different shop floor and quality control parameters	Cost of lost production per job of the machines $[C_{lp}]_{m_n}$ (in INR /hr.)		Cost of rejection per job of the machines $[C_{rej.}]_{m_n}$ (in INR /hr.)		Sampling frequency on the machines ts_{m_n}(in hr.)		Sample size on the machines S_{m_n} (in hr.)	
Machines	High	LOW	High	LOW	High	LOW	High	LOW
m_1	10000	500	10000	500	16	8	10	5
m_2	12000	800	11000	700	10	5	12	6
m_3	15000	500	14000	800	12	6	14	7
m_4	9000	300	15000	900	14	7	15	7



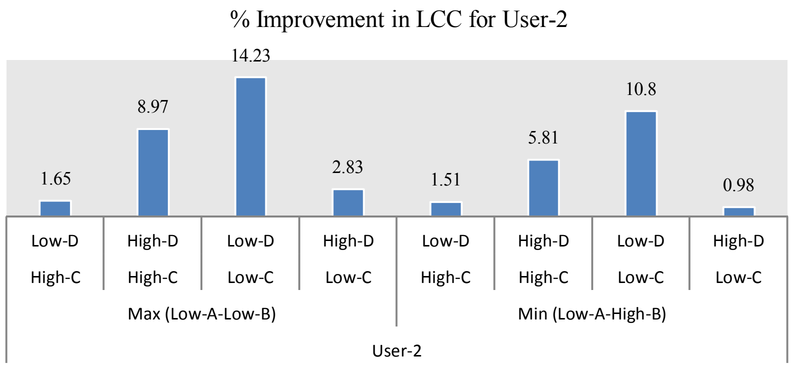
A-Cost of lost production per job of the machines B-Cost of rejection per job of the machines

Figure 6.5: Effect of cost of lost production and cost of rejection on integrated approach for different users



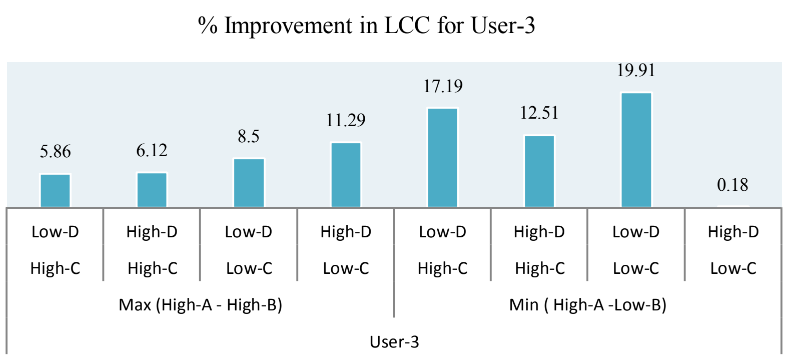
C-Sampling frequency of the machines D-Sample size of the machines

Figure 6.6-a: Effect of quality control paramteres on integrated approach for user-1



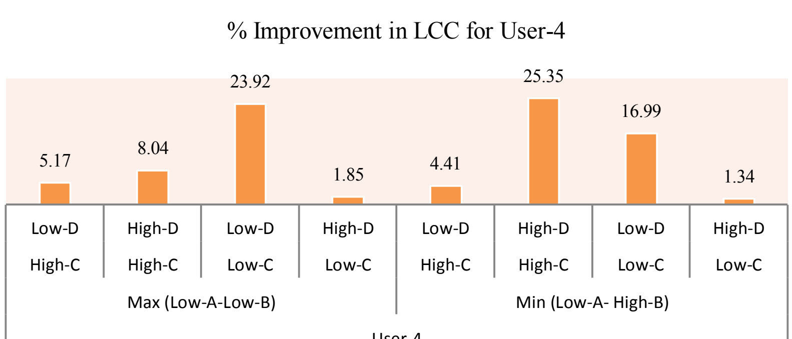
C-Sampling frequency of the machines D-Sample size of the machines

Figure 6.6-b: Effect of quality control paramteres on integrated approach for user-2



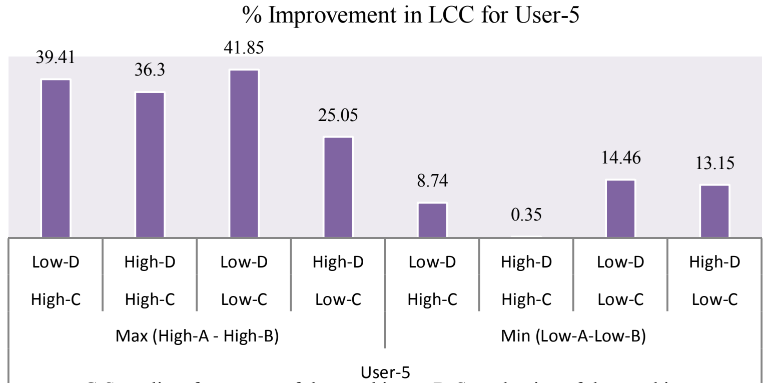
C-Sampling frequency of the machines D-Sample size of the machines

Figure 6.6-c: Effect of quality control paramteres on integrated approach for user-3



C-Sampling frequency of the machines D-Sample size of the machines

Figure 6.6-d: Effect of quality control paramteres on integrated approach for user-4



C-Sampling frequency of the machines D-Sample size of the machines

Figure 6.6-e: Effect of quality control paramteres on integrated approach for user-1

Table 6.12: Highest percentage improvement achieved in LCC

Users	Cost of lost production per job of the machines	Cost of rejection per job of the machines	Sampling frequency on the machines	Sample size on the machines
User-1	Low	Low	Low	Low
User-2	Low	Low	Low	Low
User-3	High	Low	Low	Low
User-4	Low	High	High	High
User-5	High	High	Low	Low

6.8 Summary

This chapter proposes a novel approach for the machine tool maintenance modelling considering the integrated decisions of level of repair and preventive maintenance. An integrated model considers the effect of the user's cost structure on the level of repair and preventive maintenance decisions. Different PM approaches have been applied for the different machine tool users. It also provides a decision making framework to decide which PM strategy will be beneficial to particular machine tool user in the fleet maintenance system. The results of integrated approach shows 0.18 % to 63 % improvements in LCC of the different users compare to dis-integrated approach. The importance of users cost structure and quality control policy parameters is evident from the results. To see the effect of the shop floor and quality control parameters of the different users, different scenarios are evaluated. A numerical example is presented for the different users in a machine tool fleet maintenance system. The parameters and the problem variable used in this numerical illustration are quite generic. This kind of maintenance modelling for the machine tool users is scarcely reported in the existing literature.

Chapter 7
Conclusion

7.1 Summary

The work reported in this thesis is related to the investigation of the value of integrated decision making in fleet system reliability design and maintenance planning. Various approaches are developed for the same. Three aspects of maintenance planning are considered viz., the level of repair analysis, preventive maintenance planning, and spare level of indenture items. Results highlight the importance of integration of these critical aspects in fleet maintenance systems. The chapter wise summary of the research reported in the preceding chapters of this thesis is presented hereunder.

Chapter 1 discusses the research problem in the area of fleet system reliability design and maintenance planning. It presents in details the reliability design and various aspects of fleet maintenance planning viz., level of repair analysis, preventive maintenance optimization, and spare parts optimization. The interdependencies among these decision-making aspects in the fleet system are also discussed. The scope of the research work is highlighted considering the inputs from the literature. The gaps identified from the literature are also mentioned. Overall objective and sub-objectives of the present research are presented.

In **Chapter 2**, focused literature related to reliability design, level of repair analysis, preventive maintenance optimization and multi-indenture spare parts optimization has been reviewed. Literature related to joint consideration of these planning aspects in fleet system is also discussed. The literature review has helped in identifying the overall objective and its sub-objectives for the present work.

In **Chapter 3** a methodology has been developed for joint optimization of the optimal reliability design and level of repair decisions for fleet systems. Detailed models are developed to estimate life cycle cost of fleet maintenance system. These detailed models are useful in the study the effect of user specific parameters on optimal reliability design and level of repair decisions. Life Cycle Cost is classified in two parts viz., non-recurrent cost and recurrent cost. The non-recurrent cost includes the one-time investment required for installing required maintenance facilities at multi-echelon maintenance network. The recurrent cost includes the annual failure, spare holding and stock-out cost. The annual failure cost comprises consumables cost for repair, downtime cost and transportation cost. The methodology has been solved by considering identical machines with a modular assembly. It also considers the multiple bases (i.e. multiple users) with single OEM in a fleet structure, where the base level has only replacement facility for the machine.

The discussed integrated methodology uses the constant failure rate of the components. However, literature findings say that the time-dependent behavior of the system is more realistic to decide the optimal reliability design and level of repair decision for the fleet system. This is scarcely reported in the existing literature. Therefore, the methodology is extended to model time-dependent failure rates of the components in the proposed integrated approach. It also helped to study the effect of restoration achieved during the LOR analysis. Moreover, a more complex fleet system design has been considered with multiple modular assemblies. The effect of modularization and slope of “reliability” vs. “cost of alternatives” curve is also studied.

Some thumb rules have also been suggested in this methodology to ease the decision-making processes in the absences of sufficient data and time. Though the results are not applied to any real-life case, the parameters and problem variables used in this approach are quite generic and representative of any fleet maintenance system. Thus the proposed approach may be adopted by any fleet user or OEM in optimizing the life cycle cost performance.

Chapter 4 addresses a methodology for joint optimization of LOR and spare level in fleet system. A time dependent failure rate models for components are considered in this work. It aims to decide the optimal LOR decisions and optimal number of spares of assembly or module or part in multi-echelon maintenance location. Results highlight that these decision are dependent on the users' cost structure.

In existing literature, due to the constant failure rate assumption, consideration of preventive maintenance policies with level of repair analysis is not addressed. The same is overcome in this research by considering time depended failure rate models. In **Chapter 5**, an integrated strategy has been developed to find out the optimal solution for joint optimization of preventive maintenance schedule and level of repair decisions. The developed integrated PM strategy for the fleet system leads to a better LCC performance compare to conventional approach (dis-integrated approach). The different cases of imperfect preventive maintenance action i.e. 20% Restoration Factor (RF), 30%RF, 40%RF, 50%RF, 60%RF, 70%RF and 80%RF have been applied to the components of fleet system, to see the effect of quality of PM actions on the LOR decisions. The integrated problem has been solved by considering identical machines with multiple modular assemblies. In addition to that, the problem has been solved for single base (i.e. single user) associated with single OEM in a fleet structure, where base level has significant maintenance facility for performing the corrective actions on the fleet system.

In **Chapter 6,** first time in literature, the maintenance planning of machine tools are modeled considering fleet maintenance architecture. The fleet structure used in this chapter has following characteristics:

- Multiple users having different shop floor policy parameters and cost structures
- Non identical machines at each base
- Both modular and non-modular systems
- Multiple OEMs

The machine tool failure is categorized in three Failure Consequences (FCs). Models available in the literature for calculation of cost of failures for different failure consequences are used. Other models are same as used in Chapter 5. In this chapter, an integrated strategy for preventive maintenance planning and level of repair decisions considering the machine tool user's cost structure and shop floor policies parameters are developed. The proposed approach is very useful for the machine tool manufacturers (i.e. OEMs) that are supporting the users through maintenance service contracts.

7.1.1 Outcomes of Various Approaches

A. Joint Optimization of Reliability Design and LOR

A.1 It is concluded that the most reliable design may not always result into best system performance. In other words, lower reliability configuration with appropriate LOR decisions may also give better life cycle performance for the fleet. Therefore, the integration of reliability design and LOR decisions is important at early design stage of fleet maintenance systems.

A.2 The design and LOR decisions are also dependent on user's cost structure. A customized reliability design and customized level of repair decisions is required for each base.

A.3 In the present research detailed LCC models are developed which become very useful in arriving such user specific design and LOR decisions. This will further give an opportunity to perform what if analysis with cost parameters. Users can then work on changing their cost structure to get economic advantages. For example, a user may install some redundant machines or increase spare level etc. to reduce the down time cost of the failure after checking the economic benefits of such changes.

A.4 It is concluded that more modular design leads to better life cycle performance of fleet maintenance system. We expect that this mainly happens because of modularization, as the cost of installing maintenance facilities for discard of module is generally lower than that for discard of enclosed parts of that module creating an opportunity to take LOR decisions on higher indenture item such as selection of discard decision at module level then at enclosed part level. Further, modularization creates an ease of maintenance as it reduces the service time in terms of fault diagnosis, access, and repair.

A.5 Further to the discussion on modularization, it is also found that in case of more modular design, integrated approach leads to a LCC performance level closer to that of most reliable design LCC performance. Therefore, if the alternative designs are more modular and no additional information or data are available for performing integrated design and LOR approach, as a thumb rule, most reliable design alternatives can be selected for the system configuration. However for lesser modular design, optimal design configuration using the integrated approach should be obtained.

A.6 After conducting the sensitivity analysis, it is found that the design and LOR decisions are sensitive only for maintenance facility cost and it is not sensitive to cost of consumables and transportation cost. Therefore, it is recommended that cost of maintenance facility should be captured as accurately as possible before arriving on optimal reliability design and level of repair decisions.

A.7 It is also commented from the results that if the variation in cost of alternatives design of parts are more, then integrated approach is more important. On the other hand if the variation is less, then as a thumb rule designer can go for most reliable design.

A.8 The approach is first evaluated for conventional fleet structure and considering the assumption of constant failure rate for the parts. Later, the same is extended for the case of time dependent failure rates of the parts and for more complex structure in terms of number of assemblies in the machine. The results are consistent with that presented above. However, it gives more realistic view of the problem.

B. Joint Optimization of Level of Repair and Spare Level

B.1 Joint optimization of level of repair and spare level results into better life cycle performance of the fleet. It was observed that this approach is not sensitive to down time cost, but it is sensitive to spare holding cost and transportation cost. It is recommended that spare holding cost and transportation cost should be captured as accurately as possible while optimizing level of repair decisions with spare level.

B.2 It can be seen that the integrated decision of level of repair and spare parts depends on the user's cost structure. The user's cost profile plays an important role to decide these decisions.

B.3 Another important addition to the body of knowledge is the use of time dependent failure rate model for parts failure in a machine. This has further helped in considering effect of Preventive Maintenance (PM) and Restoration Factor (RF) in LOR analysis.

C. Integrated Strategy for Preventive Maintenance and Level of Repair

C.1 The "PM schedule" and "LOR decisions" are interrelated to each other. It is concluded that "integrated strategy" helps in reducing more LCC of the fleet maintenance system as compared to the "dis-integrated strategy". This means the integration of the PM and LOR analysis is beneficial to achieve an economic LCC performance for the fleet users.

C.2 The restoration factor may change the optimal PM schedule and hence needed to be considered while optimizing the LOR decisions.

C.3 There is no specific trend in percentage of improvement in the LCC of fleet maintenance system with respect to Restoration Factors (RF). So one has to consider its specific RF during the modeling.

D. Novel Approach for Machine Tool Fleet Maintenance Planning

D.1 The integrated strategy proposed for the machine tool fleet maintenance planning gives better results than the dis-integrated strategy. We have received significant LCC improvement from 3.63% to 59.22% for different users considering the integrated strategy. The percentage improvement shows the importance of the integration of machine tool PM and LOR. Thus, the proposed integrated strategy gives better LCC performance for different users in machine tool fleet maintenance system.

D.2 The machine tool PM and LOR decisions depends on the user's cost structure and shop floor planning parameters i.e. cost of lost production and rejection per job and quality control parameter i.e. sample size and sampling frequency. By applying the different PM approach (i.e. high, medium and low degree of restorations) for different machine tool users, it is concluded that for machine tool users having a low cost of lost production and rejection per job of their machines, higher restoration during the PM is more beneficial. Whereas machine tool users with a high cost of lost production and rejection per job may go for the less restoration during the PM action. Therefore a degree of restoration plays a significant role to optimize the LOR for machine tool users. However the results are specific for the case considered in this problem.

D.3 A new system for machine tool maintenance planning is provided under the fleet maintenance architecture. This kind of maintenance planning for machine tool maintenance is not reported in the literature.

D.4 It can be seen from this approach that non modular equipment, multiple OEMs, non-identical machines etc. may also be modeled under fleet maintenance architecture.

7.2 Contribution of the Present Research

The work done in this thesis has resulted in numbers of contributions which can be summarized as follow;

- First time an approach is developed that helps in jointly selecting optimal reliability design and level of repair decisions for fleet systems.
- Detailed investigation on the value of joint selection of optimal reliability and level of repair decisions are done.
- Effect of modularity on optimal reliability design and level of repair decisions are studied.
- First time an approach is developed that considers time dependent failure rate of the parts for fleet system reliability design and maintenance planning.
- An integrated approach for level of repair and spare parts optimization considering time depended failure rates of the parts is developed.
- Detailed models to estimate life cycle cost in fleet system reliability design and maintenance planning is developed.
- First time level of repair analysis is evaluated jointly with PM strategies.
- Effect of restoration factor in level of repair analysis is studied.
- First time the maintenance modeling for machine tools are done under fleet system architecture
- The effect of user's cost structure and shop floor level operations planning parameters in level or repair analysis is studied.
- More complex fleet systems architecture in terms of number of bases, number of machines, number of assemblies, number of OEMs, etc., are considered in fleet system maintenance planning.

7.3 Usefulness of the Research Work

The proposed research is very important for OEMs who wants to servicizing their business by providing maintenance service contract to the customers. The research work provides them guidelines to consider optimal reliability design and level of repair at the design stage. The detailed outcome presented in section 7.1.1 is helpful to the OEM as well as users in decision making. The OEM can offer the

Customer Service Agreement (CSA) package to their customers by choosing between the following set of options;

1. Buy the product with optimal reliability design configuration and LOR,
2. Buy the product with LOR and PM only,
3. Buy the product with reliability LOR, PM and Spare level.

Customers may opt one of the above option in the CSA with the OEM. In the first option, OEM is responsible for the reliability design and corrective action only in the CSA. In the second option, users can add the preventive maintenance support also in a CSA. Whereas users can purchase the product with complete maintenance support, which includes the optimal reliability design, LOR, PM and spare level. Therefore, users can customize their CSA considering their budget requirements. OEM can check their profitability while offering these CSA package option with customers and users.

The present research is also defy various one dimensional assumptions of conventional fleet structure like single OEM, single base and identical machine and most importantly constant failure rate of the components. This makes more practical analysis while addressing the system specific issues. The approach applied to machine tool fleet in specific, is very helpful for machine tool users in reducing their life cycle cost by changing their cost parameters and operations policy parameters. It may become more useful for the system operated and maintained under fleet maintenance architecture such as wind turbine, naval ships, railway engines etc.

7.4 Future Scope of the Research Work

The present research work is mainly focused on the investigating the various aspect of fleet maintenance planning. The methodologies developed in this research work are specific for the capital intensive industrial goods, which are operated and maintained in the fleet maintenance architecture. Also, many inputs parameters are assumed in this research based on the some logical relationships present in the values of a specific type of parameter. For example, the "cost of repair" of components is generally more than the "cost of discard", because "repair" action requires some advance inspection facilities equipments (i.e. fault tester and tools etc.) then required for the "discard" action. Additionally, the cost of maintenance facilities also varies from the base level to OEM level. The cost of installing the maintenance facility at the base is normally more than that at the depot and OEM level. Accordingly these parameters are considered. Thus, the results in terms of the decision variable values are fleet specific and applicable for a fleet having parameters values considered in this work. One will have to capture these parameters from the particular fleet to apply the approach presented in this research. The approach is though tested for various values of these parameters. For example, multiple bases in a fleet actually vary mainly in terms of these parameter values only. Different bases having different values for these parameters have shown different improvement over the conventional approach. The results in terms of decision variable selection cannot be generalized. However, the integrated approach always gives better results. The designer may use the proposed approach to examine the value of integration for a specific fleet and may accordingly make various decisions related to reliability design and maintenance planning. The detailed models presented in the present research also help the designer to perform what-if analysis with these parameters to identify the scope of improvement by altering the parameter values, if possible. For example, if the transportation cost from a particular base to depot can be reduced then the same may give improved fleet system performance. The application of the proposed approach to a case of a specify fleet may be important to investigate in future. Following paragraphs highlights the scope for future research.

(1) *System related:* The methodology developed in the chapter 3, 4, 5, and 6 are more relevant to the capital goods. The same may require changes for consumer durable goods such as automobile and household appliances i.e. water purifier system, Air-Conditions (AC), refrigerators, washing machine, inverter etc. Implementation of the proposed research for such systems provides scope of future research. Also the use of various

objective functions for different types of systems may be explored. For example, in case of aircraft fleet mission availability may be important objective criteria. Similarly, in the case of consumer goods, more emphasis is given for the effective consumer's services (service time) and spare parts management may be more important for such case.

Additionally, in the present study, a single central depot is considered in multi-echelon maintenance network. The problem of intermediate depots can be introduced in the multi-echelon maintenance network. The intermediate depots can be useful to improve the availability of the fleet system by sharing the spare and maintenance resources. In the case of intermediate depots, the optimal location of such intermediate depots can be seen as future scope of the present research.

(2) *Maintenance technology:* Only time based preventive maintenance is considered in the present research work. Other types of the maintenance like CBM, RCM, PHM and age based PM, can be implemented in the developed fleet maintenance strategy.

(3) *Stochastic dependency:* In the developed approaches, failures of the components are considered independent. Modelling the stochastic dependency of the fleet system components can be incorporate in the developed fleet approaches.

(4) *Optimization method:* Selecting an optimal fleet maintenance decisions for the multiple system requires to evaluating all the possible combination of fleet maintenance decisions design, LOR, PM and Spares. Computationally, it is a complex problem and complexity depends on number of decision variables in the optimization model. The complexities also increases with increase in number of machines and number of enclosed modular and non-modular indenture items in the machine. Thus, we may require advanced heuristic algorithms and codes to solve such complex problem for fleet maintenance planning. Distributed fleet maintenance planning in line with the fourth industrial revolution may be useful extension for such research to overcome solution complexities.

(5) *Business point of view:* More work can be explored for the Customer Service Agreement (CSA), third party CSA and OEM CSA, etc. In the case of OEM CSA, warranty repair negotiable models can be developed. Moreover, users can incorporate other specific parameters such usage of the system in CSA.

APPENDIX-A

User-1 with PM-I

Table 1: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**900**	0
020	**1**	0	0	0	0	0	0	0	**900**	0
310	**1**	0	0	0	0	0	0	0	**900**	0
301	**1**	0	0	0	0	0	0	0	**1500**	0
302	**1**	0	0	0	0	0	0	0	**600**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**1**
112	0	0	**1**	0	0	0	0	0	**600**	**1**
113	0	0	**1**	0	0	0	0	0	**600**	**1**
114	0	0	**1**	0	0	0	0	0	**600**	**1**
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**1**
122	0	0	**1**	0	0	0	0	0	**600**	**6**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**2**
132	0	**1**	0	0	**1**	0	0	**1**	**300**	0
133	0	**1**	0	0	0	**1**	0	0	**300**	0
134	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**1**
212	0	0	**1**	0	0	0	0	0	**300**	**1**
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	0	**1**	0	**1**	0	0	0	0	**300**	0
221	0	**1**	0	0	**1**	0	0	**1**	**300**	0
222	0	**1**	0	0	**1**	0	0	**1**	**300**	0
223	0	**1**	0	0	0	**1**	0	0	**300**	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**300**	0
201	**1**	0	0	0	0	0	0	0	**3000**	0
202	**1**	0	0	0	0	0	0	0	**3900**	0
203	**1**	0	0	0	0	0	0	0	**2400**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**1**
112	0	0	**1**	0	0	0	0	0	**600**	**1**
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**1**
122	0	0	**1**	0	0	0	0	0	**300**	**1**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	**1**	0	0	0	**1**	0	0	**300**	0
132	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**1**
212	0	**1**	0	0	0	**1**	0	0	**300**	0
213	0	0	**1**	0	0	0	0	0	**300**	**1**
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	0	**1**	0	0	0	0	0	**300**	**2**
222	0	**1**	0	0	**1**	0	0	**1**	**300**	0
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	0	**1**	0	0	0	0	0	**300**	**1**
312	0	0	**1**	0	0	0	0	0	**300**	**1**
320	**1**	0	0	0	0	0	0	0	**600**	0
321	0	0	**1**	0	0	0	0	0	**600**	**2**
322	0	**1**	0	0	**1**	0	0	**1**	**600**	0
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	**1**	0	0	**1**	0	0	**1**	**300**	0
332	0	**1**	0	0	0	**1**	0	0	**300**	0

Table 1-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	1	0	0	0	0	0	0	0	300	0
310	1	0	0	0	0	0	0	0	6300	0
320	1	0	0	0	0	0	0	0	6300	0
110	1	0	0	0	0	0	0	0	300	0
111	0	1	0	0	0	1	0	0	300	0
112	0	0	1	0	0	0	0	0	300	1
113	0	1	0	0	0	1	0	0	300	0
120	0	0	1	0	0	0	0	0	300	1
121	0	0	1	0	0	0	0	0	300	0
122	0	0	1	0	0	0	0	0	300	0
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	0	1	0	0	0	0	0	300	1
133	0	0	1	0	0	0	0	0	300	1
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	0	1	0	0	300	0
212	0	1	0	0	0	1	0	0	300	0
213	0	1	0	0	0	1	0	0	300	0
220	1	0	0	0	0	0	0	0	600	0
221	0	0	1	0	0	0	0	0	600	1
222	0	0	1	0	0	0	0	0	600	1
223	0	0	1	0	0	0	0	0	600	1

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	0	1	0	1	0	0	0	0	300	0
111	0	1	0	0	0	1	0	0	300	0
112	0	1	0	0	1	0	0	1	300	0
113	0	1	0	0	1	0	0	1	300	0
120	0	0	1	0	0	0	0	0	300	1
121	0	0	1	0	0	0	0	0	300	0
122	0	0	1	0	0	0	0	0	300	0
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	0	1	0	0	0	0	0	300	1
133	0	1	0	0	0	1	0	0	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	1	0	0	1	300	0
212	0	0	1	0	0	0	0	0	300	1
213	0	1	0	0	0	1	0	0	300	0
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	1
222	0	0	1	0	0	0	0	0	300	1
223	0	1	0	0	1	0	0	1	300	0
310	1	0	0	0	0	0	0	0	300	0
311	0	0	1	0	0	0	0	0	300	1
312	0	0	1	0	0	0	0	0	300	1
313	0	1	0	0	1	0	0	1	300	0
320	1	0	0	0	0	0	0	0	300	0
321	0	1	0	0	1	0	0	1	300	0
322	0	0	1	0	0	0	0	0	300	1
330	1	0	0	0	0	0	0	0	300	0
331	0	0	1	0	0	0	0	0	300	1
332	0	0	1	0	0	0	0	0	300	1

User-1 with PM-II

Table 2: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**900**	0
020	**1**	0	0	0	0	0	0	0	**900**	0
310	**1**	0	0	0	0	0	0	0	**600**	0
301	0	**1**	0	0	**1**	0	**1**	0	**1200**	0
302	0	**1**	0	0	**1**	0	**1**	0	**300**	0
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	**1**	0	0	0	**1**	0	0	**300**	0
112	0	**1**	0	0	**1**	0	0	**1**	**300**	0
113	0	**1**	0	0	**1**	0	0	**1**	**300**	0
114	0	0	**1**	0	0	0	0	0	**300**	**1**
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**1**
122	0	0	**1**	0	0	0	0	0	**600**	**6**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**2**
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	0	**1**	0	0	0	0	0	**300**	**1**
134	0	0	**1**	0	0	0	0	0	**300**	**1**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	0	**1**	0	0	0	0	0	**300**	**1**
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	**1**	0	0	**1**	**300**	0
222	0	**1**	0	0	0	**1**	0	0	**300**	0
223	0	**1**	0	0	0	**1**	0	0	**300**	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**300**	0
201	**1**	0	0	0	0	0	0	0	**3000**	0
202	**1**	0	0	0	0	0	0	0	**3900**	0
203	**1**	0	0	0	0	0	0	0	**2400**	0
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	0	**1**	0	0	0	0	0	**300**	**1**
112	0	0	**1**	0	0	0	0	0	**300**	**1**
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**1**
122	0	0	**1**	0	0	0	0	0	**300**	**1**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**1**
132	0	0	**1**	0	0	0	0	0	**300**	**1**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	**1**	0	0	**1**	**300**	0
212	0	**1**	0	0	0	**1**	0	0	**300**	0
213	0	0	**1**	0	0	0	0	0	**300**	**1**
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	0	**1**	0	0	**300**	0
222	0	0	**1**	0	0	0	0	0	**300**	**1**
310	**1**	0	0	0	0	0	0	0	**600**	0
311	0	0	**1**	0	0	0	0	0	**600**	**1**
312	0	0	**1**	0	0	0	0	0	**600**	**1**
320	**1**	0	0	0	0	0	0	0	**600**	0
321	0	0	**1**	0	0	0	0	0	**600**	**2**
322	0	0	**1**	0	0	0	0	0	**600**	**1**
330	0	**1**	0	**1**	0	0	0	0	**300**	0
331	0	**1**	0	0	0	**1**	0	0	**300**	0
332	0	**1**	0	0	**1**	0	0	**1**	**300**	0

Table 2-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
330	1	0	0	0	0	0	0	0	300	0
310	1	0	0	0	0	0	0	0	6300	0
320	0	1	0	1	0	0	0	0	6300	0
110	1	0	0	0	0	0	0	0	300	0
111	0	0	1	0	0	0	0	0	300	1
112	0	0	1	0	0	0	0	0	300	1
113	0	1	0	0	0	1	0	0	300	0
120	1	0	0	0	0	0	0	0	300	0
121	0	0	1	0	0	0	0	0	300	1
122	0	0	1	0	0	0	0	0	300	1
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	0	1	0	0	0	0	0	300	1
133	0	0	1	0	0	0	0	0	300	1
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	1	0	0	1	300	0
212	0	1	0	0	0	1	0	0	300	0
213	0	1	0	0	1	0	0	1	300	0
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	1
222	0	1	0	0	0	1	0	0	300	0
223	0	0	1	0	0	0	0	0	300	1

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
110	1	0	0	0	0	0	0	0	300	0
111	0	1	0	0	0	1	0	0	300	0
112	0	1	0	0	0	1	0	0	300	0
113	0	1	0	0	0	1	0	0	300	0
120	0	0	1	0	0	0	0	0	300	1
121	0	0	1	0	0	0	0	0	300	0
122	0	0	1	0	0	0	0	0	300	0
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	1	0	0	0	1	0	0	300	0
133	0	1	0	0	0	1	0	0	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	0	1	0	0	0	0	0	300	1
212	0	0	1	0	0	0	0	0	300	1
213	0	1	0	0	1	0	0	1	300	0
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	1
222	0	1	0	0	0	1	0	0	300	0
223	0	0	1	0	0	0	0	0	300	3
310	1	0	0	0	0	0	0	0	300	0
311	0	1	0	0	0	1	0	0	300	0
312	0	0	1	0	0	0	0	0	300	1
313	0	1	0	0	0	1	0	0	300	0
320	1	0	0	0	0	0	0	0	300	0
321	0	1	0	0	0	1	0	0	300	0
322	0	0	1	0	0	0	0	0	300	1
330	1	0	0	0	0	0	0	0	300	0
331	0	0	1	0	0	0	0	0	300	1
332	0	0	1	0	0	0	0	0	300	1

User-1 with PM-III

Table 3: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**900**	0
020	0	**1**	0	**1**	0	0	0	0	**600**	0
310	**1**	0	0	0	0	0	0	0	**900**	0
301	0	**1**	0	**1**	0	0	0	0	**1500**	0
302	**1**	0	0	0	0	0	0	0	**600**	0
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	0	**1**	0	0	0	0	0	**300**	**1**
112	0	**1**	0	0	**1**	0	0	**1**	**300**	0
113	0	**1**	0	0	**1**	0	0	**1**	**300**	0
114	0	0	**1**	0	0	0	0	0	**300**	**1**
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**1**
122	0	0	**1**	0	0	0	0	0	**600**	**6**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**2**
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	0	**1**	0	0	0	0	0	**300**	**1**
134	0	0	**1**	0	0	0	0	0	**300**	**1**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	0	**1**	0	0	0	0	0	**300**	**1**
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	**1**	0	0	**1**	**300**	0
222	0	**1**	0	0	0	**1**	0	0	**300**	0
223	0	**1**	0	0	**1**	0	0	**1**	**300**	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**300**	0
201	**1**	0	0	0	0	0	0	0	**3000**	0
202	**1**	0	0	0	0	0	0	0	**3900**	0
203	**1**	0	0	0	0	0	0	0	**2400**	0
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	0	**1**	0	0	0	0	0	**300**	**1**
112	0	0	**1**	0	0	0	0	0	**300**	**1**
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**1**
122	0	0	**1**	0	0	0	0	0	**300**	**1**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**1**
132	0	0	**1**	0	0	0	0	0	**300**	**1**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	0	**1**	0	0	0	0	0	**300**	**1**
213	0	0	**1**	0	0	0	0	0	**300**	**1**
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	0	**1**	0	0	0	0	0	**300**	**2**
222	0	0	**1**	0	0	0	0	0	**300**	**1**
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	0	**1**	0	0	0	0	0	**300**	**1**
312	0	0	**1**	0	0	0	0	0	**300**	**1**
320	**1**	0	0	0	0	0	0	0	**300**	0
321	0	0	**1**	0	0	0	0	0	**300**	**1**
322	0	0	**1**	0	0	0	0	0	**300**	**1**
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	**1**	0	0	**1**	0	0	**1**	**300**	0
332	0	**1**	0	0	**1**	0	0	**1**	**300**	0

Table 3-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	1	0	0	0	0	0	0	0	300	0
310	1	0	0	0	0	0	0	0	6300	0
320	0	1	0	1	0	0	0	0	6300	0
110	1	0	0	0	0	0	0	0	300	0
111	0	0	1	0	0	0	0	0	300	1
112	0	0	1	0	0	0	0	0	300	1
113	0	1	0	0	0	1	0	0	300	0
120	1	0	0	0	0	0	0	0	300	0
121	0	0	1	0	0	0	0	0	300	1
122	0	0	1	0	0	0	0	0	300	1
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	0	1	0	0	0	0	0	300	1
133	0	1	0	0	0	1	0	0	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	1	0	0	1	300	0
212	0	1	0	0	0	1	0	0	300	0
213	0	1	0	0	1	0	0	1	300	0
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	1
222	0	1	0	0	0	1	0	0	300	0
223	0	0	1	0	0	0	0	0	300	1

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	1	0	0	0	0	0	0	0	300	0
111	0	1	0	0	1	0	0	1	300	0
112	0	1	0	0	0	1	0	0	300	0
113	0	1	0	0	0	1	0	0	300	0
120	0	0	1	0	0	0	0	0	300	1
121	0	0	1	0	0	0	0	0	300	0
122	0	0	1	0	0	0	0	0	300	0
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	1	0	0	0	1	0	0	300	0
133	0	1	0	0	0	1	0	0	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	0	1	0	0	300	0
212	0	0	1	0	0	0	0	0	300	1
213	0	1	0	0	1	0	0	1	300	0
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	1
222	0	1	0	0	0	1	0	0	300	0
223	0	0	1	0	0	0	0	0	300	3
310	1	0	0	0	0	0	0	0	300	0
311	0	1	0	0	0	1	0	0	300	0
312	0	0	1	0	0	0	0	0	300	1
313	0	1	0	0	0	1	0	0	300	0
320	1	0	0	0	0	0	0	0	300	0
321	0	1	0	0	0	1	0	0	300	0
322	0	0	1	0	0	0	0	0	300	1
330	1	0	0	0	0	0	0	0	600	0
331	0	0	1	0	0	0	0	0	600	1
332	0	0	1	0	0	0	0	0	600	1

User-2 with PM-I

Table 5: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	1	0	0	0	0	0	0	0	900	0
020	1	0	0	0	0	0	0	0	900	0
310	1	0	0	0	0	0	0	0	600	0
301	1	0	0	0	0	0	0	0	1500	0
302	1	0	0	0	0	0	0	0	600	0
110	1	0	0	0	0	0	0	0	300	0
111	0	0	1	0	0	0	0	0	300	1
112	0	1	0	0	0	1	0	0	300	0
113	0	0	1	0	0	0	0	0	300	1
114	0	0	1	0	0	0	0	0	300	1
120	1	0	0	0	0	0	0	0	600	0
121	0	0	1	0	0	0	0	0	600	2
122	0	0	1	0	0	0	0	0	600	8
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	3
132	0	0	1	0	0	0	0	0	300	1
133	0	0	1	0	0	0	0	0	300	1
134	0	0	1	0	0	0	0	0	300	2
210	1	0	0	0	0	0	0	0	300	0
211	0	0	1	0	0	0	0	0	300	2
212	0	1	0	0	0	1	0	0	300	0
213	0	0	1	0	0	0	0	0	300	1
220	1	0	0	0	0	0	0	0	300	0
221	0	1	0	0	0	1	0	0	300	0
222	0	1	0	0	1	0	0	1	300	0
223	0	1	0	0	0	1	0	0	300	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	1	0	0	0	0	0	0	0	300	0
201	1	0	0	0	0	0	0	0	3000	0
202	1	0	0	0	0	0	0	0	3900	0
203	1	0	0	0	0	0	0	0	2400	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	1
112	0	0	1	0	0	0	0	0	600	1
120	1	0	0	0	0	0	0	0	300	0
121	0	0	1	0	0	0	0	0	300	2
122	0	0	1	0	0	0	0	0	300	1
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	0	1	0	0	0	0	0	300	2
210	1	0	0	0	0	0	0	0	300	0
211	0	0	1	0	0	0	0	0	300	2
212	0	1	0	0	1	0	0	1	300	0
213	0	1	0	0	0	1	0	0	300	0
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	3
222	0	1	0	0	0	1	0	0	300	0
310	1	0	0	0	0	0	0	0	300	0
311	0	0	1	0	0	0	0	0	300	1
312	0	1	0	0	1	0	0	1	300	0
320	1	0	0	0	0	0	0	0	600	0
321	0	0	1	0	0	0	0	0	600	2
322	0	0	1	0	0	0	0	0	600	1
330	0	1	0	0	1	0	1	0	300	0
331	0	1	0	0	1	0	0	1	300	0
332	0	1	0	0	1	0	0	1	300	0

Table 5-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	**1**	0	0	0	0	0	0	0	**300**	0
310	**1**	0	0	0	0	0	0	0	**6300**	0
320	**1**	0	0	0	0	0	0	0	**6300**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**2**
112	0	0	**1**	0	0	0	0	0	**600**	**1**
113	0	0	**1**	0	0	0	0	0	**600**	**1**
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**2**
122	0	0	**1**	0	0	0	0	0	**600**	**2**
130	**1**	0	0	0	0	0	0	0	**600**	0
131	0	0	**1**	0	0	0	0	0	**600**	**2**
132	0	0	**1**	0	0	0	0	0	**600**	**1**
133	0	0	**1**	0	0	0	0	0	**600**	**1**
210	0	**1**	0	0	**1**	0	**1**	0	**300**	0
211	0	**1**	0	0	**1**	0	0	**1**	**300**	0
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	**1**	0	0	**1**	0	0	**1**	**300**	0
220	**1**	0	0	0	0	0	0	0	**600**	0
221	0	0	**1**	0	0	0	0	0	**600**	**2**
222	0	0	**1**	0	0	0	0	0	**600**	**2**
223	0	0	**1**	0	0	0	0	0	**600**	**1**

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	**1**	0	0	0	**1**	0	0	**300**	0
112	0	**1**	0	0	**1**	0	0	**1**	**300**	0
113	0	**1**	0	0	0	**1**	0	0	**300**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**1**
122	0	0	**1**	0	0	0	0	0	**300**	**1**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	**1**	0	0	0	**1**	0	0	**300**	0
132	0	**1**	0	0	0	**1**	0	0	**300**	0
133	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**600**	0
211	0	0	**1**	0	0	0	0	0	**600**	**3**
212	0	0	**1**	0	0	0	0	0	**600**	**1**
213	0	**1**	0	0	0	**1**	0	0	**600**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	0	**1**	0	0	0	0	0	**300**	**1**
222	0	0	**1**	0	0	0	0	0	**300**	**1**
223	0	0	**1**	0	0	0	0	0	**300**	**5**
310	**1**	0	0	0	0	0	0	0	**600**	0
311	0	0	**1**	0	0	0	0	0	**600**	**1**
312	0	0	**1**	0	0	0	0	0	**600**	**2**
313	0	0	**1**	0	0	0	0	0	**600**	**2**
320	**1**	0	0	0	0	0	0	0	**300**	0
321	0	**1**	0	0	**1**	0	0	**1**	**300**	0
322	0	0	**1**	0	0	0	0	0	**300**	**2**
330	**1**	0	0	0	0	0	0	0	**600**	0
331	0	**1**	0	0	0	**1**	0	0	**600**	0
332	0	0	**1**	0	0	0	0	0	**600**	**1**

User-2 with PM-II

Table 6: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**900**	0
020	**1**	0	0	0	0	0	0	0	**900**	0
310	**1**	0	0	0	0	0	0	0	**1500**	0
301	**1**	0	0	0	0	0	0	0	**1800**	0
302	**1**	0	0	0	0	0	0	0	**900**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**1**
112	0	**1**	0	0	0	**1**	0	0	**600**	0
113	0	0	**1**	0	0	0	0	0	**600**	**1**
114	0	0	**1**	0	0	0	0	0	**600**	**1**
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**2**
122	0	0	**1**	0	0	0	0	0	**600**	**8**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**3**
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	0	**1**	0	0	0	0	0	**300**	**1**
134	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	**1**	0	0	**1**	**300**	0
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	0	**1**	0	0	0	0	0	**300**	**1**
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	**1**	0	0	**1**	**300**	0
222	0	**1**	0	0	0	**1**	0	0	**300**	0
223	0	**1**	0	0	0	**1**	0	0	**300**	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**300**	0
201	**1**	0	0	0	0	0	0	0	**3000**	0
202	**1**	0	0	0	0	0	0	0	**3900**	0
203	**1**	0	0	0	0	0	0	0	**2400**	0
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	0	**1**	0	0	0	0	0	**300**	**1**
112	0	**1**	0	0	0	**1**	0	0	**300**	0
120	0	0	**1**	0	0	0	0	0	**300**	**2**
121	0	0	**1**	0	0	0	0	0	**300**	0
122	0	0	**1**	0	0	0	0	0	**300**	0
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**1**
132	0	0	**1**	0	0	0	0	0	**300**	**2**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	**1**	0	0	**1**	**300**	0
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	**1**	0	0	**1**	**300**	0
222	0	0	**1**	0	0	0	0	0	**300**	**2**
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	**1**	0	0	0	**1**	0	0	**300**	0
312	0	0	**1**	0	0	0	0	0	**300**	**1**
320	0	0	**1**	0	0	0	0	0	**600**	**2**
321	0	0	**1**	0	0	0	0	0	**600**	0
322	0	0	**1**	0	0	0	0	0	**600**	0
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	**1**	0	0	0	**1**	0	0	**300**	0
332	0	**1**	0	0	0	**1**	0	0	**300**	0

Table 6-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1) Repair $L_{1,1}(ijk)$	Base (e=1) Move $L_{2,1}(ijk)$	Base (e=1) Discard $L_{3,1}(ijk)$	Depot (e=2) Repair $L_{1,2}(ijk)$	Depot (e=2) Move $L_{2,2}(ijk)$	Depot (e=2) Discard $L_{3,2}(ijk)$	OEM (e=3) Repair $L_{1,3}(ijk)$	OEM (e=3) Discard $L_{3,3}(ijk)$	Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL Q(ijk)
330	1	0	0	0	0	0	0	0	300	0
310	1	0	0	0	0	0	0	0	6300	0
320	1	0	0	0	0	0	0	0	6300	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	1
112	0	0	1	0	0	0	0	0	600	1
113	0	0	1	0	0	0	0	0	600	1
120	1	0	0	0	0	0	0	0	600	0
121	0	0	1	0	0	0	0	0	600	2
122	0	0	1	0	0	0	0	0	600	2
130	1	0	0	0	0	0	0	0	600	0
131	0	0	1	0	0	0	0	0	600	2
132	0	0	1	0	0	0	0	0	600	1
133	0	1	0	0	0	1	0	0	600	0
210	0	1	0	0	0	1	0	0	600	0
211	0	1	0	0	0	1	0	0	600	0
212	0	1	0	0	0	1	0	0	600	0
213	0	1	0	0	0	1	0	0	600	0
220	0	0	1	0	0	0	0	0	600	2
221	0	0	1	0	0	0	0	0	600	0
222	0	0	1	0	0	0	0	0	600	0
223	0	0	1	0	0	0	0	0	600	0

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1) Repair $L_{1,1}(ijk)$	Base (e=1) Move $L_{2,1}(ijk)$	Base (e=1) Discard $L_{3,1}(ijk)$	Depot (e=2) Repair $L_{1,2}(ijk)$	Depot (e=2) Move $L_{2,2}(ijk)$	Depot (e=2) Discard $L_{3,2}(ijk)$	OEM (e=3) Repair $L_{1,3}(ijk)$	OEM (e=3) Discard $L_{3,3}(ijk)$	Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL Q(ijk)
110	1	0	0	0	0	0	0	0	300	0
111	0	1	0	0	0	1	0	0	300	0
112	0	1	0	0	1	0	0	1	300	0
113	0	1	0	0	0	1	0	0	300	0
120	1	0	0	0	0	0	0	0	300	0
121	0	0	1	0	0	0	0	0	300	1
122	0	0	1	0	0	0	0	0	300	1
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	1	0	0	0	1	0	0	300	0
133	0	1	0	0	0	1	0	0	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	0	1	0	0	300	0
212	0	0	1	0	0	0	0	0	300	1
213	0	1	0	0	0	1	0	0	300	0
220	1	0	0	0	0	0	0	0	300	0
221	0	1	0	0	0	1	0	0	300	0
222	0	0	1	0	0	0	0	0	300	1
223	0	1	0	0	0	1	0	0	300	0
310	1	0	0	0	0	0	0	0	600	0
311	0	0	1	0	0	0	0	0	600	1
312	0	1	0	0	0	1	0	0	600	0
313	0	0	1	0	0	0	0	0	600	2
320	1	0	0	0	0	0	0	0	600	0
321	0	1	0	0	0	1	0	0	600	0
322	0	0	1	0	0	0	0	0	600	3
330	0	1	0	1	0	0	0	0	600	0
331	0	1	0	0	0	1	0	0	600	0
332	0	1	0	0	0	1	0	0	600	0

User-2 with PM-III

Table 7: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**900**	0
020	**1**	0	0	0	0	0	0	0	**600**	0
310	**1**	0	0	0	0	0	0	0	**600**	0
301	**1**	0	0	0	0	0	0	0	**1800**	0
302	**1**	0	0	0	0	0	0	0	**900**	0
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	0	**1**	0	0	0	0	0	**300**	**1**
112	0	**1**	0	0	0	**1**	0	0	**300**	0
113	0	0	**1**	0	0	0	0	0	**300**	**1**
114	0	0	**1**	0	0	0	0	0	**300**	**1**
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**2**
122	0	0	**1**	0	0	0	0	0	**600**	**8**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**3**
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	0	**1**	0	0	0	0	0	**300**	**1**
134	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	**1**	0	0	**1**	**300**	0
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	0	**1**	0	0	0	0	0	**300**	**1**
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	**1**	0	0	**1**	**300**	0
222	0	**1**	0	0	0	**1**	0	0	**300**	0
223	0	**1**	0	0	0	**1**	0	0	**300**	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**300**	0
201	**1**	0	0	0	0	0	0	0	**3000**	0
202	**1**	0	0	0	0	0	0	0	**3900**	0
203	**1**	0	0	0	0	0	0	0	**2400**	0
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	0	**1**	0	0	0	0	0	**300**	**1**
112	0	**1**	0	0	0	**1**	0	0	**300**	0
120	0	0	**1**	0	0	0	0	0	**300**	**1**
121	0	0	**1**	0	0	0	0	0	**300**	0
122	0	0	**1**	0	0	0	0	0	**300**	0
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**1**
132	0	0	**1**	0	0	0	0	0	**300**	**2**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	**1**	0	0	**1**	**300**	0
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	**1**	0	0	**1**	**300**	0
222	0	0	**1**	0	0	0	0	0	**300**	**1**
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	**1**	0	0	0	1	0	0	**300**	0
312	0	0	**1**	0	0	0	0	0	**300**	**1**
320	0	**1**	0	0	0	**1**	0	0	**300**	0
321	0	**1**	0	0	0	**1**	0	0	**300**	0
322	0	**1**	0	0	0	**1**	0	0	**300**	0
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	**1**	0	0	0	**1**	0	0	**300**	0
332	0	**1**	0	0	0	**1**	0	0	**300**	0

Table 7-a : Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
330	**1**	0	0	0	0	0	0	0	**300**	0
310	**1**	0	0	0	0	0	0	0	**6300**	0
320	**1**	0	0	0	0	0	0	0	**6300**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**1**
112	0	0	**1**	0	0	0	0	0	**600**	**1**
113	0	0	**1**	0	0	0	0	0	**600**	**1**
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**1**
122	0	0	**1**	0	0	0	0	0	**600**	**2**
130	**1**	0	0	0	0	0	0	0	**600**	0
131	0	0	**1**	0	0	0	0	0	**600**	**2**
132	0	0	**1**	0	0	0	0	0	**600**	**1**
133	0	**1**	0	0	0	**1**	0	0	**600**	0
210	**1**	0	0	0	0	0	0	0	**600**	0
211	0	**1**	0	0	0	**1**	0	0	**600**	0
212	0	**1**	0	0	**1**	0	0	**1**	**600**	0
213	0	**1**	0	0	0	**1**	0	0	**600**	0
220	0	0	**1**	0	0	0	0	0	**600**	**2**
221	0	0	**1**	0	0	0	0	0	**600**	0
222	0	0	**1**	0	0	0	0	0	**600**	0
223	0	0	**1**	0	0	0	0	0	**600**	0

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	**1**	0	0	0	**1**	0	0	**600**	0
112	0	**1**	0	0	**1**	0	0	**1**	**600**	0
113	0	**1**	0	0	0	**1**	0	0	**600**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**1**
122	0	0	**1**	0	0	0	0	0	**300**	**1**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**1**
132	0	**1**	0	0	0	**1**	0	0	**300**	0
133	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	0	**1**	0	0	0	0	0	**300**	**1**
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	0	**1**	0	0	**300**	0
222	0	0	**1**	0	0	0	0	0	**300**	**1**
223	0	**1**	0	0	0	**1**	0	0	**300**	0
310	**1**	0	0	0	0	0	0	0	**600**	0
311	0	0	**1**	0	0	0	0	0	**600**	**1**
312	0	**1**	0	0	0	**1**	0	0	**600**	0
313	0	0	**1**	0	0	0	0	0	**600**	**2**
320	**1**	0	0	0	0	0	0	0	**600**	0
321	0	**1**	0	0	0	**1**	0	0	**600**	0
322	0	0	**1**	0	0	0	0	0	**600**	**3**
330	0	**1**	0	**1**	0	0	0	0	**600**	0
331	0	**1**	0	0	0	**1**	0	0	**600**	0
332	0	**1**	0	0	0	**1**	0	0	**600**	0

User-3 with PM-I

Table 9: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**1200**	0
020	**1**	0	0	0	0	0	0	0	**900**	0
310	**1**	0	0	0	0	0	0	0	**900**	0
301	**1**	0	0	0	0	0	0	0	**1800**	0
302	**1**	0	0	0	0	0	0	0	**900**	0
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	0	**1**	0	0	0	0	0	**300**	0
112	0	**1**	0	0	0	**1**	0	0	**300**	0
113	0	**1**	0	0	0	**1**	0	0	**300**	0
114	0	**1**	0	0	0	**1**	0	0	**300**	0
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**2**
122	0	0	**1**	0	0	0	0	0	**600**	0
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**4**
132	0	0	**1**	0	0	0	0	0	**300**	0
133	0	0	**1**	0	0	0	0	0	**300**	0
134	0	0	**1**	0	0	0	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	0	**1**	0	0	0	0	0	**300**	0
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	0	**1**	0	**1**	0	0	0	0	**300**	0
221	0	**1**	0	0	0	**1**	0	0	**300**	0
222	0	**1**	0	0	0	**1**	0	0	**300**	0
223	0	**1**	0	0	**1**	0	0	**1**	**300**	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**300**	0
201	**1**	0	0	0	0	0	0	0	**3000**	0
202	**1**	0	0	0	0	0	0	0	**3900**	0
203	**1**	0	0	0	0	0	0	0	**2400**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	0
112	0	0	**1**	0	0	0	0	0	**600**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	0
122	0	0	**1**	0	0	0	0	0	**300**	0
130	0	0	**1**	0	0	0	0	0	**600**	0
131	0	0	**1**	0	0	0	0	0	**600**	0
132	0	0	**1**	0	0	0	0	0	**600**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	0	**1**	0	0	0	0	0	**300**	0
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	0	**1**	0	0	0	0	0	**300**	**4**
222	0	**1**	0	0	**1**	0	0	**1**	**300**	0
310	**1**	0	0	0	0	0	0	0	**900**	0
311	0	0	**1**	0	0	0	0	0	**900**	**2**
312	0	0	**1**	0	0	0	0	0	**900**	0
320	**1**	0	0	0	0	0	0	0	**600**	0
321	0	0	**1**	0	0	0	0	0	**600**	**3**
322	0	**1**	0	0	0	**1**	0	0	**600**	0
330	0	**1**	0	**1**	0	0	0	0	**300**	0
331	0	**1**	0	0	**1**	0	0	**1**	**300**	0
332	0	**1**	0	0	0	**1**	0	0	**300**	0

Table 9-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	0	**1**	0	**1**	0	0	0	0	**300**	0
310	0	**1**	0	0	**1**	0	**1**	0	**6300**	0
320	**1**	0	0	0	0	0	0	0	**6300**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	0
112	0	0	**1**	0	0	0	0	0	**600**	0
113	0	0	**1**	0	0	0	0	0	**600**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**2**
122	0	0	**1**	0	0	0	0	0	**300**	0
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**2**
132	0	**1**	0	0	0	**1**	0	0	**300**	0
133	0	0	**1**	0	0	0	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	**1**	0	0	0	**1**	0	0	**300**	0
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	0	**1**	0	0	0	0	0	**300**	**2**
222	0	**1**	0	0	**1**	0	0	**1**	**300**	0
223	0	**1**	0	0	0	**1**	0	0	**300**	0

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	**1**	0	0	**1**	0	0	**1**	**300**	0
112	0	**1**	0	0	0	**1**	0	0	**300**	0
113	0	**1**	0	0	0	**1**	0	0	**300**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	0
122	0	0	**1**	0	0	0	0	0	**300**	0
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**1**
132	0	0	**1**	0	0	0	0	0	**300**	0
133	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**2**
212	0	0	**1**	0	0	0	0	0	**300**	0
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	0	**1**	0	0	0	0	0	**300**	**1**
222	0	**1**	0	0	0	**1**	0	0	**300**	0
223	0	**1**	0	0	**1**	0	0	**1**	**300**	0
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	0	**1**	0	0	0	0	0	**300**	**1**
312	0	**1**	0	0	0	**1**	0	0	**300**	0
313	0	0	**1**	0	0	0	0	0	**300**	0
320	**1**	0	0	0	0	0	0	0	**300**	0
321	0	**1**	0	0	**1**	0	0	**1**	**300**	0
322	0	0	**1**	0	0	0	0	0	**300**	0
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	0	**1**	0	0	0	0	0	**300**	**1**
332	0	0	**1**	0	0	0	0	0	**300**	0

User-3 with PM-II

Table 10: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	0	**1**	0	0	**1**	0	**1**	0	**300**	0
020	0	**1**	0	0	**1**	0	**1**	0	**600**	0
310	**1**	0	0	0	0	0	0	0	**600**	0
301	**1**	0	0	0	0	0	0	0	**1800**	0
302	**1**	0	0	0	0	0	0	0	**900**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**1**
112	0	0	**1**	0	0	0	0	0	**600**	**2**
113	0	**1**	0	0	**1**	0	0	**1**	**600**	0
114	0	**1**	0	0	0	**1**	0	0	**600**	0
120	0	0	**1**	0	0	0	0	0	**300**	**2**
121	0	0	**1**	0	0	0	0	0	**300**	0
122	0	0	**1**	0	0	0	0	0	**300**	0
130	0	0	**1**	0	0	0	0	0	**300**	**3**
131	0	0	**1**	0	0	0	0	0	**300**	0
132	0	0	**1**	0	0	0	0	0	**300**	0
133	0	0	**1**	0	0	0	0	0	**300**	0
134	0	0	**1**	0	0	0	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	**1**	0	0	0	**1**	0	0	**300**	0
213	0	**1**	0	0	**1**	0	0	**1**	**300**	0
220	0	**1**	0	0	0	**1**	0	0	**300**	0
221	0	**1**	0	0	0	**1**	0	0	**300**	0
222	0	**1**	0	0	0	**1**	0	0	**300**	0
223	0	**1**	0	0	0	**1**	0	0	**300**	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**300**	0
201	0	**1**	0	0	**1**	0	**1**	0	**3000**	0
202	**1**	0	0	0	0	0	0	0	**3900**	0
203	**1**	0	0	0	0	0	0	0	**2400**	0
110	**1**	0	0	0	0	0	0	0	**900**	0
111	0	0	**1**	0	0	0	0	0	**900**	**2**
112	0	0	**1**	0	0	0	0	0	**900**	**1**
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**2**
122	0	0	**1**	0	0	0	0	0	**300**	**1**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	**1**	0	0	0	**1**	0	0	**300**	0
132	0	0	**1**	0	0	0	0	0	**300**	**2**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	**1**	0	0	**1**	**300**	0
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	0	**1**	0	0	0	0	0	**300**	**1**
220	0	0	**1**	0	0	0	0	0	**300**	**3**
221	0	0	**1**	0	0	0	0	0	**300**	0
222	0	0	**1**	0	0	0	0	0	**300**	0
310	**1**	0	0	0	0	0	0	0	**600**	0
311	0	**1**	0	0	0	**1**	0	0	**600**	0
312	0	0	**1**	0	0	0	0	0	**600**	**1**
320	0	0	**1**	0	0	0	0	0	**900**	**3**
321	0	0	**1**	0	0	0	0	0	**900**	0
322	0	0	**1**	0	0	0	0	0	**900**	0
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	**1**	0	0	0	**1**	0	0	**300**	0
332	0	**1**	0	0	0	**1**	0	0	**300**	0

Table 10-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	**1**	0	0	0	0	0	0	0	**300**	0
310	**1**	0	0	0	0	0	0	0	**6300**	0
320	**1**	0	0	0	0	0	0	0	**6300**	0
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	0	**1**	0	0	0	0	0	**300**	**1**
112	0	0	**1**	0	0	0	0	0	**300**	**1**
113	0	**1**	0	0	0	**1**	0	0	**300**	0
120	0	0	**1**	0	0	0	0	0	**300**	**2**
121	0	0	**1**	0	0	0	0	0	**300**	0
122	0	0	**1**	0	0	0	0	0	**300**	0
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	**1**	0	0	**1**	0	0	**1**	**300**	0
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	0	**1**	0	0	0	0	0	**300**	**1**
210	0	**1**	0	**1**	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	0	**1**	0	0	0	0	0	**300**	**2**
222	0	**1**	0	0	0	**1**	0	0	**300**	0
223	0	0	**1**	0	0	0	0	0	**300**	**1**

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	**1**	0	0	**1**	0	0	**1**	**300**	0
112	0	**1**	0	0	**1**	0	0	**1**	**300**	0
113	0	**1**	0	0	0	**1**	0	0	**300**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**1**
122	0	0	**1**	0	0	0	0	0	**300**	**2**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**1**
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**2**
212	0	**1**	0	0	0	**1**	0	0	**300**	0
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	0	**1**	0	0	**300**	0
222	0	**1**	0	0	0	**1**	0	0	**300**	0
223	0	0	**1**	0	0	0	0	0	**300**	**5**
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	0	**1**	0	0	0	0	0	**300**	**1**
312	0	0	**1**	0	0	0	0	0	**300**	**1**
313	0	0	**1**	0	0	0	0	0	**300**	**2**
320	**1**	0	0	0	0	0	0	0	**300**	0
321	0	**1**	0	0	**1**	0	0	**1**	**300**	0
322	0	0	**1**	0	0	0	0	0	**300**	**3**
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	0	**1**	0	0	0	0	0	**300**	**1**
332	0	**1**	0	0	0	**1**	0	0	**300**	0

User-3 with PM-III

Table 11: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	1	0	0	0	0	0	0	0	900	0
020	1	0	0	0	0	0	0	0	1200	0
310	1	0	0	0	0	0	0	0	900	0
301	1	0	0	0	0	0	0	0	1800	0
302	1	0	0	0	0	0	0	0	900	0
110	1	0	0	0	0	0	0	0	300	0
111	0	0	1	0	0	0	0	0	300	1
112	0	1	0	0	0	1	0	0	300	2
113	0	1	0	0	0	1	0	0	300	1
114	0	1	0	0	0	1	0	0	300	0
120	1	0	0	0	0	0	0	0	600	2
121	0	0	1	0	0	0	0	0	600	0
122	0	0	1	0	0	0	0	0	600	0
130	0	0	1	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	0
132	0	0	1	0	0	0	0	0	300	1
133	0	0	1	0	0	0	0	0	300	1
134	0	0	1	0	0	0	0	0	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	0	1	0	0	300	0
212	0	0	1	0	0	0	0	0	300	0
213	0	1	0	0	0	1	0	0	300	1
220	0	1	0	0	0	1	0	0	300	0
221	0	1	0	0	0	1	0	0	300	0
222	0	1	0	0	0	1	0	0	300	0
223	0	1	0	0	0	1	0	0	300	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	1	0	0	0	0	0	0	0	300	0
201	1	0	0	0	0	0	0	0	3000	0
202	1	0	0	0	0	0	0	0	3900	0
203	1	0	0	0	0	0	0	0	2400	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	0
112	0	0	1	0	0	0	0	0	600	1
120	1	0	0	0	0	0	0	0	300	2
121	0	0	1	0	0	0	0	0	300	0
122	0	0	1	0	0	0	0	0	300	0
130	1	0	0	0	0	0	0	0	300	2
131	0	1	0	0	0	1	0	0	300	0
132	0	0	1	0	0	0	0	0	300	0
210	1	0	0	0	0	0	0	0	300	2
211	0	1	0	0	1	0	0	1	300	0
212	0	0	1	0	0	0	0	0	300	0
213	0	0	1	0	0	0	0	0	300	0
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	0
222	0	1	0	0	1	0	0	1	300	0
310	1	0	0	0	0	0	0	0	600	0
311	0	0	1	0	0	0	0	0	600	1
312	0	0	1	0	0	0	0	0	600	0
320	1	0	0	0	0	0	0	0	300	0
321	0	1	0	0	0	1	0	0	300	2
322	0	0	1	0	0	0	0	0	300	2
330	0	1	0	0	1	0	0	1	300	0
331	0	1	0	0	1	0	0	1	300	0
332	0	1	0	0	1	0	0	1	300	0

Table 11-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	0	1	0	1	0	0	0	0	300	0
310	1	0	0	0	0	0	0	0	6300	0
320	1	0	0	0	0	0	0	0	6300	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	1
112	0	0	1	0	0	0	0	0	600	1
113	0	0	1	0	0	0	0	0	600	1
120	1	0	0	0	0	0	0	0	300	0
121	0	0	1	0	0	0	0	0	300	1
122	0	0	1	0	0	0	0	0	300	1
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	0
132	0	0	1	0	0	0	0	0	300	1
133	0	0	1	0	0	0	0	0	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	0	1	0	0	300	0
212	0	1	0	0	0	1	0	0	300	0
213	0	1	0	0	1	0	0	1	300	0
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	0
222	0	1	0	0	0	1	0	0	300	0
223	0	1	0	0	0	1	0	0	300	0

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	0	1	0	1	0	0	0	0	600	0
111	0	1	0	0	0	1	0	0	600	0
112	0	1	0	0	1	0	0	1	600	0
113	0	1	0	0	0	1	0	0	600	0
120	1	0	0	0	0	0	0	0	300	2
121	0	0	1	0	0	0	0	0	300	0
122	0	0	1	0	0	0	0	0	300	0
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	0
132	0	0	1	0	0	0	0	0	300	0
133	0	1	0	0	0	1	0	0	300	0
210	0	0	1	0	0	0	0	0	900	0
211	0	0	1	0	0	0	0	0	900	2
212	0	0	1	0	0	0	0	0	900	0
213	0	0	1	0	0	0	0	0	900	1
220	0	0	1	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	1
222	0	0	1	0	0	0	0	0	300	0
223	0	0	1	0	0	0	0	0	300	4
310	1	0	0	0	0	0	0	0	300	0
311	0	0	1	0	0	0	0	0	300	0
312	0	0	1	0	0	0	0	0	300	1
313	0	0	1	0	0	0	0	0	300	0
320	1	0	0	0	0	0	0	0	300	0
321	0	1	0	0	1	0	0	1	300	2
322	0	0	1	0	0	0	0	0	300	3
330	1	0	0	0	0	0	0	0	300	0
331	0	0	1	0	0	0	0	0	300	1
332	0	1	0	0	1	0	0	1	300	0

User-4 with PM-I

Table 13: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**900**	0
020	**1**	0	0	0	0	0	0	0	**900**	0
310	**1**	0	0	0	0	0	0	0	**600**	0
301	**1**	0	0	0	0	0	0	0	**1500**	0
302	**1**	0	0	0	0	0	0	0	**600**	0
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	0	**1**	0	0	0	0	0	**300**	**1**
112	0	0	**1**	0	0	0	0	0	**300**	**3**
113	0	0	**1**	0	0	0	0	0	**300**	**1**
114	0	**1**	0	0	0	**1**	0	0	**300**	0
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**3**
122	0	0	**1**	0	0	0	0	0	**600**	**7**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**4**
132	0	0	**1**	0	0	0	0	0	**300**	**2**
133	0	0	**1**	0	0	0	0	0	**300**	**1**
134	0	0	**1**	0	0	0	0	0	**300**	**3**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**3**
212	0	0	**1**	0	0	0	0	0	**300**	**3**
213	0	0	**1**	0	0	0	0	0	**300**	**1**
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	0	**1**	0	0	**300**	0
222	0	**1**	0	0	0	**1**	0	0	**300**	0
223	0	**1**	0	0	0	**1**	0	0	**300**	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**300**	0
201	**1**	0	0	0	0	0	0	0	**3000**	0
202	**1**	0	0	0	0	0	0	0	**3900**	0
203	**1**	0	0	0	0	0	0	0	**2400**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**2**
112	0	0	**1**	0	0	0	0	0	**600**	**1**
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**2**
122	0	0	**1**	0	0	0	0	0	**300**	**2**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**2**
132	0	0	**1**	0	0	0	0	0	**300**	**3**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**2**
212	0	0	**1**	0	0	0	0	0	**300**	**2**
213	0	0	**1**	0	0	0	0	0	**300**	**1**
220	**1**	0	0	0	0	0	0	0	**600**	0
221	0	0	**1**	0	0	0	0	0	**600**	**4**
222	0	0	**1**	0	0	0	0	0	**600**	**3**
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	0	**1**	0	0	0	0	0	**300**	**1**
312	0	**1**	0	0	0	**1**	0	0	**300**	0
320	**1**	0	0	0	0	0	0	0	**600**	0
321	0	0	**1**	0	0	0	0	0	**600**	**3**
322	0	**1**	0	0	0	**1**	0	0	**600**	0
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	**1**	0	0	**1**	0	0	**1**	**300**	0
332	0	**1**	0	0	0	**1**	0	0	**300**	0

Table 13-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	**1**	0	0	0	0	0	0	0	**300**	0
310	**1**	0	0	0	0	0	0	0	**6300**	0
320	**1**	0	0	0	0	0	0	0	**6300**	0
110	0	0	**1**	0	0	0	0	0	**600**	**2**
111	0	0	**1**	0	0	0	0	0	**600**	0
112	0	0	**1**	0	0	0	0	0	**600**	0
113	0	0	**1**	0	0	0	0	0	**600**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**2**
122	0	0	**1**	0	0	0	0	0	**300**	**3**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**2**
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	0	**1**	0	0	0	0	0	**300**	**1**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	**1**	0	0	**1**	0	0	**1**	**300**	0
220	**1**	0	0	0	0	0	0	0	**600**	0
221	0	0	**1**	0	0	0	0	0	**600**	**2**
222	0	0	**1**	0	0	0	0	0	**600**	**3**
223	0	0	**1**	0	0	0	0	0	**600**	**2**

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	**1**	0	0	**1**	0	0	**1**	**300**	0
112	0	**1**	0	0	**1**	0	0	**1**	**300**	0
113	0	**1**	0	0	0	**1**	0	0	**300**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**2**
122	0	0	**1**	0	0	0	0	0	**300**	**2**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	**1**	0	0	0	**1**	0	0	**300**	0
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**3**
212	0	0	**1**	0	0	0	0	0	**300**	**1**
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	0	**1**	0	0	0	0	0	**300**	**1**
222	0	0	**1**	0	0	0	0	0	**300**	**2**
223	0	0	**1**	0	0	0	0	0	**300**	**5**
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	0	**1**	0	0	0	0	0	**300**	**1**
312	0	0	**1**	0	0	0	0	0	**300**	**1**
313	0	**1**	0	0	0	**1**	0	0	**300**	0
320	**1**	0	0	0	0	0	0	0	**300**	0
321	0	**1**	0	0	**1**	0	0	**1**	**300**	0
322	0	**1**	0	0	**1**	0	0	**1**	**300**	0
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	**1**	0	0	**1**	0	0	**1**	**300**	0
332	0	0	**1**	0	0	0	0	0	**300**	**1**

User-4 with PM-II

Table 14: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	1	0	0	0	0	0	0	0	900	0
020	1	0	0	0	0	0	0	0	900	0
310	1	0	0	0	0	0	0	0	600	0
301	1	0	0	0	0	0	0	0	1500	0
302	1	0	0	0	0	0	0	0	900	0
110	1	0	0	0	0	0	0	0	300	0
111	0	0	1	0	0	0	0	0	300	1
112	0	0	1	0	0	0	0	0	300	2
113	0	0	1	0	0	0	0	0	300	1
114	0	1	0	0	0	1	0	0	300	0
120	1	0	0	0	0	0	0	0	600	0
121	0	0	1	0	0	0	0	0	600	2
122	0	0	1	0	0	0	0	0	600	7
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	4
132	0	0	1	0	0	0	0	0	300	1
133	0	0	1	0	0	0	0	0	300	1
134	0	0	1	0	0	0	0	0	300	2
210	1	0	0	0	0	0	0	0	300	0
211	0	0	1	0	0	0	0	0	300	2
212	0	0	1	0	0	0	0	0	300	3
213	0	0	1	0	0	0	0	0	300	1
220	1	0	0	0	0	0	0	0	300	0
221	0	1	0	0	0	1	0	0	300	0
222	0	1	0	0	0	1	0	0	300	0
223	0	1	0	0	0	1	0	0	300	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	1	0	0	0	0	0	0	0	300	0
201	1	0	0	0	0	0	0	0	3000	0
202	1	0	0	0	0	0	0	0	3900	0
203	1	0	0	0	0	0	0	0	2400	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	2
112	0	0	1	0	0	0	0	0	600	1
120	1	0	0	0	0	0	0	0	300	0
121	0	0	1	0	0	0	0	0	300	2
122	0	0	1	0	0	0	0	0	300	2
130	1	0	0	0	0	0	0	0	300	0
131	0	1	0	0	0	1	0	0	300	0
132	0	0	1	0	0	0	0	0	300	2
210	1	0	0	0	0	0	0	0	300	0
211	0	0	1	0	0	0	0	0	300	2
212	0	0	1	0	0	0	0	0	300	2
213	0	0	1	0	0	0	0	0	300	1
220	1	0	0	0	0	0	0	0	300	0
221	0	1	0	0	0	1	0	0	300	0
222	0	1	0	0	0	1	0	0	300	0
310	1	0	0	0	0	0	0	0	600	0
311	0	0	1	0	0	0	0	0	600	2
312	0	1	0	0	0	1	0	0	600	0
320	1	0	0	0	0	0	0	0	300	0
321	0	0	1	0	0	0	0	0	300	3
322	0	1	0	0	1	0	0	1	300	0
330	1	0	0	0	0	0	0	0	300	0
331	0	1	0	0	1	0	0	1	300	0
332	0	1	0	0	0	1	0	0	300	0

Table 14-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	**1**	0	0	0	0	0	0	0	**300**	0
310	**1**	0	0	0	0	0	0	0	**6300**	0
320	**1**	0	0	0	0	0	0	0	**6300**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**2**
112	0	0	**1**	0	0	0	0	0	**600**	**1**
113	0	0	**1**	0	0	0	0	0	**600**	**1**
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**2**
122	0	0	**1**	0	0	0	0	0	**300**	**2**
130	0	0	**1**	0	0	0	0	0	**600**	**3**
131	0	0	**1**	0	0	0	0	0	**600**	0
132	0	0	**1**	0	0	0	0	0	**600**	0
133	0	0	**1**	0	0	0	0	0	**600**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	**1**	0	0	**1**	0	0	**1**	**300**	0
220	**1**	0	0	0	0	0	0	0	**600**	0
221	0	0	**1**	0	0	0	0	0	**600**	**2**
222	0	0	**1**	0	0	0	0	0	**600**	**2**
223	0	0	**1**	0	0	0	0	0	**600**	**2**

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	0	**1**	0	0	**1**	0	**1**	0	**600**	0
111	0	**1**	0	0	**1**	0	0	**1**	**600**	0
112	0	**1**	0	0	**1**	0	0	**1**	**600**	0
113	0	**1**	0	0	**1**	0	0	**1**	**600**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**2**
122	0	0	**1**	0	0	0	0	0	**300**	**2**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	**1**	0	0	0	**1**	0	0	**300**	0
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	**1**	0	0	0	**1**	0	0	**300**	0
210	0	0	**1**	0	0	0	0	0	**300**	**2**
211	0	0	**1**	0	0	0	0	0	**300**	0
212	0	0	**1**	0	0	0	0	0	**300**	0
213	0	0	**1**	0	0	0	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	0	**1**	0	0	0	0	0	**300**	**1**
222	0	0	**1**	0	0	0	0	0	**300**	**2**
223	0	**1**	0	0	**1**	0	0	**1**	**300**	0
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	0	**1**	0	0	0	0	0	**300**	**1**
312	0	**1**	0	0	**1**	0	0	**1**	**300**	0
313	0	0	**1**	0	0	0	0	0	**300**	**2**
320	**1**	0	0	0	0	0	0	0	**300**	0
321	0	**1**	0	0	**1**	0	0	**1**	**300**	0
322	0	**1**	0	0	**1**	0	0	**1**	**300**	0
330	**1**	0	0	0	0	0	0	0	**600**	0
331	0	0	**1**	0	0	0	0	0	**600**	**2**
332	0	0	**1**	0	0	0	0	0	**600**	**1**

User-4 with PM-III

Table 15: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	1	0	0	0	0	0	0	0	900	0
020	1	0	0	0	0	0	0	0	900	0
310	1	0	0	0	0	0	0	0	600	0
301	0	1	0	1	0	0	0	0	1500	0
302	1	0	0	0	0	0	0	0	900	0
110	1	0	0	0	0	0	0	0	300	0
111	0	0	1	0	0	0	0	0	300	1
112	0	0	1	0	0	0	0	0	300	2
113	0	0	1	0	0	0	0	0	300	1
114	0	1	0	0	0	1	0	0	300	0
120	1	0	0	0	0	0	0	0	600	0
121	0	0	1	0	0	0	0	0	600	2
122	0	0	1	0	0	0	0	0	600	7
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	4
132	0	0	1	0	0	0	0	0	300	1
133	0	0	1	0	0	0	0	0	300	1
134	0	0	1	0	0	0	0	0	300	2
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	0	1	0	0	300	0
212	0	0	1	0	0	0	0	0	300	3
213	0	0	1	0	0	0	0	0	300	1
220	0	1	0	0	1	0	0	1	300	0
221	0	1	0	0	1	0	0	1	300	0
222	0	1	0	0	1	0	0	1	300	0
223	0	1	0	0	1	0	0	1	300	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
010	1	0	0	0	0	0	0	0	300	0
201	1	0	0	0	0	0	0	0	3000	0
202	1	0	0	0	0	0	0	0	3900	0
203	1	0	0	0	0	0	0	0	2400	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	2
112	0	0	1	0	0	0	0	0	600	1
120	1	0	0	0	0	0	0	0	300	0
121	0	0	1	0	0	0	0	0	300	2
122	0	0	1	0	0	0	0	0	300	2
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	2
132	0	0	1	0	0	0	0	0	300	2
210	1	0	0	0	0	0	0	0	300	0
211	0	0	1	0	0	0	0	0	300	2
212	0	0	1	0	0	0	0	0	300	3
213	0	0	1	0	0	0	0	0	300	1
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	3
222	0	1	0	0	1	0	0	1	300	0
310	1	0	0	0	0	0	0	0	600	0
311	0	0	1	0	0	0	0	0	600	2
312	0	0	1	0	0	0	0	0	600	1
320	1	0	0	0	0	0	0	0	300	0
321	0	0	1	0	0	0	0	0	300	3
322	0	1	0	0	0	1	0	0	300	0
330	1	0	0	0	0	0	0	0	300	0
331	0	1	0	0	1	0	0	1	300	0
332	0	1	0	0	0	1	0	0	300	0

Table 15-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1) Repair	Base (e=1) Move	Base (e=1) Discard	Depot (e=2) Repair	Depot (e=2) Move	Depot (e=2) Discard	OEM (e=3) Repair	OEM (e=3) Discard	Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	**1**	0	0	0	0	0	0	0	**300**	0
310	**1**	0	0	0	0	0	0	0	**6300**	0
320	**1**	0	0	0	0	0	0	0	**6300**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**2**
112	0	0	**1**	0	0	0	0	0	**600**	**1**
113	0	0	**1**	0	0	0	0	0	**600**	**1**
120	0	0	**1**	0	0	0	0	0	**600**	**2**
121	0	0	**1**	0	0	0	0	0	**600**	0
122	0	0	**1**	0	0	0	0	0	**600**	0
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**2**
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	0	**1**	0	0	0	0	0	**300**	**1**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	**1**	0	0	0	**1**	0	0	**300**	0
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**600**	0
221	0	0	**1**	0	0	0	0	0	**600**	**2**
222	0	0	**1**	0	0	0	0	0	**600**	**2**
223	0	0	**1**	0	0	0	0	0	**600**	**2**

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1) Repair	Base (e=1) Move	Base (e=1) Discard	Depot (e=2) Repair	Depot (e=2) Move	Depot (e=2) Discard	OEM (e=3) Repair	OEM (e=3) Discard	Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	0	**1**	0	0	**1**	0	0	**1**	**600**	0
111	0	**1**	0	0	**1**	0	0	**1**	**600**	0
112	0	**1**	0	0	**1**	0	0	**1**	**600**	0
113	0	**1**	0	0	**1**	0	0	**1**	**600**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**1**
122	0	0	**1**	0	0	0	0	0	**300**	**2**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	**1**	0	0	0	**1**	0	0	**300**	0
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	**1**	0	0	0	**1**	0	0	**300**	0
210	0	0	**1**	0	0	0	0	0	**900**	**2**
211	0	0	**1**	0	0	0	0	0	**900**	0
212	0	0	**1**	0	0	0	0	0	**900**	0
213	0	0	**1**	0	0	0	0	0	**900**	0
220	0	0	**1**	0	0	0	0	0	**300**	**4**
221	0	0	**1**	0	0	0	0	0	**300**	0
222	0	0	**1**	0	0	0	0	0	**300**	0
223	0	0	**1**	0	0	0	0	0	**300**	0
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	0	**1**	0	0	0	0	0	**300**	**1**
312	0	0	**1**	0	0	0	0	0	**300**	**1**
313	0	**1**	0	0	0	**1**	0	0	**300**	0
320	**1**	0	0	0	0	0	0	0	**300**	0
321	0	**1**	0	0	**1**	0	0	**1**	**300**	0
322	0	0	**1**	0	0	0	0	0	**300**	**3**
330	**1**	0	0	0	0	0	0	0	**600**	0
331	0	0	**1**	0	0	0	0	0	**600**	**1**
332	0	0	**1**	0	0	0	0	0	**600**	**1**

User-5 with PM-I

Table 17: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	1	0	0	0	0	0	0	0	1200	0
020	1	0	0	0	0	0	0	0	1200	0
310	1	0	0	0	0	0	0	0	900	0
301	1	0	0	0	0	0	0	0	1800	0
302	1	0	0	0	0	0	0	0	900	0
110	1	0	0	0	0	0	0	0	900	0
111	0	0	1	0	0	0	0	0	900	2
112	0	0	1	0	0	0	0	0	900	3
113	0	0	1	0	0	0	0	0	900	2
114	0	0	1	0	0	0	0	0	900	3
120	1	0	0	0	0	0	0	0	600	0
121	0	0	1	0	0	0	0	0	600	3
122	0	0	1	0	0	0	0	0	600	5
130	1	0	0	0	0	0	0	0	300	0
131	0	1	0	0	1	0	0	1	300	0
132	0	0	1	0	0	0	0	0	300	2
133	0	0	1	0	0	0	0	0	300	1
134	0	1	0	0	1	0	0	1	300	0
210	1	0	0	0	0	0	0	0	300	0
211	0	0	1	0	0	0	0	0	300	3
212	0	1	0	0	0	1	0	0	300	0
213	0	1	0	0	0	1	0	0	300	0
220	0	1	0	0	0	1	0	0	300	0
221	0	1	0	0	0	1	0	0	300	0
222	0	1	0	0	0	1	0	0	300	0
223	0	1	0	0	0	1	0	0	300	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	1	0	0	0	0	0	0	0	300	0
201	1	0	0	0	0	0	0	0	3000	0
202	1	0	0	0	0	0	0	0	3900	0
203	1	0	0	0	0	0	0	0	2400	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	2
112	0	0	1	0	0	0	0	0	600	1
120	1	0	0	0	0	0	0	0	300	0
121	0	0	1	0	0	0	0	0	300	2
122	0	0	1	0	0	0	0	0	300	2
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	2
132	0	0	1	0	0	0	0	0	300	3
210	1	0	0	0	0	0	0	0	300	0
211	0	0	1	0	0	0	0	0	300	2
212	0	1	0	0	1	0	0	1	300	0
213	0	0	1	0	0	0	0	0	300	1
220	1	0	0	0	0	0	0	0	300	0
221	0	0	1	0	0	0	0	0	300	4
222	0	1	0	0	1	0	0	1	300	0
310	1	0	0	0	0	0	0	0	900	0
311	0	0	1	0	0	0	0	0	900	3
312	0	0	1	0	0	0	0	0	900	1
320	1	0	0	0	0	0	0	0	600	0
321	0	0	1	0	0	0	0	0	600	4
322	0	1	0	0	0	1	0	0	600	0
330	1	0	0	0	0	0	0	0	300	0
331	0	1	0	0	0	1	0	0	300	0
332	0	1	0	0	0	1	0	0	300	0

Table 17-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	**1**	0	0	0	0	0	0	0	**300**	0
310	**1**	0	0	0	0	0	0	0	**6300**	0
320	**1**	0	0	0	0	0	0	0	**6300**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**3**
112	0	0	**1**	0	0	0	0	0	**600**	**2**
113	0	0	**1**	0	0	0	0	0	**600**	**3**
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**3**
122	0	0	**1**	0	0	0	0	0	**600**	**3**
130	**1**	0	0	0	0	0	0	0	**600**	0
131	0	0	**1**	0	0	0	0	0	**600**	**4**
132	0	0	**1**	0	0	0	0	0	**600**	**2**
133	0	0	**1**	0	0	0	0	0	**600**	**2**
210	0	**1**	0	**1**	0	0	0	0	**300**	0
211	0	**1**	0	0	0	**1**	0	0	**300**	0
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	**1**	0	0	**1**	0	0	**1**	**300**	0
220	**1**	0	0	0	0	0	0	0	**600**	0
221	0	0	**1**	0	0	0	0	0	**600**	**3**
222	0	0	**1**	0	0	0	0	0	**600**	**3**
223	0	0	**1**	0	0	0	0	0	**600**	**2**

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	**1**	0	0	0	0	0	0	0	**300**	0
111	0	**1**	0	0	0	**1**	0	0	**300**	0
112	0	**1**	0	0	**1**	0	0	**1**	**300**	0
113	0	**1**	0	0	0	**1**	0	0	**300**	0
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**2**
122	0	0	**1**	0	0	0	0	0	**300**	**2**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	**1**	0	0	0	**1**	0	0	**300**	0
132	0	0	**1**	0	0	0	0	0	**300**	**1**
133	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**600**	0
211	0	0	**1**	0	0	0	0	0	**600**	**4**
212	0	0	**1**	0	0	0	0	0	**600**	**2**
213	0	**1**	0	0	0	**1**	0	0	**600**	0
220	**1**	0	0	0	0	0	0	0	**600**	0
221	0	0	**1**	0	0	0	0	0	**600**	**2**
222	0	0	**1**	0	0	0	0	0	**600**	**3**
223	0	0	**1**	0	0	0	0	0	**600**	**5**
310	0	0	**1**	0	0	0	0	0	**300**	**1**
311	0	0	**1**	0	0	0	0	0	**300**	0
312	0	0	**1**	0	0	0	0	0	**300**	0
313	0	0	**1**	0	0	0	0	0	**300**	0
320	**1**	0	0	0	0	0	0	0	**300**	0
321	0	**1**	0	0	**1**	0	0	**1**	**300**	0
322	0	0	**1**	0	0	0	0	0	**300**	**3**
330	**1**	0	0	0	0	0	0	0	**600**	0
331	0	0	**1**	0	0	0	0	0	**600**	**2**
332	0	0	**1**	0	0	0	0	0	**600**	**2**

User-5 with PM-II

Table 18: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**1200**	0
020	**1**	0	0	0	0	0	0	0	**1200**	0
310	**1**	0	0	0	0	0	0	0	**1500**	0
301	**1**	0	0	0	0	0	0	0	**1800**	0
302	0	**1**	0	0	**1**	0	**1**	0	**600**	0
110	**1**	0	0	0	0	0	0	0	**900**	0
111	0	0	**1**	0	0	0	0	0	**900**	**2**
112	0	0	**1**	0	0	0	0	0	**900**	**3**
113	0	0	**1**	0	0	0	0	0	**900**	**2**
114	0	0	**1**	0	0	0	0	0	**900**	**3**
120	**1**	0	0	0	0	0	0	0	**600**	0
121	0	0	**1**	0	0	0	0	0	**600**	**3**
122	0	0	**1**	0	0	0	0	0	**600**	**5**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	**1**	0	0	**1**	0	0	**1**	**300**	0
132	0	0	**1**	0	0	0	0	0	**300**	**2**
133	0	0	**1**	0	0	0	0	0	**300**	**1**
134	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**2**
212	0	0	**1**	0	0	0	0	0	**300**	**3**
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	0	**1**	0	0	**1**	0	**1**	0	**300**	0
221	0	**1**	0	0	**1**	0	0	**1**	**300**	0
222	0	**1**	0	0	**1**	0	0	**1**	**300**	0
223	0	**1**	0	0	**1**	0	0	**1**	**300**	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**300**	0
201	**1**	0	0	0	0	0	0	0	**3000**	0
202	**1**	0	0	0	0	0	0	0	**3900**	0
203	0	**1**	0	**1**	0	0	0	0	**2400**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**2**
112	0	0	**1**	0	0	0	0	0	**600**	**2**
120	**1**	0	0	0	0	0	0	0	**300**	0
121	0	0	**1**	0	0	0	0	0	**300**	**3**
122	0	0	**1**	0	0	0	0	0	**300**	**2**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**3**
132	0	0	**1**	0	0	0	0	0	**300**	**4**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**2**
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	0	**1**	0	0	0	0	0	**300**	**1**
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	0	**1**	0	0	**300**	0
222	0	0	**1**	0	0	0	0	0	**300**	**2**
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	**1**	0	0	**1**	0	0	**1**	**300**	0
312	0	0	**1**	0	0	0	0	0	**300**	**1**
320	0	**1**	0	0	0	**1**	0	0	**300**	0
321	0	**1**	0	0	0	**1**	0	0	**300**	0
322	0	**1**	0	0	0	**1**	0	0	**300**	0
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	**1**	0	0	0	**1**	0	0	**300**	0
332	0	**1**	0	0	0	**1**	0	0	**300**	0

Table 18-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
330	0	1	0	0	1	0	1	0	300	0
310	1	0	0	0	0	0	0	0	6300	0
320	0	1	0	1	0	0	0	0	6300	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	2
112	0	1	0	0	1	0	0	1	600	0
113	0	0	1	0	0	0	0	0	600	2
120	1	0	0	0	0	0	0	0	600	0
121	0	0	1	0	0	0	0	0	600	2
122	0	0	1	0	0	0	0	0	600	3
130	1	0	0	0	0	0	0	0	600	0
131	0	0	1	0	0	0	0	0	600	3
132	0	0	1	0	0	0	0	0	600	2
133	0	0	1	0	0	0	0	0	600	2
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	0	1	0	0	300	0
212	0	1	0	0	0	1	0	0	300	0
213	0	1	0	0	1	0	0	1	300	0
220	1	0	0	0	0	0	0	0	600	0
221	0	0	1	0	0	0	0	0	600	3
222	0	0	1	0	0	0	0	0	600	3
223	0	1	0	0	0	1	0	0	600	0

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$		Q(ijk)
110	1	0	0	0	0	0	0	0	300	0
111	0	1	0	0	1	0	0	1	300	0
112	0	1	0	0	1	0	0	1	300	0
113	0	1	0	0	0	1	0	0	300	0
120	1	0	0	0	0	0	0	0	300	0
121	0	0	1	0	0	0	0	0	300	2
122	0	0	1	0	0	0	0	0	300	2
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	0	1	0	0	0	0	0	300	1
133	0	0	1	0	0	0	0	0	300	3
210	1	0	0	0	0	0	0	0	600	0
211	0	0	1	0	0	0	0	0	600	3
212	0	0	1	0	0	0	0	0	600	2
213	0	1	0	0	0	1	0	0	600	0
220	1	0	0	0	0	0	0	0	300	0
221	0	1	0	0	0	1	0	0	300	0
222	0	0	1	0	0	0	0	0	300	2
223	0	0	1	0	0	0	0	0	300	5
310	1	0	0	0	0	0	0	0	300	0
311	0	0	1	0	0	0	0	0	300	1
312	0	1	0	0	0	1	0	0	300	0
313	0	1	0	0	0	1	0	0	300	0
320	1	0	0	0	0	0	0	0	300	0
321	0	1	0	0	1	0	0	1	300	0
322	0	0	1	0	0	0	0	0	300	3
330	1	0	0	0	0	0	0	0	600	0
331	0	0	1	0	0	0	0	0	600	2
332	0	1	0	0	0	1	0	0	600	0

User-5 with PM-III

Table 19: Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**900**	0
020	**1**	0	0	0	0	0	0	0	**1200**	0
310	**1**	0	0	0	0	0	0	0	**900**	0
301	**1**	0	0	0	0	0	0	0	**1800**	0
302	0	**1**	0	0	**1**	0	**1**	0	**600**	0
110	**1**	0	0	0	0	0	0	0	**900**	0
111	0	0	**1**	0	0	0	0	0	**900**	**2**
112	0	0	**1**	0	0	0	0	0	**900**	**3**
113	0	0	**1**	0	0	0	0	0	**900**	**2**
114	0	0	**1**	0	0	0	0	0	**900**	**3**
120*	**1**	0	0	0	0	0	0	0	**600**	0
121*	0	0	**1**	0	0	0	0	0	**600**	**3**
122*	0	0	**1**	0	0	0	0	0	**600**	**5**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	**1**	0	0	**1**	0	0	**1**	**300**	0
132	0	0	**1**	0	0	0	0	0	**300**	**2**
133	0	0	**1**	0	0	0	0	0	**300**	**1**
134	0	**1**	0	0	0	**1**	0	0	**300**	0
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**2**
212	0	0	**1**	0	0	0	0	0	**300**	**3**
213	0	**1**	0	0	0	**1**	0	0	**300**	0
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	**1**	0	0	**1**	**300**	0
222	0	**1**	0	0	**1**	0	0	**1**	**300**	0
223	0	**1**	0	0	**1**	0	0	**1**	**300**	0

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
010	**1**	0	0	0	0	0	0	0	**300**	0
201	**1**	0	0	0	0	0	0	0	**3000**	0
202	**1**	0	0	0	0	0	0	0	**3900**	0
203	0	**1**	0	**1**	0	0	0	0	**2400**	0
110	**1**	0	0	0	0	0	0	0	**600**	0
111	0	0	**1**	0	0	0	0	0	**600**	**2**
112	0	0	**1**	0	0	0	0	0	**600**	**1**
120*	**1**	0	0	0	0	0	0	0	**300**	0
121*	0	0	**1**	0	0	0	0	0	**300**	**2**
122*	0	0	**1**	0	0	0	0	0	**300**	**2**
130	**1**	0	0	0	0	0	0	0	**300**	0
131	0	0	**1**	0	0	0	0	0	**300**	**2**
132	0	0	**1**	0	0	0	0	0	**300**	**2**
210	**1**	0	0	0	0	0	0	0	**300**	0
211	0	0	**1**	0	0	0	0	0	**300**	**2**
212	0	**1**	0	0	**1**	0	0	**1**	**300**	0
213	0	0	**1**	0	0	0	0	0	**300**	**1**
220	**1**	0	0	0	0	0	0	0	**300**	0
221	0	**1**	0	0	0	**1**	0	0	**300**	0
222	0	0	**1**	0	0	0	0	0	**300**	**2**
310	**1**	0	0	0	0	0	0	0	**300**	0
311	0	**1**	0	0	**1**	0	0	**1**	**300**	0
312	0	**1**	0	0	0	**1**	0	0	**300**	0
320	0	**1**	0	**1**	0	0	0	0	**300**	0
321	0	**1**	0	0	**1**	0	0	**1**	**300**	0
322	0	**1**	0	0	0	**1**	0	0	**300**	0
330	**1**	0	0	0	0	0	0	0	**300**	0
331	0	**1**	0	0	0	**1**	0	0	**300**	0
332	0	**1**	0	0	0	**1**	0	0	**300**	0

Table 19-a: Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
330	0	1	0	1	0	0	0	0	300	0
310	1	0	0	0	0	0	0	0	6300	0
320	0	1	0	1	0	0	0	0	6300	0
110	1	0	0	0	0	0	0	0	600	0
111	0	0	1	0	0	0	0	0	600	2
112	0	1	0	0	0	1	0	0	600	0
113	0	0	1	0	0	0	0	0	600	2
120*	1	0	0	0	0	0	0	0	600	0
121*	0	0	1	0	0	0	0	0	600	2
122*	0	0	1	0	0	0	0	0	600	3
130	1	0	0	0	0	0	0	0	600	0
131	0	0	1	0	0	0	0	0	600	3
132	0	0	1	0	0	0	0	0	600	2
133	0	0	1	0	0	0	0	0	600	2
210	1	0	0	0	0	0	0	0	300	0
211	0	1	0	0	0	1	0	0	300	0
212	0	1	0	0	0	1	0	0	300	0
213	0	1	0	0	1	0	0	1	300	0
220	1	0	0	0	0	0	0	0	600	0
221	0	0	1	0	0	0	0	0	600	3
222	0	0	1	0	0	0	0	0	600	3
223	0	1	0	0	0	1	0	0	600	0

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimum PM Schedule (in Hours)	Spare Parts Inventory 95% SL
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard		
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)		Q(ijk)
110	0	1	0	1	0	0	0	0	600	0
111	0	1	0	0	0	1	0	0	600	0
112	0	1	0	0	1	0	0	1	600	0
113	0	1	0	0	0	1	0	0	600	0
120*	1	0	0	0	0	0	0	0	300	0
121*	0	0	1	0	0	0	0	0	300	2
122*	0	0	1	0	0	0	0	0	300	2
130	1	0	0	0	0	0	0	0	300	0
131	0	0	1	0	0	0	0	0	300	1
132	0	0	1	0	0	0	0	0	300	1
133	0	0	1	0	0	0	0	0	300	3
210	1	0	0	0	0	0	0	0	600	0
211	0	0	1	0	0	0	0	0	600	3
212	0	0	1	0	0	0	0	0	600	2
213	0	1	0	0	0	1	0	0	600	0
220	1	0	0	0	0	0	0	0	300	0
221	0	1	0	0	0	1	0	0	300	0
222	0	0	1	0	0	0	0	0	300	2
223	0	1	0	0	1	0	0	1	300	0
310	1	0	0	0	0	0	0	0	600	0
311	0	0	1	0	0	0	0	0	600	1
312	0	0	1	0	0	0	0	0	600	2
313	0	0	1	0	0	0	0	0	600	3
320	1	0	0	0	0	0	0	0	300	0
321	0	1	0	0	1	0	0	1	300	0
322	0	0	1	0	0	0	0	0	300	3
330	1	0	0	0	0	0	0	0	300	0
331	0	1	0	0	0	1	0	0	300	0
332	0	1	0	0	0	1	0	0	300	0

APPENDIX-B

User-1

Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
010	**1**	0	0	0	0	0	0	0	**6300**	**1500**	**300**
020	**1**	0	0	0	0	0	0	0	**1500**	**1500**	**5100**
310	**1**	0	0	0	0	0	0	0	**1800**	**5700**	**900**
301	**1**	0	0	0	0	0	0	0	**2700**	**3000**	**900**
302	**1**	0	0	0	0	0	0	0	**600**	**600**	**900**
110	**1**	0	0	0	0	0	0	0	**600**	**300**	**900**
111	0	0	**1**	0	0	0	0	0	**600**	**300**	**900**
112	0	0	**1**	0	0	0	0	0	**600**	**300**	**900**
113	0	0	**1**	0	0	0	0	0	**600**	**300**	**900**
114	0	0	**1**	0	0	0	0	0	**600**	**300**	**900**
120*	**1**	0	0	0	0	0	0	0	**300**	**2100**	**600**
121*	0	0	**1**	0	0	0	0	0	**300**	**2100**	**600**
122*	0	0	**1**	0	0	0	0	0	**300**	**2100**	**600**
130	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
131	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
132	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
133	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
134	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
210	**1**	0	0	0	0	0	0	0	**600**	**300**	**300**
211	0	0	**1**	0	0	0	0	0	**600**	**300**	**300**
212	0	0	**1**	0	0	0	0	0	**600**	**300**	**300**
213	0	0	**1**	0	0	0	0	0	**600**	**300**	**300**
220	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
221	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
222	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
223	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
010	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
201	**1**	0	0	0	0	0	0	0	**3000**	**2700**	**1200**
202	**1**	0	0	0	0	0	0	0	**300**	**3000**	**2100**
203	**1**	0	0	0	0	0	0	0	**300**	**1200**	**300**
110	**1**	0	0	0	0	0	0	0	**600**	**900**	**1800**
111	0	0	**1**	0	0	0	0	0	**600**	**900**	**1800**
112	0	0	**1**	0	0	0	0	0	**600**	**900**	**1800**
120*	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
121*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
122*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
130	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
131	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
132	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
210	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
211	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
212	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
213	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
220	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
221	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
222	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
310	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
311	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
312	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
320	**1**	0	0	0	0	0	0	0	**3000**	**900**	**300**
321	0	0	**1**	0	0	0	0	0	**3000**	**900**	**300**
322	0	0	**1**	0	0	0	0	0	**3000**	**900**	**300**
330	**1**	0	0	0	0	0	0	0	**300**	**300**	**600**
331	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**600**
332	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**600**

Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
330	0	1	0	1	0	0	0	0	**300**	**300**	**300**
310	1	0	0	0	0	0	0	0	**4500**	**2700**	**6300**
320	1	0	0	0	0	0	0	0	**4500**	**6300**	**4200**
110	1	0	0	0	0	0	0	0	**300**	**300**	**300**
111	0	0	1	0	0	0	0	0	**300**	**300**	**300**
112	0	0	1	0	0	0	0	0	**300**	**300**	**300**
113	0	0	1	0	0	0	0	0	**300**	**300**	**300**
120*	1	0	0	0	0	0	0	0	**600**	**300**	**300**
121*	0	0	1	0	0	0	0	0	**600**	**300**	**300**
122*	0	0	1	0	0	0	0	0	**600**	**300**	**300**
130	1	0	0	0	0	0	0	0	**300**	**300**	**300**
131	0	0	1	0	0	0	0	0	**300**	**300**	**300**
132	0	0	1	0	0	0	0	0	**300**	**300**	**300**
133	0	0	1	0	0	0	0	0	**300**	**300**	**300**
210	1	0	0	0	0	0	0	0	**600**	**300**	**300**
211	0	1	0	0	0	1	0	0	**600**	**300**	**300**
212	0	1	0	0	0	1	0	0	**600**	**300**	**300**
213	0	1	0	0	0	1	0	0	**600**	**300**	**300**
220	1	0	0	0	0	0	0	0	**900**	**300**	**600**
221	0	0	1	0	0	0	0	0	**900**	**300**	**600**
222	0	1	0	0	1	0	0	1	**900**	**300**	**600**
223	0	0	1	0	0	0	0	0	**900**	**300**	**600**

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
110	0	1	0	0	0	1	0	0	**300**	**600**	**300**
111	0	1	0	0	0	1	0	0	**300**	**600**	**300**
112	0	1	0	0	0	1	0	0	**300**	**600**	**300**
113	0	1	0	0	0	1	0	0	**300**	**600**	**300**
120*	1	0	0	0	0	0	0	0	**300**	**300**	**300**
121*	0	0	1	0	0	0	0	0	**300**	**300**	**300**
122*	0	0	1	0	0	0	0	0	**300**	**300**	**300**
130	1	0	0	0	0	0	0	0	**300**	**300**	**600**
131	0	0	1	0	0	0	0	0	**300**	**300**	**600**
132	0	0	1	0	0	0	0	0	**300**	**300**	**600**
133	0	0	1	0	0	0	0	0	**300**	**300**	**600**
210	1	0	0	0	0	0	0	0	**300**	**1200**	**300**
211	0	0	1	0	0	0	0	0	**300**	**1200**	**300**
212	0	0	1	0	0	0	0	0	**300**	**1200**	**300**
213	0	0	1	0	0	0	0	0	**300**	**1200**	**300**
220	1	0	0	0	0	0	0	0	**300**	**300**	**300**
221	0	1	0	0	1	0	0	1	**300**	**300**	**300**
222	0	1	0	0	0	1	0	0	**300**	**300**	**300**
223	0	0	1	0	0	0	0	0	**300**	**300**	**300**
310	0	0	1	0	0	0	0	0	**300**	**300**	**300**
311	0	0	1	0	0	0	0	0	**300**	**300**	**300**
312	0	0	1	0	0	0	0	0	**300**	**300**	**300**
313	0	0	1	0	0	0	0	0	**300**	**300**	**300**
320	1	0	0	0	0	0	0	0	**3300**	**300**	**300**
321	0	0	1	0	0	0	0	0	**3300**	**300**	**300**
322	0	0	1	0	0	0	0	0	**3300**	**300**	**300**
330	1	0	0	0	0	0	0	0	**300**	**1500**	**2400**
331	0	0	1	0	0	0	0	0	**300**	**1500**	**2400**
332	0	0	1	0	0	0	0	0	**300**	**1500**	**2400**

User-2

Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)	PM-I	PM-II	PM-III
010	1	0	0	0	0	0	0	0	**900**	**4500**	**3000**
020	1	0	0	0	0	0	0	0	**900**	**5400**	**5700**
310	1	0	0	0	0	0	0	0	**600**	**6300**	**5700**
301	1	0	0	0	0	0	0	0	**1500**	**6600**	**1800**
302	1	0	0	0	0	0	0	0	**600**	**5100**	**1800**
110	1	0	0	0	0	0	0	0	**300**	**900**	**1800**
111	0	0	1	0	0	0	0	0	**300**	**900**	**1800**
112	0	0	1	0	0	0	0	0	**300**	**900**	**1800**
113	0	0	1	0	0	0	0	0	**300**	**900**	**1800**
114	0	1	0	0	1	0	0	1	**300**	**900**	**1800**
120*	0	0	1	0	0	0	0	0	**300**	**1200**	**2100**
121*	0	0	1	0	0	0	0	0	**300**	**1200**	**2100**
122*	0	0	1	0	0	0	0	0	**300**	**1200**	**2100**
130	1	0	0	0	0	0	0	0	**300**	**300**	**300**
131	0	1	0	0	0	1	0	0	**300**	**300**	**300**
132	0	1	0	0	1	0	0	1	**300**	**300**	**300**
133	0	0	1	0	0	0	0	0	**300**	**300**	**300**
134	0	0	1	0	0	0	0	0	**300**	**300**	**300**
210	1	0	0	0	0	0	0	0	**300**	**300**	**1500**
211	0	0	1	0	0	0	0	0	**300**	**300**	**1500**
212	0	0	1	0	0	0	0	0	**300**	**300**	**1500**
213	0	0	1	0	0	0	0	0	**300**	**300**	**1500**
220	1	0	0	0	0	0	0	0	**300**	**300**	**600**
221	0	1	0	0	0	1	0	0	**300**	**300**	**600**
222	0	1	0	0	0	1	0	0	**300**	**300**	**600**
223	0	1	0	0	1	0	0	1	**300**	**300**	**600**

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}$(ijk)	$L_{2,1}$(ijk)	$L_{3,1}$(ijk)	$L_{1,2}$(ijk)	$L_{2,2}$(ijk)	$L_{3,2}$(ijk)	$L_{1,3}$(ijk)	$L_{3,3}$(ijk)	PM-I	PM-II	PM-III
010	1	0	0	0	0	0	0	0	**300**	**300**	**300**
201	0	1	0	1	0	0	0	0	**3000**	**1200**	**2400**
202	1	0	0	0	0	0	0	0	**3900**	**600**	**3600**
203	1	0	0	0	0	0	0	0	**2400**	**1800**	**1800**
110	1	0	0	0	0	0	0	0	**600**	**1800**	**600**
111	0	1	0	0	0	1	0	0	**600**	**1800**	**600**
112	0	0	1	0	0	0	0	0	**600**	**1800**	**600**
120*	0	0	1	0	0	0	0	0	**300**	**300**	**300**
121*	0	0	1	0	0	0	0	0	**300**	**300**	**300**
122*	0	0	1	0	0	0	0	0	**300**	**300**	**300**
130	1	0	0	0	0	0	0	0	**300**	**300**	**900**
131	0	0	1	0	0	0	0	0	**300**	**300**	**900**
132	0	0	1	0	0	0	0	0	**300**	**300**	**900**
210	1	0	0	0	0	0	0	0	**300**	**600**	**300**
211	0	0	1	0	0	0	0	0	**300**	**600**	**300**
212	0	0	1	0	0	0	0	0	**300**	**600**	**300**
213	0	0	1	0	0	0	0	0	**300**	**600**	**300**
220	1	0	0	0	0	0	0	0	**300**	**300**	**600**
221	0	0	1	0	0	0	0	0	**300**	**300**	**600**
222	0	0	1	0	0	0	0	0	**300**	**300**	**600**
310	1	0	0	0	0	0	0	0	**900**	**600**	**600**
311	0	0	1	0	0	0	0	0	**900**	**600**	**600**
312	0	0	1	0	0	0	0	0	**900**	**600**	**600**
320	0	0	1	0	0	0	0	0	**600**	**600**	**300**
321	0	0	1	0	0	0	0	0	**600**	**600**	**300**
322	0	0	1	0	0	0	0	0	**600**	**600**	**300**
330	1	0	0	0	0	0	0	0	**300**	**600**	**300**
331	0	1	0	0	0	1	0	0	**300**	**600**	**300**
332	0	1	0	0	0	1	0	0	**300**	**600**	**300**

Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
330	**1**	0	0	0	0	0	0	0	**300**	**2700**	**3300**
310	**1**	0	0	0	0	0	0	0	**6300**	**5700**	**5100**
320	**1**	0	0	0	0	0	0	0	**6300**	**6000**	**5700**
110	**1**	0	0	0	0	0	0	0	**600**	**1500**	**900**
111	0	0	**1**	0	0	0	0	0	**600**	**1500**	**900**
112	0	0	**1**	0	0	0	0	0	**600**	**1500**	**900**
113	0	0	**1**	0	0	0	0	0	**600**	**1500**	**900**
120*	**1**	0	0	0	0	0	0	0	**600**	**1500**	**600**
121*	0	0	**1**	0	0	0	0	0	**600**	**1500**	**600**
122*	0	0	**1**	0	0	0	0	0	**600**	**1500**	**600**
130	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
131	0	1	0	0	0	**1**	0	0	**300**	**300**	**300**
132	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
133	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
210	0	**1**	0	**1**	0	0	0	0	**300**	**600**	**300**
211	0	**1**	0	0	**1**	0	0	**1**	**300**	**600**	**300**
212	0	**1**	0	0	**1**	0	0	**1**	**300**	**600**	**300**
213	0	**1**	0	0	0	**1**	0	0	**300**	**600**	**300**
220	**1**	0	0	0	0	0	0	0	**600**	**600**	**2400**
221	0	0	**1**	0	0	0	0	0	**600**	**600**	**2400**
222	0	0	**1**	0	0	0	0	0	**600**	**600**	**2400**
223	0	0	**1**	0	0	0	0	0	**600**	**600**	**2400**

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
110	**1**	0	0	0	0	0	0	0	**600**	**300**	**300**
111	0	**1**	0	0	0	**1**	0	0	**600**	**300**	**300**
112	0	**1**	0	0	0	**1**	0	0	**600**	**300**	**300**
113	0	**1**	0	0	0	**1**	0	0	**600**	**300**	**300**
120*	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
121*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
122*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
130	**1**	0	0	0	0	0	0	0	**300**	**600**	**300**
131	0	0	**1**	0	0	0	0	0	**300**	**600**	**300**
132	0	0	**1**	0	0	0	0	0	**300**	**600**	**300**
133	0	0	**1**	0	0	0	0	0	**300**	**600**	**300**
210	**1**	0	0	0	0	0	0	0	**600**	**600**	**900**
211	0	0	**1**	0	0	0	0	0	**600**	**600**	**900**
212	0	0	**1**	0	0	0	0	0	**600**	**600**	**900**
213	0	0	**1**	0	0	0	0	0	**600**	**600**	**900**
220	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
221	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
222	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
223	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
310	**1**	0	0	0	0	0	0	0	**600**	**600**	**1800**
311	0	0	**1**	0	0	0	0	0	**600**	**600**	**1800**
312	0	0	**1**	0	0	0	0	0	**600**	**600**	**1800**
313	0	**1**	0	0	0	**1**	0	0	**600**	**600**	**1800**
320	**1**	0	0	0	0	0	0	0	**600**	**3600**	**3300**
321	0	0	**1**	0	0	0	0	0	**600**	**3600**	**3300**
322	0	**1**	0	0	0	**1**	0	0	**600**	**3600**	**3300**
330	**1**	0	0	0	0	0	0	0	**600**	**1800**	**900**
331	0	0	**1**	0	0	0	0	0	**600**	**1800**	**900**
332	0	**1**	0	0	0	**1**	0	0	**600**	**1800**	**900**

User-3

Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
010	**1**	0	0	0	0	0	0	0	**1200**	**1200**	**2100**
020	**1**	0	0	0	0	0	0	0	**900**	**900**	**1800**
310	**1**	0	0	0	0	0	0	0	**900**	**3000**	**2400**
301	**1**	0	0	0	0	0	0	0	**600**	**1800**	**1800**
302	**1**	0	0	0	0	0	0	0	**1800**	**2700**	**1200**
110	**1**	0	0	0	0	0	0	0	**600**	**600**	**600**
111	0	**1**	0	0	**1**	0	0	**1**	**600**	**600**	**600**
112	0	0	**1**	0	0	0	0	0	**600**	**600**	**600**
113	0	0	**1**	0	0	0	0	0	**600**	**600**	**600**
114	0	0	**1**	0	0	0	0	0	**600**	**600**	**600**
120*	**1**	0	0	0	0	0	0	0	**900**	**900**	**900**
121*	0	0	**1**	0	0	0	0	0	**900**	**900**	**900**
122*	0	0	**1**	0	0	0	0	0	**900**	**900**	**900**
130	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
131	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
132	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
133	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
134	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
210	**1**	0	0	0	0	0	0	0	**600**	**300**	**600**
211	0	0	**1**	0	0	0	0	0	**600**	**300**	**600**
212	0	0	**1**	0	0	0	0	0	**600**	**300**	**600**
213	0	0	**1**	0	0	0	0	0	**600**	**300**	**600**
220	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
221	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
222	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
223	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
010	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
201	**1**	0	0	0	0	0	0	0	**3000**	**3000**	**2700**
202	**1**	0	0	0	0	0	0	0	**3600**	**3600**	**3900**
203	**1**	0	0	0	0	0	0	0	**1500**	**2400**	**2400**
110	**1**	0	0	0	0	0	0	0	**600**	**600**	**300**
111	0	**1**	0	0	0	**1**	0	0	**600**	**600**	**300**
112	0	0	**1**	0	0	0	0	0	**600**	**600**	**300**
120*	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
121*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
122*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
130	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
131	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
132	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
210	**1**	0	0	0	0	0	0	0	**600**	**300**	**300**
211	0	0	**1**	0	0	0	0	0	**600**	**300**	**300**
212	0	0	**1**	0	0	0	0	0	**600**	**300**	**300**
213	0	0	**1**	0	0	0	0	0	**600**	**300**	**300**
220	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
221	0	**1**	0	0	1	0	0	**1**	**300**	**300**	**300**
222	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
310	0	0	**1**	0	0	0	0	0	**3000**	**900**	**600**
311	0	0	**1**	0	0	0	0	0	**3000**	**900**	**600**
312	0	0	**1**	0	0	0	0	0	**3000**	**900**	**600**
320	**1**	0	0	0	0	0	0	0	**3000**	**1200**	**1200**
321	0	0	**1**	0	0	0	0	0	**3000**	**1200**	**1200**
322	0	0	**1**	0	0	0	0	0	**3000**	**1200**	**1200**
330	0	**1**	0	**1**	0	0	0	0	**2700**	**1200**	**900**
331	0	**1**	0	0	0	**1**	0	0	**2700**	**1200**	**900**
332	0	**1**	0	0	0	**1**	0	0	**2700**	**1200**	**900**

Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimal PM Schedules with Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
330	1	0	0	0	0	0	0	0	300	300	300
310	1	0	0	0	0	0	0	0	5100	3600	6300
320	1	0	0	0	0	0	0	0	5400	6300	3600
110	1	0	0	0	0	0	0	0	300	300	300
111	0	1	0	0	1	0	0	1	300	300	300
112	0	0	1	0	0	0	0	0	300	300	300
113	0	0	1	0	0	0	0	0	300	300	300
120*	1	0	0	0	0	0	0	0	300	600	600
121*	0	0	1	0	0	0	0	0	300	600	600
122*	0	0	1	0	0	0	0	0	300	600	600
130	0	1	0	1	0	0	0	0	300	300	300
131	0	1	0	0	0	1	0	0	300	300	300
132	0	1	0	0	0	1	0	0	300	300	300
133	0	1	0	0	0	1	0	0	300	300	300
210	0	1	0	1	0	0	0	0	300	300	300
211	0	1	0	0	1	0	0	1	300	300	300
212	0	1	0	0	0	1	0	0	300	300	300
213	0	1	0	0	0	1	0	0	300	300	300
220	1	0	0	0	0	0	0	0	600	600	600
221	0	0	1	0	0	0	0	0	600	600	600
222	0	0	1	0	0	0	0	0	600	600	600
223	0	0	1	0	0	0	0	0	600	600	600

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Optimal PM Schedules with Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
110	0	1	0	1	0	0	0	0	300	300	600
111	0	1	0	0	1	0	0	1	300	300	600
112	0	1	0	0	0	1	0	0	300	300	600
113	0	1	0	0	0	1	0	0	300	300	600
120*	0	0	1	0	0	0	0	0	300	300	300
121*	0	0	1	0	0	0	0	0	300	300	300
122*	0	0	1	0	0	0	0	0	300	300	300
130	1	0	0	0	0	0	0	0	300	300	300
131	0	0	1	0	0	0	0	0	300	300	300
132	0	1	0	0	1	0	0	1	300	300	300
133	0	0	1	0	0	0	0	0	300	300	300
210	1	0	0	0	0	0	0	0	300	300	300
211	0	0	1	0	0	0	0	0	300	300	300
212	0	0	1	0	0	0	0	0	300	300	300
213	0	0	1	0	0	0	0	0	300	300	300
220	1	0	0	0	0	0	0	0	300	300	300
221	0	0	1	0	0	0	0	0	300	300	300
222	0	1	0	0	0	1	0	0	300	300	300
223	0	1	0	0	1	0	0	1	300	300	300
310	1	0	0	0	0	0	0	0	300	300	300
311	0	0	1	0	0	0	0	0	300	300	300
312	0	1	0	0	0	1	0	0	300	300	300
313	0	1	0	0	0	1	0	0	300	300	300
320	1	0	0	0	0	0	0	0	2100	300	300
321	0	0	1	0	0	0	0	0	2100	300	300
322	0	1	0	0	0	1	0	0	2100	300	300
330	1	0	0	0	0	0	0	0	300	300	300
331	0	1	0	0	1	0	0	1	300	300	300
332	0	1	0	0	1	0	0	1	300	300	300

User-4

Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
010	**1**	0	0	0	0	0	0	0	**300**	**5400**	**900**
020	**1**	0	0	0	0	0	0	0	**4800**	**2700**	**900**
310	0	**1**	0	0	**1**	0	**1**	0	**6300**	**300**	**300**
301	**1**	0	0	0	0	0	0	0	**3000**	**4500**	**1500**
302	**1**	0	0	0	0	0	0	0	**1200**	**5400**	**900**
110	**1**	0	0	0	0	0	0	0	**600**	**600**	**300**
111	0	**1**	0	0	**1**	0	0	**1**	**600**	**600**	**300**
112	0	0	**1**	0	0	0	0	0	**600**	**600**	**300**
113	0	0	**1**	0	0	0	0	0	**600**	**600**	**300**
114	0	**1**	0	0	0	**1**	0	0	**600**	**600**	**300**
120*	0	0	**1**	0	0	0	0	0	**2400**	**2400**	**300**
121*	0	0	**1**	0	0	0	0	0	**2400**	**2400**	**300**
122*	0	0	**1**	0	0	0	0	0	**2400**	**2400**	**300**
130	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
131	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
132	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
133	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
134	0	**1**	0	0	0	1	0	0	**300**	**300**	**300**
210	**1**	0	0	0	0	0	0	0	**1200**	**300**	**300**
211	0	0	**1**	0	0	0	0	0	**1200**	**300**	**300**
212	0	0	**1**	0	0	0	0	0	**1200**	**300**	**300**
213	0	0	**1**	0	0	0	0	0	**1200**	**300**	**300**
220	**1**	0	0	0	0	0	0	0	**900**	**300**	**300**
221	0	**1**	0	0	0	**1**	0	0	**900**	**300**	**300**
222	0	**1**	0	0	0	**1**	0	0	**900**	**300**	**300**
223	0	**1**	0	0	0	**1**	0	0	**900**	**300**	**300**

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
010	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
201	**1**	0	0	0	0	0	0	0	**1500**	**600**	**3000**
202	**1**	0	0	0	0	0	0	0	**3600**	**300**	**3900**
203	**1**	0	0	0	0	0	0	0	**2400**	**1500**	**2400**
110	**1**	0	0	0	0	0	0	0	**600**	**300**	**300**
111	0	**1**	0	0	0	**1**	0	0	**600**	**300**	**300**
112	0	0	**1**	0	0	0	0	0	**600**	**300**	**300**
120*	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
121*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
122*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
130	**1**	0	0	0	0	0	0	0	**600**	**2400**	**300**
131	0	**1**	0	0	0	**1**	0	0	**600**	**2400**	**300**
132	0	0	**1**	0	0	0	0	0	**600**	**2400**	**300**
210	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
211	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
212	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
213	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
220	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
221	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
222	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
310	0	0	**1**	0	0	0	0	0	**600**	**900**	**600**
311	0	0	**1**	0	0	0	0	0	**600**	**900**	**600**
312	0	0	**1**	0	0	0	0	0	**600**	**900**	**600**
320	**1**	0	0	0	0	0	0	0	**900**	**6600**	**600**
321	0	0	**1**	0	0	0	0	0	**900**	**6600**	**600**
322	0	0	**1**	0	0	0	0	0	**900**	**6600**	**600**
330	**1**	0	0	0	0	0	0	0	**900**	**300**	**300**
331	0	**1**	0	0	**1**	0	0	**1**	**900**	**300**	**300**
332	0	**1**	0	0	0	**1**	0	0	**900**	**300**	**300**

Optimal LOR decisions for Machine-3

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
330	**1**	0	0	0	0	0	0	0	**6600**	**900**	**300**
310	**1**	0	0	0	0	0	0	0	**6300**	**4800**	**6300**
320	**1**	0	0	0	0	0	0	0	**5100**	**1200**	**6300**
110	**1**	0	0	0	0	0	0	0	**1500**	**300**	**600**
111	0	0	**1**	0	0	0	0	0	**1500**	**300**	**600**
112	0	0	**1**	0	0	0	0	0	**1500**	**300**	**600**
113	0	0	**1**	0	0	0	0	0	**1500**	**300**	**600**
120*	**1**	0	0	0	0	0	0	0	**300**	**600**	**600**
121*	0	0	**1**	0	0	0	0	0	**300**	**600**	**600**
122*	0	0	**1**	0	0	0	0	0	**300**	**600**	**600**
130	**1**	0	0	0	0	0	0	0	**300**	**900**	**300**
131	0	**1**	0	0	0	**1**	0	0	**300**	**900**	**300**
132	0	0	**1**	0	0	0	0	0	**300**	**900**	**300**
133	0	**1**	0	0	0	**1**	0	0	**300**	**900**	**300**
210	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
211	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
212	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
213	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
220	**1**	0	0	0	0	0	0	0	**600**	**600**	**300**
221	0	0	**1**	0	0	0	0	0	**600**	**600**	**300**
222	0	0	**1**	0	0	0	0	0	**600**	**600**	**300**
223	0	**1**	0	0	0	**1**	0	0	**600**	**600**	**300**

Optimal LOR decisions for Machine-4

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
110	**1**	0	0	0	0	0	0	0	**300**	**3600**	**300**
111	0	**1**	0	0	**1**	0	0	**1**	**300**	**3600**	**300**
112	0	**1**	0	0	0	**1**	0	0	**300**	**3600**	**300**
113	0	**1**	0	0	0	**1**	0	0	**300**	**3600**	**300**
120*	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
121*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
122*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
130	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
131	0	**1**	0	0	1	0	0	**1**	**300**	**300**	**300**
132	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
133	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
210	0	0	**1**	0	0	0	0	0	**2700**	**2100**	**900**
211	0	0	**1**	0	0	0	0	0	**2700**	**2100**	**900**
212	0	0	**1**	0	0	0	0	0	**2700**	**2100**	**900**
213	0	0	**1**	0	0	0	0	0	**2700**	**2100**	**900**
220	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
221	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
222	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
223	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
310	**1**	0	0	0	0	0	0	0	**600**	**900**	**300**
311	0	**1**	0	0	**1**	0	0	**1**	**600**	**900**	**300**
312	0	**1**	0	0	0	**1**	0	0	**600**	**900**	**300**
313	0	0	**1**	0	0	0	0	0	**600**	**900**	**300**
320	**1**	0	0	0	0	0	0	0	**2100**	**3000**	**600**
321	0	0	**1**	0	0	0	0	0	**2100**	**3000**	**600**
322	0	0	**1**	0	0	0	0	0	**2100**	**3000**	**600**
330	**1**	0	0	0	0	0	0	0	**1500**	**300**	**600**
331	0	0	**1**	0	0	0	0	0	**1500**	**300**	**600**
332	0	0	**1**	0	0	0	0	0	**1500**	**300**	**600**

User-5

Optimal LOR decisions for Machine-1

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
010	0	1	0	0	1	0	1	0	300	300	300
020	1	0	0	0	0	0	0	0	1200	1200	300
310	1	0	0	0	0	0	0	0	900	600	900
301	1	0	0	0	0	0	0	0	1800	1800	300
302	1	0	0	0	0	0	0	0	900	1200	1200
110	1	0	0	0	0	0	0	0	300	300	300
111	0	0	1	0	0	0	0	0	300	300	300
112	0	1	0	0	0	1	0	0	300	300	300
113	0	1	0	0	0	1	0	0	300	300	300
114	0	1	0	0	0	1	0	0	300	300	300
120*	1	0	0	0	0	0	0	0	600	600	300
121*	0	0	1	0	0	0	0	0	600	600	300
122*	0	0	1	0	0	0	0	0	600	600	300
130	1	0	0	0	0	0	0	0	300	300	300
131	0	1	0	0	0	1	0	0	300	300	300
132	0	1	0	0	1	0	0	1	300	300	300
133	0	1	0	0	1	0	0	1	300	300	300
134	0	1	0	0	0	1	0	0	300	300	300
210	1	0	0	0	0	0	0	0	300	300	300
211	0	1	0	0	0	1	0	0	300	300	300
212	0	0	1	0	0	0	0	0	300	300	300
213	0	0	1	0	0	0	0	0	300	300	300
220	1	0	0	0	0	0	0	0	300	300	300
221	0	1	0	0	0	1	0	0	300	300	300
222	0	1	0	0	1	0	0	1	300	300	300
223	0	1	0	0	0	1	0	0	300	300	300

Optimal LOR decisions for Machine-2

(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
010	1	0	0	0	0	0	0	0	300	300	300
201	1	0	0	0	0	0	0	0	3000	3000	600
202	1	0	0	0	0	0	0	0	3900	3900	1200
203	1	0	0	0	0	0	0	0	2400	2400	300
110	1	0	0	0	0	0	0	0	600	300	300
111	0	1	0	0	1	0	0	1	600	300	300
112	0	1	0	0	0	1	0	0	600	300	300
120*	0	0	1	0	0	0	0	0	300	300	300
121*	0	0	1	0	0	0	0	0	300	300	300
122*	0	0	1	0	0	0	0	0	300	300	300
130	1	0	0	0	0	0	0	0	300	300	300
131	0	1	0	0	0	1	0	0	300	300	300
132	0	0	1	0	0	0	0	0	300	300	300
210	1	0	0	0	0	0	0	0	300	300	300
211	0	1	0	0	0	1	0	0	300	300	300
212	0	1	0	0	0	1	0	0	300	300	300
213	0	0	1	0	0	0	0	0	300	300	300
220	1	0	0	0	0	0	0	0	600	600	300
221	0	0	1	0	0	0	0	0	600	600	300
222	0	0	1	0	0	0	0	0	600	600	300
310	1	0	0	0	0	0	0	0	900	600	300
311	0	0	1	0	0	0	0	0	900	600	300
312	0	1	0	0	0	1	0	0	900	600	300
320	1	0	0	0	0	0	0	0	600	300	300
321	0	0	1	0	0	0	0	0	600	300	300
322	0	1	0	0	1	0	0	1	600	300	300
330	1	0	0	0	0	0	0	0	300	300	300
331	0	1	0	0	0	1	0	0	300	300	300
332	0	1	0	0	0	1	0	0	300	300	300

Optimal LOR decisions for Machine-3											
(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
330	**1**	0	0	0	0	0	0	0	**6600**	**900**	**300**
310	**1**	0	0	0	0	0	0	0	**6300**	**4800**	**6300**
320	**1**	0	0	0	0	0	0	0	**5100**	**1200**	**6300**
110	**1**	0	0	0	0	0	0	0	**1500**	**300**	**600**
111	0	0	**1**	0	0	0	0	0	**1500**	**300**	**600**
112	0	0	**1**	0	0	0	0	0	**1500**	**300**	**600**
113	0	0	**1**	0	0	0	0	0	**1500**	**300**	**600**
120*	**1**	0	0	0	0	0	0	0	**300**	**600**	**600**
121*	0	0	**1**	0	0	0	0	0	**300**	**600**	**600**
122*	0	0	**1**	0	0	0	0	0	**300**	**600**	**600**
130	**1**	0	0	0	0	0	0	0	**300**	**900**	**300**
131	0	**1**	0	0	0	**1**	0	0	**300**	**900**	**300**
132	0	0	**1**	0	0	0	0	0	**300**	**900**	**300**
133	0	**1**	0	0	0	**1**	0	0	**300**	**900**	**300**
210	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
211	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
212	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
213	0	**1**	0	0	0	**1**	0	0	**300**	**300**	**300**
220	**1**	0	0	0	0	0	0	0	**600**	**600**	**300**
221	0	0	**1**	0	0	0	0	0	**600**	**600**	**300**
222	0	0	**1**	0	0	0	0	0	**600**	**600**	**300**
223	0	**1**	0	0	0	**1**	0	0	**600**	**600**	**300**

Optimal LOR decisions for Machine-4											
(ijk)	Base (e=1)			Depot (e=2)			OEM (e=3)		Different PM Strategy		
	Repair	Move	Discard	Repair	Move	Discard	Repair	Discard			
	$L_{1,1}(ijk)$	$L_{2,1}(ijk)$	$L_{3,1}(ijk)$	$L_{1,2}(ijk)$	$L_{2,2}(ijk)$	$L_{3,2}(ijk)$	$L_{1,3}(ijk)$	$L_{3,3}(ijk)$	PM-I	PM-II	PM-III
110	**1**	0	0	0	0	0	0	0	**300**	**3600**	**300**
111	0	**1**	0	0	**1**	0	0	**1**	**300**	**3600**	**300**
112	0	**1**	0	0	0	**1**	0	0	**300**	**3600**	**300**
113	0	**1**	0	0	0	**1**	0	0	**300**	**3600**	**300**
120*	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
121*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
122*	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
130	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
131	0	**1**	0	0	1	0	0	**1**	**300**	**300**	**300**
132	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
133	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
210	0	0	**1**	0	0	0	0	0	**2700**	**2100**	**900**
211	0	0	**1**	0	0	0	0	0	**2700**	**2100**	**900**
212	0	0	**1**	0	0	0	0	0	**2700**	**2100**	**900**
213	0	0	**1**	0	0	0	0	0	**2700**	**2100**	**900**
220	**1**	0	0	0	0	0	0	0	**300**	**300**	**300**
221	0	0	**1**	0	0	0	0	0	**300**	**300**	**300**
222	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
223	0	**1**	0	0	**1**	0	0	**1**	**300**	**300**	**300**
310	**1**	0	0	0	0	0	0	0	**600**	**900**	**300**
311	0	**1**	0	0	**1**	0	0	**1**	**600**	**900**	**300**
312	0	**1**	0	0	0	**1**	0	0	**600**	**900**	**300**
313	0	0	**1**	0	0	0	0	0	**600**	**900**	**300**
320	**1**	0	0	0	0	0	0	0	**2100**	**3000**	**600**
321	0	0	**1**	0	0	0	0	0	**2100**	**3000**	**600**
322	0	0	**1**	0	0	0	0	0	**2100**	**3000**	**600**
330	**1**	0	0	0	0	0	0	0	**1500**	**300**	**600**
331	0	0	**1**	0	0	0	0	0	**1500**	**300**	**600**
332	0	0	**1**	0	0	0	0	0	**1500**	**300**	**600**

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