An integrated strategy for fleet maintenance planning

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Abstract

Purpose – Conventionally, fleet maintenance decisions are made based on the level of repair (LOR) analysis. A general assumption made during LOR analysis is the consideration of the lifetime distribution with constant failure rate (CFR). However, industries do use preventive maintenance (PM) to extend the life of such components, which in turn may affect the LOR decisions such as repair/move/discard. The CFR assumption does not allow the consideration of effect of PM in LOR analysis. The purpose of this paper is to develop a more practical LOR analysis approach, considering the time-dependent failure rate (TDFR) of components and the effect of PM.

Design/methodology/approach – In the proposed methodology, first, a detailed life cycle model considering the effect of various parameters related to LOR and PM is developed. A simulation-based genetic algorithm approach is then used to obtain an integrated solution for LOR and PM schedule decisions. The model is also evaluated for the various cases of quality of maintenance measured in terms of degree of restoration.

Findings – The results, from the illustrative example for a multi-indenture and multi-echelon fleet maintenance network, show that the proposed integrated strategy leads to better LCC performance compare to the conventional approach. Additionally, it is identified that the degree of restoration also affects the PM schedule as well as LOR decisions of the fleet system. Therefore, consideration of TDFR is important to truly optimize the LOR decisions. The proposed approach can be applied to fleet of any equipment.

Research limitations/implications – The approach is illustrated using a hypothetical example of an industrial system. A more complex system structure in terms of number of machines, types of machines (identical vs non-identical), number of echelons, possible repair actions at various echelons, etc. may be present for a particular industrial case. However, the approach presented is generic and can be extended to any system. Moreover, the aim of the paper is to highlight the importance of the considering PM and quality of maintenance in LOR decision making.

Originality/value – To the best of the authors' knowledge, this is the first work which considers the effect of PM and quality of maintenance on LOR analysis. Consideration of TDFR and imperfect maintenance while optimizing LOR decisions is a complex problem. Thus, the work is of high significance from the research point of view. Also, most of the real life fleet systems use PM to extend the life of the equipment. Thus, present paper is a more practical approach for LOR analysis of such systems.

Keywords Preventive maintenance, Life cycle cost, Fleet, Level of repair analysis, Maintenance modelling, Multi-indenture and multi-echelon maintenance system

Paper type Research paper

Nomenclature

PV_{LCC}	is the present value of LCC for the machines in a fleet system maintenance
l	indicates the expected life of each machine
R	indicates the annual discount rate
m	represents number of identical machines at operated at base
$[C_{mf}]_{r,e}(ijk)]$	represents the one-time maintenance facility cost for the indenture level (ijk) based on selected repair action r and echelon e
$[CC(ijk)]_{PM}$	represents the cost of consumables for indenture level (ijk) during preventive repair action

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$CC_{r,e}$ (ijk)	represents the cost of consumables for the indenture level (ijk) based on selected repair action r and echelon e
$\left[NPM(ijk)_{t_{\mathrm{pm}}(\mathbf{ijk})}\right]_y$	indicates the number of preventive repair action for the indenture level (ijk)in yth year based on given PM schedule $\boldsymbol{t_{pm}}$ $\boldsymbol{(ijk)}$
$\left[\mathrm{nof}(ijk)_{t_{\mathrm{pm}}(\mathbf{ijk})}\right]_y$	indicates the number of failures of the indenture level (ijk)in yth year based on given PM schedule $\boldsymbol{t}_{\mathbf{pm}}(\mathbf{ijk})$
TTRPM$(ij0)$	indicates time to repair for the module $(ij0)$ during the preventive repair action
C_{dt}	denotes the down time cost per hour
$[\mathrm{TC}(ijk)]_{b-D}$	represents the cost of transportation for the indenture level (ijk) from the base to depot level
$[\mathrm{TC}(ijk)]_{d-\mathrm{OEM}}$	represents the cost of transportation for the indenture level (ijk) from the depot level to OEM level
$t_{\mathrm{opert.}}$	indicates the total operating time of the machines
$(\mathrm{T}_{\mathrm{Delay}})b-d$	denotes transportation time between base and depot
$(T_{\mathrm{Delay}})_{d-\mathrm{OEM}}$	denotes transportation time between depot level and OEM level
$h(ijk)$	represents the holding cost per year of an indenture items (ijk)
$\mathrm{PP}_{\boldsymbol{Q}(\mathbf{ijk})}$	denotes to the Poisson probability of an indenture items (ijk)
$\mathrm{PC}_{\boldsymbol{Q}(\mathbf{ijk})\mathrm{SL}}$	denotes to the Poisson cumulative probability for $\boldsymbol{Q}$ quantity of an indenture items (ijk)
$PC_{>\mathbf{Q}(\mathbf{ijk})_{SL}}$	indicates the probability of more than $\boldsymbol{Q}$ quantity of an indenture item (ijk) with predefine service level
SL	denotes to the predefine service level

1. Introduction

Efficient maintenance planning is important for industrial systems such as wind turbines, aircrafts, mining earth movers, and defense systems, in which unexpected failures create high repair and downtime costs. Most of such industrial systems/equipment/machines normally have "multi-indenture structure" as they are made up of assemblies, modules, and parts. They are generally operated as fleet. A fleet is a group of identical/non-identical machines operating at one location or different locations that share some common maintenance facilities (Rawat and Lad, 2015). Maintenance of such equipment or machines in the fleet is done under the multi-echelon maintenance network of base, central depot, and original equipment manufacturer (OEM). Conventionally, level of repair (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.

Significant amount of literature is available that deals with the optimization of LOR decisions considering LCC as performance criteria. In general, focus of these literatures is on the use of more efficient optimization techniques like integer programming (Barros, 1998), mixed integer programming (Brick and Uchoa, 2009), genetic algorithm (Saranga and Kumar, 2006), hybrid genetic algorithm (Bouachera *et al.* (2010), simulation-based approach (Cranshaw *et al.*, 2014; Rawat and Lad, 2015), etc. Literature also considers various system structures in terms of indenture level and echelon level. Barros (1998) considered only two indenture system (i.e. subsystem and module), on the other hand, Barros and Riley (2001), Basten *et al.* (2009), Basten (2009), Bouachera *et al.* (2010), Brick and Uchoa (2009), Rawat and Lad (2015) and Saranga and Kumar (2006) considered multi-indenture structure (i.e. assembly, module, and part). Similarly, Barros (1998) and Barros and Riley (2001) have considered only two echelons maintenance facility for the computer and aircraft industries, respectively, whereas Saranga and Kumar (2006) studied the multi-echelon maintenance location (i.e. base, depot, and OEM) dedicated for the aircraft environment. Few of the researchers also integrated LOR analysis with decisions on the location of repair facility and spare parts optimization. For example, Basten *et al.* (2011) and Brick and Uchoa (2009) proposed an integrated approach to optimize LOR and repair facility location. Integration of LOR and spare parts optimization is studied in Basten *et al.* (2012, 2015), Cranshaw *et al.* (2014), and Rawat and Lad (2015). One of the common assumptions made during the LOR analysis in the above literature is the consideration of constant failure rate (CFR) of the parts. However, as highlight by Wilkins (2002), and Saranga and Kumar (2006) many of the real systems do not exhibit CFR. This is particularly true for the case of mechanical components with deterioration as the primary failure mode. Moreover, CFR assumption does not allow the consideration of the effect of preventive action on the failure pattern of the parts. Therefore, it is important to optimize LOR decisions considering the time-dependent failure rate (TDFR) of the parts. Moreover, industries perform PM based on predefined schedule to reduce the failure rate and extend the life of the components. For modular system such as multi-indenture system, it is often preferable to perform PM at module level. Optimization of PM schedule is important for effective system performance. In the existing literature, PM optimization models have been intensively researched by many researchers. Uematsu and Nishida (1987) used a non-homogenous Poisson process to determine interval reliability, and developed an optimal replacement models based on various costs. They used a more general repair model where each interval of equipment function is subject to the influence of all previous failure history. Dekker and Smeitink (1991) consider a block replacement model, in which a component can only be replaced preventively at maintenance opportunities. Özekici (1988) studied a system whose components are stochastically and economically dependent and discussed the effect of these dependencies on periodic replacement policies. Gustavsson *et al.* (2014) proposed a preventive maintenance (PM) scheduling over a finite and discretized time horizon based on the interval costs. Maintenance optimization models of multi-component systems are widely reviewed in by Dekker *et al.* (1997), Nicolai and Dekker (2008), Wang (2002), Pham and Wang (1996), Wang and Pham (2006), Nowakowski and Werbińka (2009), and Wu and Zuo (2010). Bai and Pham (2006) have presented some results for multi-component systems on renewable full-service warranty policies. Similarly, optimal PM schedule for a multi-component system is presented by Tam *et al.* (2007). In many of the multi-component maintenance models, the emphasis is on three main groups of multi-component maintenance optimization models: the block replacement models, group maintenance models, and opportunistic maintenance models. Apart from this, imperfect repair is also widely studied in the maintenance literature. 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. Mainly such models are either based on the concept of virtual age or failure rate. For example, Kijima (1989) has used a virtual age concept to model the imperfect maintenance, which essentially says that the system is younger than that before the maintenance action by some interval. The same approach is used in the paper and is discussed in detail later. 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). It says that the failure rate function after an imperfect repair is different from the function before repair. Wu and Clements-Croome (2006) studied optimal maintenance policies under different operational schedules, in which three models are presented and cost functions are 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 modeled using system improvement model of Zhang and Jardine (1998).

As far as the integration of PM and LOR is concerned, no attempt has been found in the literature. The 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 often planned separately in a fleet system. Optimizing only the LOR decisions without considering the effect of PM schedule on the fleet system may not be effective. Hence, it is important to study the value of joint optimization of these two decisions in the fleet system, which is the prime focus of the present paper.

The rest of paper is organized as follows: Section 2 illustrates the system details and problem description. Section 3 narrates the development of optimization model and its complexities. The details of the developed LCC models are provided in the Section 4 followed by detailed analysis of the integrated results in Section 5. Section 6 concludes the paper and identifies the future scope of the work.

2. System details and problem description

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. Figure 1 shows the details of various indentures of a machine. Let the machine indenture levels are represented by an order triplet, i.e. ijk, where ($i00$) denotes the enclosed ith assembly at the first

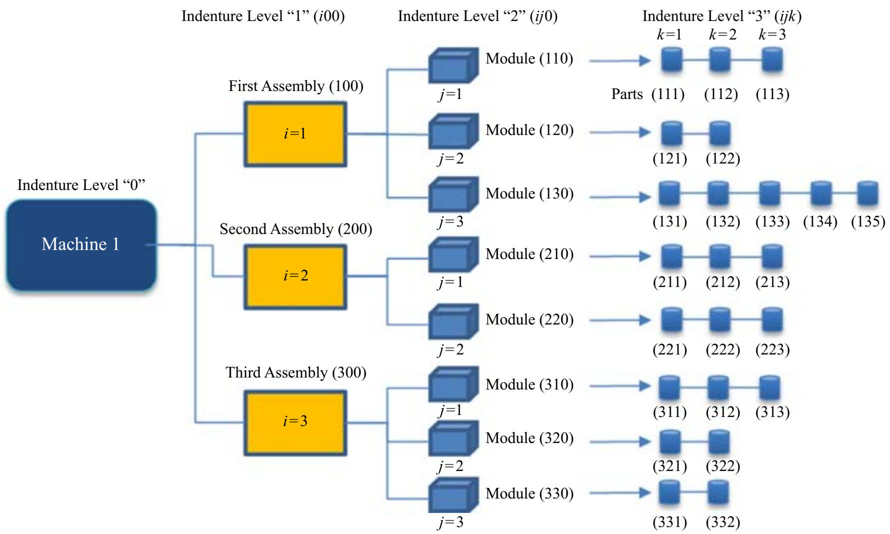

Figure 1.
Pictorial view of multi-indenture items for a machine operated at base

indenture level of a machine, ($ij0$) denotes the enclosed jth module of ith assembly at the second indenture level and (ijk) denotes the enclosed kth part of jth module of ith assembly of third indenture level. In the current problem, each machine is considered to be made up of three assemblies (i.e. $i=1$-3). Each assembly mainly varies in terms of number of the modules and parts enclosed in the assembly. Figure 1 shows the pictorial view of the multi-indenture system considered in this work. Let us assume that each assembly and its enclosed indenture levels are arranged reliability wise in series. Failures of machine occur because of failures of the lowest indenture level, i.e. part (ijk). The time to failures of each part follow a two parameters Weibull distribution. Let η_{ijk} indicates the characteristic life of a part (ijk) and β_{ijk} represents the shape parameter of a part (ijk). Table I shows reliability parameters and costs for each of the parts considered in this work. Let there be three echelons maintenance network of "Base ($e=1$)" or operating site, "Depot ($e=2$)" or central maintenance facility and "OEM ($e=3$)". Let each machine be operated 8,760 hours per year at the base. Whenever a machine fails at the base, the repair decision for the same is made based on the LOR analysis. Apart from this, machines are preventively maintained to reduce the failure rates of the components and extend the life of the components. It is, therefore, also important to optimize the PM schedule of the machine parts. LOR decisions and PM schedule optimization are discussed in the following sections.

2.1 LOR analysis

The LOR analysis, as discussed earlier, aims to decide followings:

(1) which indenture level ("module" or "part") to perform a repair action;

(2) what repair action ("repair" or "move" or "discard") to perform; and

(3) at which echelon level ("base" or "depot" or "OEM") to perform above two decisions.

These three types of decisions generally lead to sequential decision-making process. Figure 2 shows the flow chart of this decision-making process considered in this research work. The Figure 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 options as indicated in Figure 2. For example, the repair decision of the module will follow the process highlighted in italic in Figure 2. It says that the repair decision of module leads

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 INR)	Modules ($ij0$)	Part (ijk)	η_{ijk} (in hr)	β_{ijk}	Cost (in INR)	Modules ($ij0$)	Part (ijk)	ηijk (in hr)	βijk	Cost (inINR)
110	111	6,000	3.2	3,500	210	211	3,000	3	5,000	310	311	2,500	2.4	4,373
	112	3,500	2.6	2,500		212	3,500	3.2	5,650		312	3,850	2	4,665
	113	5,000	3.1	4,000		213	4,500	3	7,500		313	3,260	2.2	5,000
120	121	5,000	2.2	4,000	220	221	2,500	2.2	4,550	320	321	7,600	4	3,000
	122	4,000	2.3	3,000		222	2,200	2.1	2,500		322	6,100	2.5	3,500
130	131	2,500	2.6	5,000		223	3,600	3	2,500	330	331	2,000	2.83	3,500
	132	2,000	2	4,000							332	2,670	3	4,500
	133	3,000	2.7	6,000										
	134	4,000	3	3,000										
	135	5,000	2.5	6,500										

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

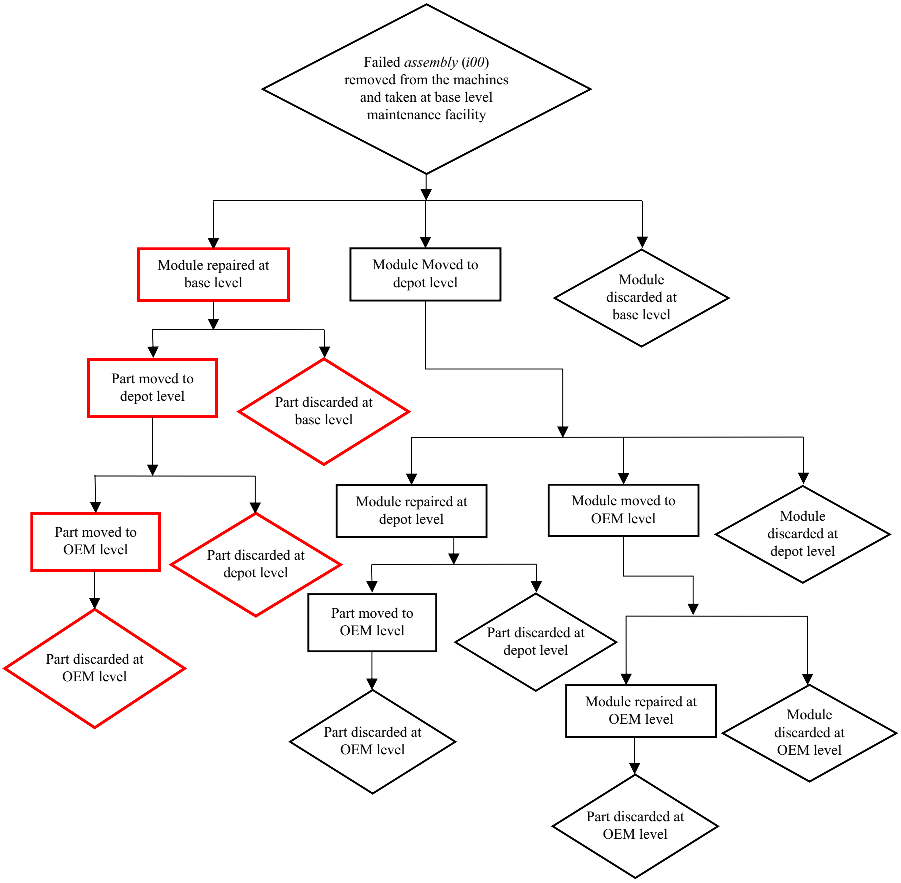

Figure 2.
Flow chart for the decision process considered during LOR analysis

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 can be read from the Figure 2. 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. If the decision of discard is made at depot or OEM then the failed assembly will have to wait till the replaced module or part reaches the base. It is assumed that the depot or OEM always has the sufficient spare items to perform the discard decisions.

The obvious difference in the above discussed 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, and repair action compared to replacement at part level. It will also reduce maintenance skill requirement and amount of repair equipment. However, replacement at 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 cost of inventory holding. The LOR analysis is, thus, done to obtain optimal LOR decisions for the machines that minimize the overall maintenance cost of the fleet system.

2.2 PM schedule

PM is generally done to reduce the failure rate and increase the useful life of the machine components. However, PM 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 PM that minimizes the life cycle cost or cost of maintenance. For modular systems such as multi-indenture systems, it is often preferable to perform PM at module level.

2.3 Integrated strategy

The PM schedule and LOR are two important activities in fleet maintenance. These activities are typically performed independently despite the clear relationship that exists between them. Therefore, an integrated strategy is required that minimizes the LCC of the fleet maintenance while selecting the following decisions:

- optimal LOR decisions, and
- optimal decisions for PM schedule.

Next section presents the problem formulation used in this research work.

3. Problem formulation

As mentioned in Section 2.3, in the proposed integrated strategy, 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 follows.

Minimize:

$$\mathrm{PV_{LCC}} = f\left[\boldsymbol{t}_{\mathbf{pm}}(\mathbf{ijk}),\ \boldsymbol{L}_{\mathbf{r,e}}(\mathbf{ijk}),\ \text{model parameters}\right] \tag{1}$$

subject to LOR decision constraints; where, $\boldsymbol{t}_{\mathbf{pm}}(\mathbf{ijk})$ represents matrix of decision of PM schedule for enclosed kth part of jth module of ith assembly. In this research work, the fixed calendar time-based PM policy is considered, where PM varies from $\boldsymbol{t}_{\mathbf{pm}} = 500$ to 8,760 hr. During each preventive action, all parts (ijk) of a module will be restored with some restoration factors (RFs). In this research, different cases for RF such as 20, 30, 40, 50, 60, 70, and 80 percent are used to evaluate the integrated strategy. In this work, Kijima's (1989) virtual model is used to update the age of the component under imperfect maintenance. The model can be summarized as follows: consider a unit of equipment that, at any point in time, is in one of two states, functioning or under maintenance (corrective or preventive); and assume that the unit is initially (at time $t = 0$) functioning. Let D_j denotes the duration of the period between the completion of the ($j-1$)th maintenance action, and the jth maintenance action; and let V_j denotes the virtual age of the unit at the time of completion of the jth maintenance action. Kijima's model of virtual age is:

$$V_j = V_{j-1} + (1-\mathrm{RF}) \cdot D_j \tag{2}$$

where RF is a constant, such that $0 \leqslant \mathrm{RF} \leqslant 1$. It captures the degree of equipment restoration achieved through repair action. The RF is used to determine the age of the component after any maintenance (corrective or preventive) action. The RF is defined as a number between 0 and 1 and has the following effect: a RF of 1 (100 percent) implies that the component is as good as new after repair, which in effect implies that the age of the component after maintenance again becomes 0. A RF of 0 implies that the component age is the same as it was prior to repair, which in effect implies that the age of the component after maintenance remains the same as it was at the time of maintenance. Accordingly, a RF of 0.25 (25 percent) implies that the age of the component after maintenance is equal to 75 percent of the age of the component at the time of maintenance.

$\boldsymbol{L}_{\mathbf{r,e}}$ (**ijk**) denotes to LOR decision matrix for enclosed kth part of jth module of ith assembly, where **r** denotes to the repair action decisions; $r = 1$ denoting to "repair decision", $r = 2$ denoting to "move decision," and $r = 3$ denoting to "discard decision." These repair actions are performed at different echelons in fleet structure 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) In the optimization model these LOR decision is considered as follows:

$$\mathbf{L}_{\mathbf{r},\mathbf{e}}(ijk) = \left\{ \begin{array}{ll} 1, & \text{repair action “}\mathbf{r}\text{” at echelon “}\mathbf{e}\text{” is selected for indenture item } (ijk); \\ 0, & \text{otherwise} \end{array} \right\}$$

The life cycle cost model, shown in Equation (1), has various parameters like costs, repair, and failure. For example, cost parameters are non-recurrent cost (NRC), consumable costs, transportation costs, etc. Similarly time parameters are shape and scale parameters of Weibull distribution, and repair parameters are the mean and standard deviation of normal time to repair distribution, etc.

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.

Assumptions:

(1) It is assumed that the failures of parts are independent.

(2) It is assumed that only one maintenance action will be taken at each echelon for each indenture items ijk, i.e. $\sum \boldsymbol{L}_{\mathbf{r},1}$ (**ijk**) $= 1$, $\sum \boldsymbol{L}_{\mathbf{r},2}$ (**ijk**) $= 1$ and $\sum \boldsymbol{L}_{\mathbf{r},3}$ (**ijk**) $= 1$.

(3) If the "move" decision is made at echelon 1 (i.e. at base) then at least one maintenance action is made at echelon 2 (i.e. at depot), i.e. $\boldsymbol{L}_{2,1}$ (**ijk**) $= \sum_{r=1}^{3} \boldsymbol{L}_{\mathbf{r},2}(\mathbf{ijk}) = 1$. Similarly, it is considered for the depot, i.e. $\boldsymbol{L}_{2,2}$ (**ijk**) $= \sum_{r=1}^{3} \boldsymbol{L}_{\mathbf{r},3}(\mathbf{ijk}) = 1$.

(4) If a higher indenture item is discarded or moved, subsequently its enclosed lower indenture items are also discarded or moved at same echelon. For example, if a discard decision is made for module at the depot level, subsequently enclosed parts are discarded at that echelon as well, i.e. $\boldsymbol{L}_{\mathbf{r,e}}$ (**ij**0) $\leqslant \boldsymbol{L}_{\mathbf{r,e}}$ (**ijk**), where $r = 2$, 3 and $e = 1$, 2, 3.

4. Life cycle cost models

The LCC is one of the key parameters considered in evaluating the cost effectiveness of any system (Fabrycky, 1991). 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. NRC and annual average recurrent cost (AARC). In this research work, NRC and AARC are further divided into different costs as described in Table II. Whenever a maintenance action, i.e. PM and CM, is performed, the NRC and AARC are incurred. The NRC is considered as one-time investment cost made in installing the maintenance facility at multi-echelon maintenance locations. These maintenance facilities can be utilized to perform the maintenance actions on the fleet machines. The AARC is cost consumed recurrently in every year, thought the life of the machines. Table II provided the details of AARC used in the current problem.

4.1 NRC

NRC 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). The DINRC is sum of the total cost for acquiring and installing the all-purpose maintenance equipment and other facilities at base, depot, and OEM level. However, it does not affect the decision variables. Therefore, DINRC is not included in estimating the LCC in the present work. DDNRC is one-time investment required at multi-echelon maintenance locations based on given LOR decisions. For example, cost of maintenance facility for repair of a module will be more as compare to discard of the module. Similarly, cost of maintenance facility for repair at the base level is more as compare to repair at depot level or OEM level. It is mainly because the depot and OEM generally have more advanced maintenance equipment than that at the base-level maintenance facility. This cost is considered in such a way that if the discard decision is made for module at the base only discard maintenance facility cost for that module will be considered at the base. Therefore, the DDNRC can be calculated as follows:

$$DDNRC = \sum_{ijk} \sum_{r=1}^{3} \sum_{e=1}^{3} \left[C_{mf}\right]_{r,e}(ijk)\left[\boldsymbol{L}_{\mathbf{r},\mathbf{e}}(\mathbf{ijk})\right] \tag{3}$$

Table III provides the details of the DDNRC for the different assemblies of a machine, respectively.

4.2 AARC

AARC 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 PM, whereas the annual average down time cost (AADTC), annual average transportation cost (AATC), annual average consumable cost (AACC), annual average spare holding cost (AASHC), and annual average stock-out cost (AASOC) are the costs associated with LOR analysis.

4.2.1 AADTC. The AADTC 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 research work, as two maintenance actions, i.e. PM and LOR, are performed on the machines; therefore, down time of the machines are estimated based on

Breakdown structure of life cycle costs	
Non-recurrent cost (NRC)	Annual average recurrent cost (AARC)
	Annual average consumable cost (AACC)
Decisions independent non-recurrent cost (DINRC)	Annual average down time cost (AADTC)
	Annual average transportation cost (AATC)
Decisions dependent non-recurrent cost (DDNRC)	Annual average spare holding cost (AASHC)
	Annual average stock-out cost (AASOC)

Table II. Description of the life cycle costs

Table III. Decision dependent non-recurrent cost for machine indenture items (*ijk*) (in INR)

		Base (echelon 1)			Depot (echelon 2)			OEM (echelon 3)	
Assemblies (*i*00)	Indenture level (*ijk*)	Repair $L_{1,1}$ (*ijk*)	Move $L_{2,1}$ (*ijk*)	Discard $L_{3,1}$ (*ijk*)	Repair $L_{1,2}$ (*ijk*)	Move $L_{2,2}$ (*ijk*)	Discard $L_{3,2}$ (*ijk*)	Repair $L_{1,3}$ (*ijk*)	Discard $L_{3,3}$ (*ijk*)
	(110)	1,500	0	375	1,100	0	275	825	137.5
Assembly (100)	(111)	–	0	100	–	0	100	–	50
	(112)	–	0	100	–	0	100	–	50
	(113)	–	0	100	–	0	100	–	50
	(120)	1,000	0	na	800	0	200	600	100
	(121)	–	0		–	0	75	–	37.5
	(122)	–	0		–	0	75	–	37.5
	(130)	1,100	0	275	1,200	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)	1,200	0	na	1,050	0	262.5	787.5	131.25
	(211)	–	0		–	0	100	–	50
	(212)	–	0		–	0	100	–	50
	(213)	–	0		–	0	100	–	50
	(220)	1,050	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)	1,500	0	na	1,200	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

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 performed 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). It is divided in two parts $MTTR_1$ 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 *i*th assembly is indicated by $MTTR_1$ (*i*00).
- $MTTR_2$: 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:

$$\begin{aligned}\mathrm{MTTR}_2(ijk) = {} & ([MTTR(ijk)]_b \cdot \boldsymbol{L}_{3,1}(\mathbf{ijk}) + \left(\left[T_{\mathrm{Delay}}\right]_{b-D}\right) \cdot \left[\boldsymbol{L}_{2,1}(\mathbf{ijk})\right] \\ & + [\mathrm{MTTR}(ijk)]_D \cdot \boldsymbol{L}_{3,2}(ijk) + \left(\left[T_{\mathrm{Delay}}\right]_{d-\mathrm{OEM}}\right) \cdot \left[\boldsymbol{L}_{2,2}(\mathbf{ijk})\right] \\ & + \left([\mathrm{MTTR}(ijk)]_{\mathrm{OEM}}\right) \cdot \left[\boldsymbol{L}_{2,3}(\mathbf{ijk})\right]\big) \end{aligned} \tag{4}$$

Therefore, the TMTTR for an indenture item (*ijk*) is the summation of $\mathrm{MTTR}_1(i00)$ and $\mathrm{MTTR}_2(ijk)$ as shown below:

$$\mathrm{TMTTR}(ijk) = \mathrm{MTTR}_1(i00) + \mathrm{MTTR}_2(ijk)$$

Therefore, the AADTC is estimated by the Equation (5).

$$\begin{aligned}\mathrm{AADTC} = {} & \sum_{ij0}\left\{[\mathrm{TTRPM}(ij0)] \times \mathrm{NPM}(ij0)_{\boldsymbol{t}_{\mathbf{pm}(\mathbf{ijk})}} \times m \times C_{dt}\right\} \\ & + \sum_{ijk}\left\{\mathrm{TMTTR}(ijk) \times \left[\mathrm{nof}(ijk)_{\boldsymbol{t}_{\mathbf{pm}(\mathbf{ijk})}}\right]_y \times m \times C_{dt}\right\}\end{aligned} \tag{5}$$

Table IV 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 V 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 INR1,000/hours.

4.2.2 AACC. The AACC 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 the given LOR decisions. 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

Module (*ij*0)	(110)	(120)	(130)	(210)	(220)	(310)	(320)	(330)
TTRPM (*ij*0) in hr.	10	6	8	8	8	8	6	6

Notes: Time to repair for the different modules (*ij*0) of a machine during the PM action

Table IV. Time consumed during the PM action for each module (*ij*0)

Table V. 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)

$TTR_1(100)$ (Part *ijk*)	Assembly (100) $(TTR_2)_b$	(2, 0.8) $(TTR_2)_D$	$(TTR_2)_{OEM}$	$TTR_1(200)$ (Part *ijk*)	Assembly (200) $(TTR_2)_b$	(3, 0.6) $(TTR_2)_D$	$(TTR_2)_{OEM}$	$TTR_1(300)$ (Part *ijk*)	Assembly (300) $(TTR_2)_b$	(4, 0.4) $(TTR_2)_D$	$(TTR_2)_{OEM}$
(110)	(8, 0.8)	(5, 0.5)	(3, 0.3)	(210)	na	(5, 0.5)	(3, 0.3)	(310)		(5, 0.5)	(3, 0.3)
(111)	(12, 1)	(9, 1)	(6, 0.6)	(211)		(9, 1)	(6, 0.6)	(311)	na	(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 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)	$[TDelay]_{b-D}$		$[TDelay]d_{-OEM}$					
(134)	(21, 3)	(18, 3)	(10, 2)	75 hr		96 hr					
(135)	(14, 2)	(10, 2)	(7, 0.7)								

Note: "na" indicates the maintenance and repair constraints for that items (*ijk*) at echelon e 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. Therefore, the AACC is the summation of consumable cost incurs during the PM action and LOR analysis. Thus, it can be calculated as:

$$\mathrm{AACC} = \sum_{ijk} \mathrm{CC}(ijk)_{\mathrm{PM}} \times \mathrm{NPM}(ijk)_{(\boldsymbol{t}_{\mathbf{pm}}(\mathbf{ijk}))} \times m + \sum_{ijk} \sum_{r=1}^{3} \sum_{e=1}^{3} \left(\mathrm{CC}_{r,e}(ijk) \times \left[\mathrm{nof}(ijk)_{\boldsymbol{t}_{\mathbf{pm}}(\mathbf{ijk})} \right]_y \times m \right) \cdot \left[\boldsymbol{L}_{\boldsymbol{r},\boldsymbol{e}}(\mathbf{ijk}) \right] \quad (6)$$

The costs of consumable during the PM are considered as some percentage of the indenture cost. In the present work, 1 percent of module and 3 percent of part cost is considered. The consumable costs for respective LOR decisions for modules and parts of different assemblies are mentioned in Table VI.

4.2.3 AATC. 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:

$$\mathrm{AATC} = \sum_{ijk} \left(\mathrm{TC}(ijk)_{b-D} \times \left[\mathrm{nof}(ijk)_{\boldsymbol{t}_{\mathbf{pm}}(\mathbf{ijk})} \right]_y \times m \right) \cdot \boldsymbol{L}_{2,1}(\mathbf{ijk}) + \sum_{ijk} \left(\mathrm{TC}(ijk)_{D-\mathrm{OEM}} \times \left[\mathrm{nof}(ijk)_{\boldsymbol{t}_{\mathbf{pm}}(\mathbf{ijk})} \right]_y \times m \right) \cdot \boldsymbol{L}_{2,2}(\mathbf{ijk}) \quad (7)$$

Generally, the transportation cost is calculated as some percentage of cost of indenture items as described in Table VII. The transportation cost given in Table VII includes "to and fro" cost between two echelons.

4.2.4 AASHC. The AASHC in fleet structure includes holding cost at base, depot, and OEM. In current problem, it is assumed that the annual spare quantity and holding cost at depot and OEM is fixed. 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. The base-level maintenance facility maintains spare parts with a predefined 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 next sub-section gives the details of that algorithm.

4.2.4.1 Estimation of spares considering predefined SL. The SL is the confidence level of keeping spare of repaired indenture items for not hitting the stock out at base. Faraci (2008) proposes an optimization algorithm considering the Poisson cumulative probability for estimating the recommended spares with predefined SL. Here, the same algorithm is used to estimate the spares of indenture items (ijk) based on predefined SL (SL%). According to this, the spares of an indenture item based on predefine SL (SL%) is equal to the summation of Poisson cumulative probability with recommended spares quantity of that indenture item $\boldsymbol{Q}(\mathbf{ijk})$. Thus, Poisson probability of exactly $\boldsymbol{Q}(\mathbf{ijk})$ spare of an indenture item (ijk) at the base is

Assemblies (i00)	Indenture items (*ij*0)/(*ijk*)	Base (echelon 1) Repair $L_{1,1}$ (*ijk*)	Move $L_{2,1}$ (*ijk*)	Discard $L_{3,1}$ (*ijk*)	Depot (echelon 2) Repair $L_{1,2}$ (*ijk*)	Move $L_{2,2}$ (*ijk*)	Discard $L_{3,2}$ (*ijk*)	OEM (echelon 3) Repair $L_{1,3}$ (*ijk*)	Discard $L_{3,3}$ (*ijk*)
Assembly (100)	(110)	200	50	11,000	200	50	11,000	200	11,000
	(111)	–	50	3,500	–	50	3,500	–	3,500
	(112)	–	50	2,500	–	50	2,500	–	2,500
	(113)	–	50	4,000	–	50	4,000	–	4,000
	(120)	150	50	na	150	50	7,700	150	7,700
	(121)	–	50		–	50	4,000	–	4,000
	(122)	–	50		–	50	3,000	–	3,000
	(130)	350	50	26,950	350	50	26,950	350	26,950
	(131)	–	50	5,000	–	50	5,000	–	5,000
	(132)	–	50	4,000	–	50	4,000	–	4,000
	(133)	–	50	6,000	–	50	6,000	–	6,000
	(134)	–	50	3,000	–	50	3,000	–	3,000
	(135)	–	50	6,500	–	50	6,500	–	6,500
Assembly (200)	(210)	200	50	na	200	50	19,965	200	19,965
	(211)	–	50		–	50	5,000	–	5,000
	(212)	–	50		–	50	5,650	–	5,650
	(213)	–	50		–	50	7,500	–	7,500
	(220)	200	50	10,505	200	50	10,505	200	10,505
	(221)	–	50	4,550	–	50	4,550	–	4,550
	(222)	–	50	2,500	–	50	2,500	–	2,500
	(223)	–	50	2,500	–	50	2,500	–	2,500
Assembly (300)	(310)	200	50	na	200	50	15,441.8	200	15,441.8
	(311)	–	50		–	50	4,373	–	4,373
	(312)	–	50		–	50	4,665	–	4,665
	(313)	–	50		–	50	5,000	–	5,000
	(320)	150	50	7,150	150	50	7,150	150	7,150
	(321)	–	50	3,000	–	50	3,000	–	3,000
	(322)	–	50	3,500	–	50	3,500	–	3,500
	(330)	150	50	8,800	150	50	8,800	150	8,800
	(331)	–	50	3,500	–	50	3,500	–	3,500
	(332)	–	50	4,500	–	50	4,500	–	4,500

Table VI. Consumable cost for different assemblies based on repair action "**r**" at echelon "**e**" (in INR)

Indenture level (*ijk*)	Transportation cost between base to depot $\mathrm{TC}(ijk)_{b-D}$	Transportation cost between depot to OEM $\mathrm{TC}(ijk)_{D-\mathrm{OEM}}$
Module (*ij*0) (%)	18	20
Parts (*ijk*) (%)	8	10

Table VII. Cost of transportation for an indenture items (*ijk*) between different echelons

calculated as follows:

$$\mathrm{PP}_{\boldsymbol{Q}(\mathbf{ijk})} = \left(\frac{\left(\left(\left[\left[\mathrm{nof}(ijk)_{\boldsymbol{t}_{\mathbf{pm}(\mathbf{ijk})}} \right]_y \times m \times t_{\mathrm{opert.}} \right] \right) \right)^{\boldsymbol{Q}(\mathbf{ijk})} \times e^{-\left(\left(\left[\left[\mathrm{nof}\ (ijk)_{\boldsymbol{t}_{\mathbf{pm}(\mathbf{ijk})}} \right]_y \times m \right] \times t_{\mathrm{opert.}} \right) \right)}}{\boldsymbol{Q}(\mathbf{ijk})!} \right) \cdot \left[\boldsymbol{L}_{3,1}(\mathbf{ijk}) \right] \tag{8}$$

The Poisson cumulative probability of exactly $\boldsymbol{Q}(\mathbf{ijk})$ or less spares of an indenture item (ijk) at base is calculated as follows:

$$\mathrm{PP}_{\boldsymbol{Q}(\mathbf{ijk})_{SL}} = \left(\sum_{j(ijk)=0}^{\boldsymbol{Q}(\mathbf{ijk})} \frac{\left(\left[\left[\mathrm{nof}(ijk)_{\boldsymbol{t}_{\mathbf{pm(ijk)}}}\right]_y \times m \times t_{\mathrm{opert.}}\right]\right)^{j(\mathrm{ijk})} \times e^{-\left(\left[\left[\mathrm{nof}(\mathrm{ijk})_{\boldsymbol{t}_{\mathbf{pm(ijk)}}}\right]_y \times m\right] \times t_{\mathrm{opert.}}\right)}}{j(ijk)!} \right) \cdot \left[\boldsymbol{L}_{3,1}(\mathbf{ijk})\right] \tag{9}$$

Therefore, the following equation should be fulfilled for estimating the spares of an indenture item (ijk) with predefined SL. In all, 95 percent SL is used in this problem:

$$\mathrm{PC}_{\boldsymbol{Q}(\mathbf{ijk})_{\mathrm{SL}}} \geqslant (\mathrm{SL}\%) \tag{10}$$

Now the AASHC at base-level maintenance facility can be calculated as follows:

$$\mathrm{AASHC} = \left(\left[\boldsymbol{Q}(\mathbf{ijk})_{\mathrm{SL}}\right] \times [h(\mathrm{ijk})] \times \mathrm{PC}_{\boldsymbol{Q}(\mathbf{ijk})_{\mathrm{SL}}}\right) \tag{11}$$

Normally, cost for holding an indenture item is estimated based on percentage (i.e. 50 percent as used in this work) of that indenture items. It includes annualized insurance, physical handling, inventory storage cost such as cost to rent, lease, or finance for storage facility and inventory risk cost, etc.

4.2.5 AASOC. AASOC is the cost of down time due to the unavailability of spares of indenture items at base. In this problem the stock-out situation is the situation where there is no spare available at the base. Now the stock-out situation is considered based on estimated probabilities of more than $\boldsymbol{Q}(\mathbf{ijk})$ quantity with predefined SL required at base. Therefore, the probability of more than $\boldsymbol{Q}(\mathbf{ijk})$ recommend spares with SL requires at the base level is estimated as follows:

$$\mathrm{PC}_{>\boldsymbol{Q}(\mathbf{ijk})_{\mathrm{SL}}} = 1 - \mathrm{PC}_{\boldsymbol{Q}(\mathbf{ijk})_{\mathrm{SL}}} \tag{12}$$

Thus, the AASOC is calculated as follows:

$$\mathrm{AASOC} = \left(\left[\mathrm{PC}_{>\boldsymbol{Q}(\mathbf{ijk})_{\mathrm{SL}}}\right] \times \left(\left[T_{\mathrm{Delay}}\right]_{b-d} \times C_{dt} + \mathrm{TC}(ijk)_{b-D}\right)\right) \tag{13}$$

During the stock out situation, the stock out spare will be called from the depot level. Therefore, the stock out cost is calculated based on costs, i.e. down time cost; it includes transportation delay time between base and depot and transportation cost.

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 following equations, respectively:

$$\mathrm{AARC} = \mathrm{AADTC} + \mathrm{AATC} + \mathrm{AACC} + \mathrm{AASHC} + \mathrm{AASOC} \tag{14}$$

$$\mathrm{NRC} = \mathrm{DINRC} + \mathrm{DDNRC} \tag{15}$$

Therefore, total LCC for fleet maintenance is the summation of AARC and NRC. Let the life of each machine at the base be $l=10$ years and discounting factor for money be 5 percent which remains constant throughout the life of machine. Therefore, LCC of fleet maintenance system is the discounted sum of NRC and AARC over the life of the system. Then PV of fleet maintenance LCC is estimated as follows:

$$\mathrm{PV_{LCC}} = \mathrm{NRC} + \sum_{y=1}^{l} \left\{ \frac{1}{(1-R)^{y}} \times \mathrm{AARC} \right\} \tag{16}$$

5. Solution methods and results

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 eight number of enclosed indenture items (i.e. 2 modules + 8 parts of corresponding modules), whereas third assembly of the machine has ten indenture items. Similarly, the number of repair actions available at base, depot, and OEM for each indenture item are eight (i.e. 3 at base + 3 at depot + 2 at OEM). Therefore, the total number of "LOR decision" would be [Total number of LOR decisions$^{\text{(Number of indenture item in an assembly)}}$], 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 to 8,760 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 three, two and three, respectively; therefore, total number of PM schedule decisions would be [Total number of PM schedule decisions $^{\text{(Number of module in an assembly)}}$], 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:

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

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. Therefore, a simulation-based GA is used in this research to solve the above problem. In this illustration the value of genetic algorithm parameters are used as follows: the population size $=50$, cross-over probability $=0.75$, and mutation rate $=0.1$.

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 a parts (*ijk*), if the individual part of the module is discard.
- Case 2: numbers of failures of a module (*ij*0), if the module consisting of the all enclosed part is discarded.

First case can be seen as the repair at module level with different degree of restoration. Second is the case of discard at module level. The discard of the whole module creates the higher degree of restoration as compare to discard the individual part. The number of failures is estimated using simulation.

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

5.1 Results and discussion

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 RFs are described in Table IX. Figure 3 shows the percentage improvement of LCC considering the “integrated strategy” over “without 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 “without 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 trend in percentage of improvement with respect to RFs.

The obtained optimal “PM schedule” for different modules of the machine for all the cases of restoration is summarized in Table X. It can be seen from Table X that the optimal

		No PM		500 hr		3,200 hr		5,000 hr	
Modules (*ij*0)	Part (*ijk*)	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	2.8428	0.1838	0.2176	1.6254	2.1382	2.042	2.5154
	(113)	1.532	2.8428	0.0256	0.2176	0.635	2.1382	1.0506	2.5154
(120)	(121)	1.601	2.664	0.184	0.4374	0.978	2.0938	1.2444	2.3952
	(122)	2.0882	2.664	0.2548	0.4374	1.3976	2.0938	1.7444	2.3952
(130)	(131)	3.5412	7.2172	0.3508	1.912	2.7278	6.3684	3.1358	6.774
	(132)	4.5832	7.2172	1.2564	1.912	3.9012	6.3684	4.2238	6.774
	(133)	2.8624	7.2172	0.184	1.912	1.9896	6.3684	2.469	6.774
	(134)	2.007	7.2172	0.05	1.912	1.03	6.3684	1.608	6.774
	(135)	1.5806	7.2172	0.0742	1.912	0.7486	6.3684	1.111	6.774

Table VIII. Number of failures of considering different PM schedules for each parts of assembly 1

	Different cases of restoration factor (RF)						
Descriptions	20% RF	30% RF	40% RF	50% RF	60% RF	70% RF	80% RF
LCC (PV_{LCC}) × 10^7 in INR (in “Integ. Straty.”)	35.94	34.02	29.29	32.70	32.59	29.28	30.97
Total CM cost (×10^6) in INR (in “Integ. Straty.”)	24.9	24.72	21.05	21.66	21.34	19.17	20.37
Total PM cost (×10^6) in INR (in “Integ. Straty.”)	22.11	19.17	16.8	20.33	20.87	17.51	19.77

Table IX. LCC achieved considering the different cases of restoration factor

PM schedule for module (110) is 2,300 hr in 20%RF, 2,600 hr in 30%RF, 1,700 hr in 40%RF, 50%RF, 60%RF, 70%RF, and 2,000 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 RF may change the optimal PM schedule and, hence, needed to be considered while optimizing the LOR decisions.

The optimal results of LOR decision for one of the case of restoration (i.e. 20%RF) are described in Table XI. 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 XI. The recommended spares with 95 percent SL for the indenture items at base level are also describes in Table XI.

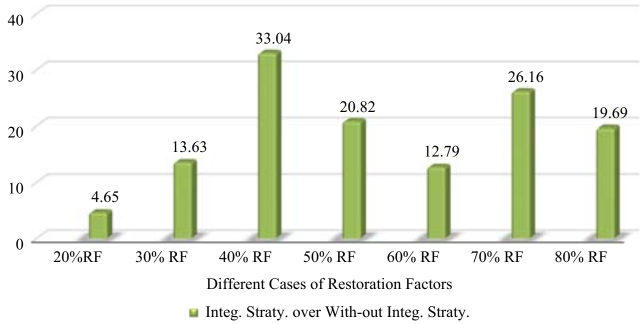

Figure 3. Percentage improvement of LCC considering the Integ. Straty. over dis-Integ. Straty

Table X. Optimum "PM schedule" (in hours) for different enclosed modules of assemblies

Modules (*ij*0)	Parts (*ijk*)	Different cases of restoration factor (RF) 20%	30%	40%	50%	60%	70%	80%
Module (110)	(111)	2,300	2,600	1,700	1,700	1,700	1,700	2,000
	(112)	2,300	2,600	1,700	1,700	1,700	1,700	2,000
	(113)	2,300	2,600	1,700	1,700	1,700	1,700	2,000
Module (120)	(121)	800	800	500	500	800	800	500
	(122)	800	800	500	500	800	800	500
Module (130)	(131)	500	1,100	1,700	800	500	1,400	800
	(132)	500	1,100	1,700	800	500	1,400	800
	(133)	500	1,100	1,700	800	500	1,400	800
	(134)	500	1,100	1,700	800	500	1,400	800
	(135)	500	1,100	1,700	800	500	1,400	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	2,000	800	800	800	800
	(222)	800	800	2,000	800	800	800	800
	(223)	800	800	2,000	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)	1,100	500	1,100	1,100	1,100	1,400	1,400
	(322)	1,100	500	1,100	1,100	1,100	1,400	1,400
Module (330)	(331)	2,000	2,000	2,000	2,000	2,000	2,000	2,000
	(332)	2,000	2,000	2,000	2,000	2,000	2,000	2,000

(ijk)	Base (e = 1) Repair $L_{1,1}$ (ijk)	Move $L_{2,1}$(ijk)	Discard $L_{3,1}$ (ijk)	Depot (e = 2) Repair $L_{1,2}$ (ijk)	Move $L_{2,2}$ (ijk)	Discard $L_{3,2}$ (ijk)	OEM (e = 3) Repair $L_{1,3}$ (ijk)	Discard $L_{3,3}$(ijk)	Optimum PM schedule (in hr)	Spare parts inventory 95% SL Q(ijk)
(110)	1	0	0	0	0	0	0	0	2,000	–
(111)	0	0	1	0	0	0	0	0	2,000	1
(112)	0	0	1	0	0	0	0	0	2,000	3
(113)	0	0	1	0	0	0	0	0	2,000	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		0	0	0	0	0	800	na
(211)	0	1	na	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		0	0	0	0	0	500	na
(311)	0	1	na	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	1,100	4
(321)	0	0	1	0	0	0	0	0	1,100	–
(322)	0	0	1	0	0	0	0	0	1,100	–
(330)	1	0	0	0	0	0	0	0	2,000	–
(331)	0	0	1	0	0	0	0	0	2,000	1
(332)	0	1	0	0	0	1	0	0	2,000	–

Table XI. Optimal LOR decisions for different assembly of a machine for 20%RF

For example, in the case of 20%RF, the recommended spare, i.e. ***Q*(ijk)** with 95 percent SL for part (111) is 1, for part (112), it is 3 and for part (113), it is 1.

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) obtained different optimal decisions of PM schedule and LOR. Table XII 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 TDFR of the parts plays an important role to achieve the better system performance as it helps in considering the effect of PM while optimize the LOR decisions.

6. Conclusions

The paper proposes an integrated approach which may be adopted by any fleet user in optimizing their fleet life cycle performance. We have presented an integrated strategy that finds optimal solution for integrated PM schedule and LOR analysis. Such strategy for the LOR optimization considering the TDFR is scarcely reported in the literature. In addition,

Different restoration case	(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 hr)
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	1,100
	(131)	0	0	1	0	0	0	0	0	1,100
	(132)	0	1	0	0	0	1	0	0	1,100
	(133)	0	1	0	0	0	1	0	0	1,100
	(134)	0	0	1	0	0	0	0	0	1,100
	(135)	0	1	0	0	1	0	0	1	1,100
40% RF	(130)	1	0	0	0	0	0	0	0	1,700
	(131)	0	0	1	0	0	0	0	0	1,700
	(132)	0	1	0	0	0	1	0	0	1,700
	(133)	0	0	1	0	0	0	0	0	1,700
	(134)	0	0	1	0	0	0	0	0	1,700
	(135)	0	1	0	0	0	1	0	0	1,700
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		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	1,400
	(131)	0	0	1	0	0	0	0	0	1,400
	(132)	0	1	0	0	0	1	0	0	1,400
	(133)	0	0	1	0	0	0	0	0	1,400
	(134)	0	0	1	0	0	0	0	0	1,400
	(135)	0	0	1	0	0	0	0	0	1,400
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

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

consideration of PM policies with LOR analysis is not addressed effectively. The results clearly indicate that the proposed integrated strategy leads to better LCC performance compared to non-integrated strategy. Additionally, the effect of the degree of restoration on PM schedule and LOR decisions of the fleet machines is discussed. 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. In future, other types of the maintenance strategies, such as condition-based maintenance, reliability-centered maintenance, and age-based PM can be modeled with the LOR analysis.

In addition, it will be useful to investigate the reliability design issues with LOR analysis. From modeling point of view, consideration of the stochastic dependency of the fleet system components can be incorporated in the developed fleet approaches.

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Further reading

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