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REVIEW PAPER

Multi-echelon Repair Inventory Systems: Select Issues in Modular Electronic Equipment

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ABSTRACT

Flow of modules/printed circuit boards (PCBs) in a multi-echelon repair inventory system pertaining to modular electronic equipment for large maintenance organisations having large inventory in range and depth, like defence has been critically examined using a case study. Desirable features of the proposed system are identified and a general framework suggested for examining its feasibility and implementation in an organisation. An analytical model with an objective to reduce number of echelons is also suggested and compared with the base model. It is suggested that various models can be compared through simulation and their performance measured using balanced scorecard approach.

Keywords: Multi-echelon repair inventory, modular equipment, maintenance

1. INTRODUCTION

Inventory systems determine optimal policies and procedures relating to stocks to be maintained in the system to meet future demands. A real life inventory problem of any significance is likely to involve items stocked and going through a number of locations before these finally reach the point of demand. But, compared to multi-location problems, the quantum of work reported on single inventory models is extremely large.

In multi-echelon inventory systems, the items are stocked nearer to point of consumption, rather than meeting the customers demand directly from the source. However, there are advantages associated with centrally controlled systems. It is possible to control over-stocking or under-stocking at individual locations by means of transshipment, returns and disposals. In addition, decisions can be made effectively and expeditiously even in emergencies, if the information about the entire system is recorded at a centre location.

Most of the real life physical distribution systems constitute the multi-echelon inventory system configuration relating to items of various categories like consumables, perishables, etc. Some of the multi-echelon inventory systems involve recoverable inventory, i.e. where the items are not consumable in nature, and can be economically repaired at some echelons. These systems are called repair-inventory systems. The complexities involved with multi-echelons systems are much more compared to single inventory systems due to various decisions to be made like choice of distribution channels, number of echelons, etc.

The decision for a multi-echelon repair inventory systems become even more complex as a large number of additional parameters affect the optimal decision making. Furthermore, the performance of this inventory sub-system is significantly influenced by other parameters of the system like the location of central repair and storage facilities, the level of maintenance manpower, the maintenance effectiveness of the repair facility, transshipment, cannibalisation of spares, etc.

A number of multi-echelons repair inventory systems are in place in various types of organisations. The multi-echelon repair inventory systems pertaining to electronic repairable of an Indian maintenance organisation has been studied in detail and various improvements suggested.

Modern electronic equipment are modular in construction and incorporates replaceable modules and printed circuit boards (PCBs). On equipment becoming faulty, these modules/PCBs are easily identified and replaced so that equipment can be restored quickly in lower repair echelons. However, these modules and PCBs are complex and costly and their quick repair and recycling in to the inventory systems at various echelons is of vital importance. Total inventory cost of modules/PCBs at various repair/stocking echelons depends on the type and size of the organisation.

Utility considerations of these organisations require quick fault diagnosis of repairable electronic equipment and replacement of faulty modules and PCBs in forward echelons to restore the equipment quickly. But due to their complexity, the faulty modules/PCBs need elaborate arrangements like special test equipments (STEs), jigs, fixtures and controlled environmental conditions for diagnosis and repairs. Therefore, the repairs to faulty modules/PCBs are carried out at nodal repair centres in the rear echelons and repaired modules/PCBs recycled back in the inventory system.

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The above multi-echelon repair inventory system for modular electronic equipment already exists in various maintenance organisations of several countries. The monitoring of each repair echelon in respect of most of these organisations in various countries is presently done only on the basis of the average turn around time for various modules/PCBs by monitoring cells at various levels (i.e., at corresponding echelons) which ensure quick recycling of modules.

Large number of published papers pertains to determining stock levels at each location for achieving optimum inventory levels with minimum backorders, ordering policy for batches, emergency lateral transhipments, etc. Some of the recent works discuss impact of repair priorities in spare part networks and using simulation to gain insights into multi echelon inventory optimisation. Few issues on maintenance management, performance measurement systems using balanced scorecard approach and flexibility in maintenance have also been covered.

Muckstadt[1] describes a mathematical model, called MOD-METRIC, for control of a multi-item, multi-echelon, multi-indenture inventory system for recoverable items. Babu[2] has analysed multi-echelon repair-inventory systems of slow moving, expensive spares related to road transport organisations and considered minimisation of total system cost as the objective. Shanker[3] investigates a two-echelon (base-depot) inventory system of recoverable items. The arrivals of demand at the bases are in a Poisson manner and the order sizes are random. Inspection of the failed units is carried out in the batches they arrive. Graves[4] addresses a similar problem to determine the inventory stock levels in a multi-echelon inventory system for a repairable item. Moinzadeh and Lee[5] argue that in a multi-echelon repairable inventory system with high set up cost for order and/or high demand rates, the use of batch ordering may be more cost-effective than the common (S-1, S) ordering policy. Lee and Moinzadeh[6] present a model for multi-echelon repairable systems with batch ordering policy at the bases. Such an ordering policy is desirable when demand rates and the set up cost for ordering are relatively high. Lee[7] presents a multi-echelon inventory model for repairable items with emergency lateral transhipments.

Diaz and Fu[8] analyse the multi-echelon inventory models for repairable items from the strategical aspect. They match the existing mathematical models in this area with the industries for heavily utilised equipment according to their applicability. To achieve this, they revisit the METRIC theory and the extensions.

Guide and Srivastava[9] classify and tabulate the previous studies according to the solution methodologies proposed and the number of echelons in the model used. Besides the classification of the studies, they categorise the applications in the related field. Different from the other review papers, Kennedy[10], *et al.* provide a discussion of maintenance inventories and a discussion of the future research needed.

Fu and Diaz[11] provide approximations for multi-echelon repairable item inventory systems with limited repair capacities. They defend the idea of assuming unlimited capacities will lead to underestimated results of recoverable item requirements.

Lee[12], *et al.* and Cachon and Fisher[13] discuss the value of shared information in a multi-echelon inventory management and stress that implementing information technology to accelerate and smooth the physical flow of goods through a supply chain is significantly more valuable than using information technology to expand the flow of information. Bainman[14], *et al.* discuss various issues concerning the performance measurement and design of supply chains.

Teunter[15] presents a deterministic EOQ model of an inventory system with items that can be recovered. Simple square root EOQ formulas for both the manufacturing batch quantity and the recovery batch quantity have been derived.

Jung[16], *et al.* concern the problem of determining the optimal spare inventory level for a multi-echelon repairable-item inventory system, which has several bases and a central depot.

Lee[17], *et al.* in his paper discusses two case study problems in the area of inventory management to illustrate the applicability of a multi-objective simulation-optimisation solution framework (MOCBA) to address real world complex and difficult problems.

Sleptchenko[18], *et al.* examined impact of repair priorities in spare part networks and developed several heuristics for assigning priorities to items as well as optimising stock levels are developed, extending the well-known VARI-METRIC method.

Chang[19], *et al.* reports that demand for spare parts can sometimes be classified into critical and non-critical demands, depending on the criticality of the equipment for production.

Lau[20], *et al.* in his paper consider a multi-echelon single-indenture repairable item inventory system for technical corrective maintenance under passivation. They propose an analytical approach to accurately compute time-varying EBO and operational availability.

Garg and Deshmukh[21] suggest possible gaps and highlight application of balanced scorecard for managing performance, still a less explored area that needs further research.

Rappold and Van Roo[22] propose an approach to model and solve the joint problem of facility location, inventory allocation and capacity investment in a two-echelon, single-item; service parts supply chain with stochastic demand.

Chandra and Garbis[23] note the potential opportunities offered by flexibility of a system in enhancing its functionalities and capabilities. It describes flexibility in a supply chain, pertinent issues, and potential tools and techniques utilised for designing and modelling flexibility in it.

2. UNDERSTANDING EXISTING MODEL

2.1 General Information

ABC[1], government organisation in India, is undertaking repairs to electronic equipment held in large range and depth and operationally deployed in the locations of hostilities over widely dispersed locations in the country. It has mobile maintenance units and static maintenance units for detailed repairs. Figure 1 depicts architecture of the existing system for repair of modular electronic equipment wherein the inventory flow is in the form a multi-echelon repair inventory system. The system consists of five echelons, out Echelons 1 and 2 are replacement/stocking echelons, Echelons 3 and 4 are repair and replacement/stocking echelons, while Echelon 5 is purely a stocking echelon.

Echelon 1 is an integral part of each operational unit that is mobile in nature. There are six hundred Echelon 1 units in ABC. Echelon 2 is an independent replacement/ stocking mobile maintenance unit having six to eight echelons 1-maintenance units dependent on it. The average distance between echelon 2 and echelon 1-maintenance unit's set-ups is approximately 8-10 km. There are 75 such echelon 2-maintenance units in ABC. At any level of echelons, all echelons are homogeneous having the same repair/replacement/ stocking capability. In the existing system, flow of complete equipment is till echelon 2 and beyond this, i.e., to rear echelons 3 to 5, only defective modules/PCBs are sent for undertaking repairs/replacements. Echelon 3 is static in nature and provides repair to six echelon 2-maintenance units under its responsibility. The average maximum distance between echelon 3 and echelon 2 maintenance units is 75 km. A maximum of twelve such echelon 3 maintenance units are present in ABC.

Echelon 4 is again static in nature and consists of maximum five echelon 3 maintenance units under its responsibility. The average distance between echelon 4 and echelon 3 maintenance units ranges between 75-600 km in ABC. Echelon 4 is restricted to five in numbers due to the requirement of large infrastructure and manpower. Mother depot (i.e., echelon 5) is only one, static in nature and co-located with one of the echelon 4 maintenance units. Balance echelon 4 repair/ stocking maintenance units are located at an approximately distance of 600-1500 km.

2.2 Understanding Equipment Construction

Modern communication equipment is modular in nature having easily identifiable modules/PCBs. Due to the complexity, these modules/PCBs need elaborate arrangements like special test equipments, jigs, fixtures, controlled environmental conditions, careful handling and packing for diagnosis, repairs and storage which are created at echelons 3 and 4. In addition, there are also a number of components external to modules/PCBs, the replacements for which being simple are undertaken only at echelons 1 and 2. These echelons also identify defective modules/PCBs and forward these to rear echelons 3 and 4 for repairs.

Figure 2 shows a sketch of a general telecommunication equipment of the size 30" × 24" × 18" which houses up to 30 modules in a cabinet along with large number of components (e.g. diodes, capacitors, transistors, etc) external

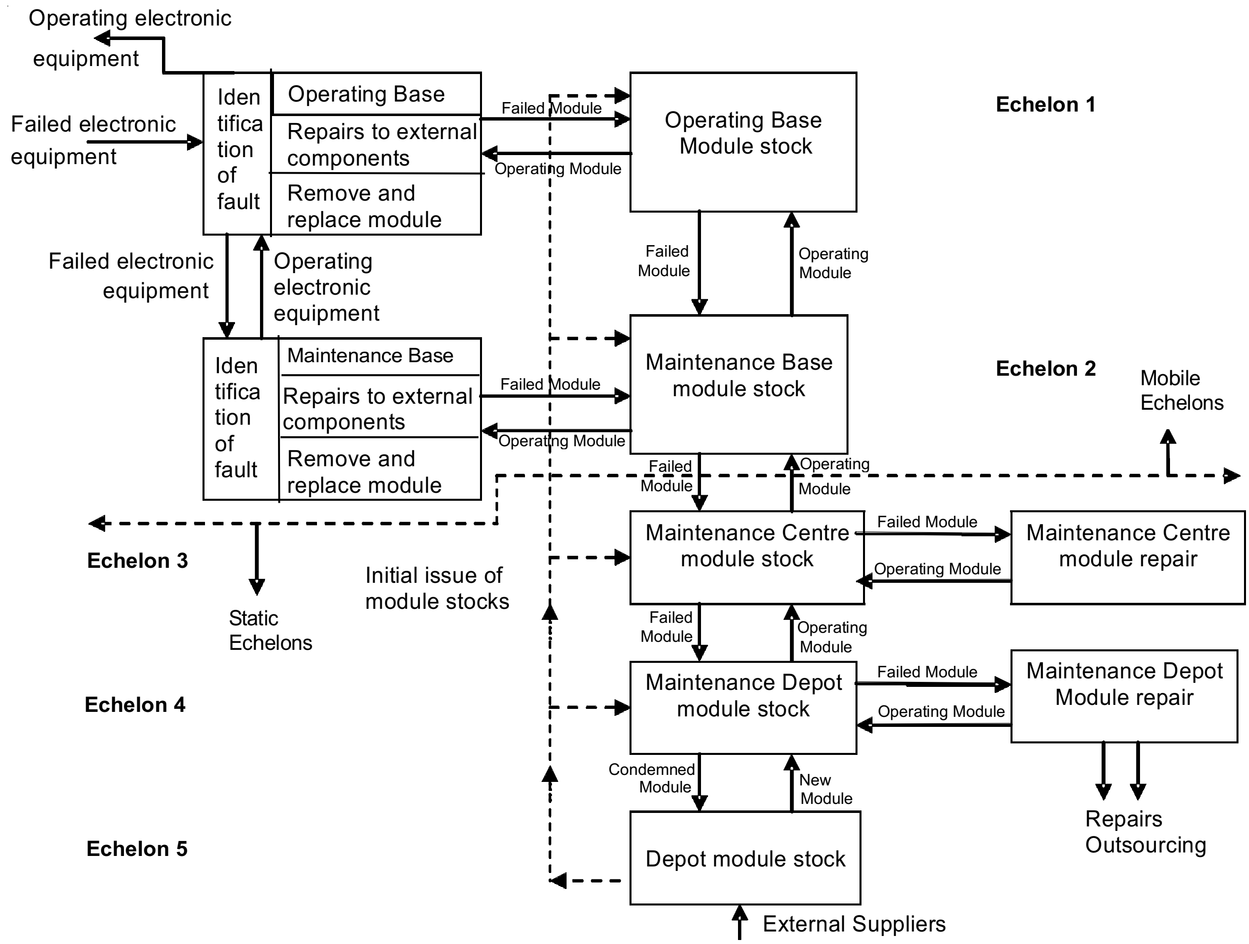

Figure 1. Architecture of the existing model in ABC.

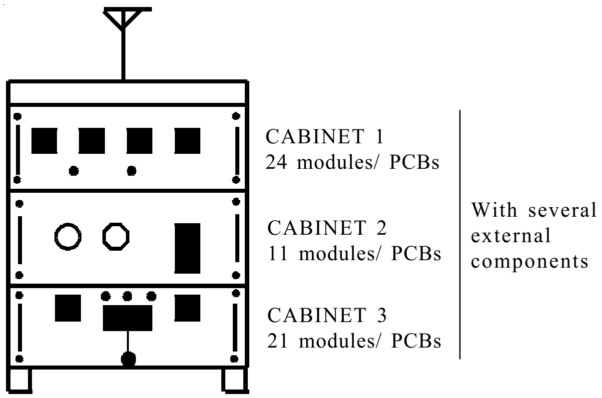

Figure 2. A telecommunication equipment xyz having three cabinets.

to these and may consist of 1 to 3 cabinets. XYZ[1] is telecommunication equipment in organisation ABC with 56 modules having three cabinets.

2.3 Stocking and Repair Capability Criteria

Work allocated to a particular echelon automatically includes the work allotted to lower echelons. Thus, echelon 2 repair/ stocking centre will also carry out echelon 1 repairs that are found necessary on the equipment it repairs. This is specified in a document known as 'repair schedule-permissible'. It may be appreciated that repairs to the complete equipment is arrested at echelon 2 itself, i.e., within a distance of 10-12 km of the exploitation of the equipment and only defective modules/PCBs travel rearwards thereafter up to a distance of 600 km.

Scale of the inventory, i.e., modules/PCBs to be held at each of the echelons is given in a document called maintenance scale. The range of modules/PCBs stocked at each echelon depends on defect proneness, cost, availability of controlled environmental conditions for diagnosis of defect, etc. The depth of stocking for each module/PCB depends upon the equipment load on that echelon and is calculated as per block sizes contained in the maintenance scale. In the above example, equipment xyz having 56 modules/ PCBs the stocking/repair responsibilities distributed among various echelons is given in Table 1.

Echelon 5, i.e., mother depot has the following two major tasks:

(a) Provision of serviceable stocks as a one-time measure to all echelons 1 to 4 against their demands worked out based on maintenance scales for the equipment on maintenance load. Subsequently, issues from mother depot are not permitted and only recycling of repaired modules/PCBs takes place in a closed loop among echelons 1 to 4.

(b) In case some modules cannot be repaired, the replacement for these is provided only to echelon 4 on clean exchange basis with no other echelon permitted to seek replacement directly from the mother depot.

2.4 Flow of Equipment and Modules/PCBs

Electronic equipment in operational unit on its failure is taken to echelon 1 for repairs. Faulty modules/PCBs are replaced out of the serviceable stock held at Echelon 1. Stocks at this echelon are replenished immediately from the stocks held at echelon. 2. Else, the complete equipment is sent to echelon 2 accompanied with investigations of echelon 1-repair technicians. The replacement of the defective modules/PCBs by echelon 2 is out of the serviceable inventory initially held the mother depot. Replacements of the unserviceable module/PCB are received from the serviceable stocks held at echelon 3.

In case, the replacement to defective module/ PCB is out of stock at echelon 2 (due to inventory stocks for that module/PCB getting exhausted and under recycle), the equipment is declared out of action and returned to user in unserviceable condition. The work order associated with such a module/PCB is accordingly marked 'out of action' while forwarding the same to higher echelons for replacement so that necessary priority is given at each echelon.

It may be appreciated that the stocks of lower echelons are replenished on priority basis by taking the replacements from the rear echelons. Stores section, echelon 3 after receipt of unserviceable inventory, depending on the permissibility of the repair schedule either sends these stores to repair elements of echelon 3 or to stores section, echelon 4 to seek replacements. Initial stocks at echelon 4 are made up through repair elements of echelon 4 that

Table 1. Modules/ PCBs stocking/ repair responsibilities for an equipment xyz

Echelon	Repair responsibility	Stocking responsibility	Remarks
1	Repairs to components external to modules/ PCBs.	14 (easily identifiable and simple modules)	Depth of stocking calculated from block sizes given in the maintenance scale of the equipment.
2	Repairs to components external to modules/ PCBs and identification of defective modules/ PCBs	56	
3	22 modules/ PCBs	56	
4	56 modules/ PCBs	56	
5	No repair responsibility	56	

have extensive repair facilities.

The repair section, echelon 4 explores all possibilities for repair of modules including repairs through "outsourcing". The replacement for damaged or "can not be repaired" modules/PCBs is then obtained from echelon 5, i.e., mother depot by this section to make up deficiencies in their serviceable stock levels. The damaged or "can not be repaired" modules/PCBs are deposited in salvage section co-located with mother depot where all serviceable individual components are retrieved and merged with the stocks at store section, echelon 4.

2.5 Transportation and Cannibalisation

Modules/PCBs of electronic equipment are delicate, expensive, and some even sensitive to human touch. These are handled carefully and transported only in suitable packing under the responsibility of stores sections at various echelons that carefully mark and package module/PCBs before passing them for repairs in higher echelons. To avoid administrative bottlenecks, all modules in the chain are transported using couriers especially deputed and trained for such jobs. The average lead-time for recycling of defective modules/PCBs for most of the maintenance organisations is 4 weeks for Echelon 3 and 10 weeks for Echelon 4.

2.6 Monitoring Cells and Performance Measurement

Monitoring cells are present at every level to monitor activity of each echelon. The basic performance measurement of the multi-echelon repair inventory system is the lead-time as stipulated above. The equipment 'not in action' is reported separately and its modules/PCBs marked accordingly to ensure speedy processing. Lead-time for such modules/ PCBs is not applicable and are monitored on case-to-case basis. The transfer of modules/PCBs to make up deficiencies in the store sections of various echelons is also ordered by the highest monitoring cell and not by the intermediate cells. The policy on newly inducted equipment is also formulated by these monitoring cells which in addition ensures that various echelons obtain the initial stocks from the base depot as per authorisation given in the maintenance scale of this equipment. Monitoring cells also liaise with OEMs for modification in the equipment, training of repair technicians, and critical spares availability.

2.7 Relevance of Maintenance and Inventory Management Process

Telecommunication equipment XYZ having 3 cabinets and a total of 56 modules/PCBs was operationally exploited at Echelon 1 in the ABC (Figs 1 and 2). Spare stocks of modules/PCBs pertaining to this equipment held at various echelons as mentioned at Table 1. Echelon 1 stocks 14 modules/PCBs out of total 56 while Echelons 2-5 stock all 56 modules/PCBs in various depths depending on the cost and fault proneness of the module/PCB as per the recommendations of the equipment manufacturer and field trials. Echelons 1 and 2 are only replacement echelons while Echelons 3 and 4 are repair/replacement echelons. Echelon 3 can repair up to 22 different types of modules/ PCBs while Echelon 4 can repair all 56 types of modules/ PCBs.

Equipment XYZ reports to Echelon 1 on becoming faulty. Echelon 1 undertakes replacement of defective module/ PCB out of 14 serviceable stocks held and seeks replacement of replaced item from 56 modules/PCBs held at Echelon 2. Echelon 2 seeks replacement from Echelon 3 stocks to replenish its holding. In case, the defective module at Echelon 3 is the repair responsibility of Echelon 3 (i.e., out of 22 modules/PCBs), the same is repaired at Echelon 3 and stocks replenished. Else, the replacement of the module/ PCB is taken from Echelon 4. The stocks at Echelon 4 are replenished either through repairs at Echelon 4 or seeking a replacement from Echelon 5. The flow of defective equipment and module/PCB is given at Fig. 3.

2.8 Bottlenecks in the Case Study Requiring OR/IE Modelling

The above maintenance and inventory management process has been configured on the basis of the past experiences. A requirement of reduction in total number of echelons has been felt in the above maintenance/inventory supply chain loop. The lead time for repair of telecommunication equipment or modules/PCBs will reduce with the reduction in number of echelons. However, creating additional infrastructure at lower echelons in terms of repair facilities, test equipment, manpower may not be cost effective. The

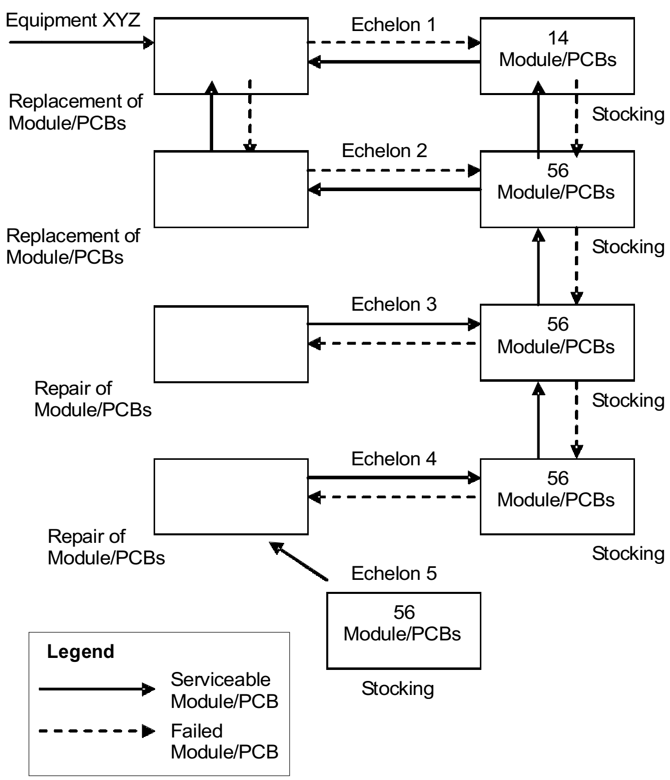

Figure 3. Defective module/PCB flow diagram of equipment xyz.

lead-time can also be reduced by holding additional stocks of modules/PCBs at lower echelons. The dependence of lead time on the above factors needs to be examined using a suitable OR/IE modelling technique. Similarly, the stocks issued to various echelons are as per the recommendations of the manufacturer/field trials and no mathematical modelling has been applied to arrive at the optimum stock levels. It is therefore desirable that OR/IE modelling is undertaken to resolve this issue without compromising the desired assurance levels in an operational scenario.

An effective information system helps in strategic, tactical, and operational decisions for any supply chain. In the present system, information flow is only within the echelon. Other echelons or the tactical commanders are not able to view the inventory status at any of the echelons. Sharing of information on the maintenance load, availability of manpower, reasons of frequent breakdowns, availability of spares etc will lead to reduction in the lead time. Therefore, an information system needs to be designed for this multi-echelon repair inventory system which may be able to run on the wide area network for effective information sharing.

Presently, the only performance measure in the entire supply chain is the lead time. This measurement system does not take into account number of other factors like developing sound maintenance practices, competence of maintenance personal, maximising allocation and utilisation of resources, etc. Therefore, a suitable performance measurement system (PMS) needs to be put in place containing appropriate performance indicators (PIs) relating to both maintenance and inventory management processes. Integration of the developed PMS with the information system on wide area network will help quantify the performance of one or more number of echelons. Thus, tactical commanders at various levels may compare the performance of echelons and accordingly assign responsibilities.

3. OBSERVATIONS ON THE EXISTING SYSTEM

The salient features of the above system are summarised as under:

- Emphasis is on reduced recycling time and correct handling of modules/ PCBs that are delicate, sensitive and expensive.
- Recycling of unserviceable inventory is undertaken at every echelon.
- Fresh issue of serviceable inventory is only from echelon 5 i.e. mother depot to echelon 4.
- Equipment flow is only till echelon 2 and beyond it only defective modules/PCBs get recycled.
- Echelon 2 also declares complete equipment unserviceable when damaged due to unforeseen circumstances and permits heavy cannibalisation of serviceable modules/ PCBs that are merged with its stocks.
- Echelons 1 and 2 are only replacement points and no repairs to modules/PCBs are undertaken.
- Echelon 1 is an integral part of the user mobile set-up.
- Various echelons also act as transshipment nodes for the modules/ PCBs that are not on their repair responsibility. Echelon 3 in Table 1 has only 22 modules/PCBs out of a total of 56 modules/PCBs as its repair responsibility. Rest of the 34 modules/ PCBs will also be routed through Echelon 3 to higher echelons. Similarly, repaired modules/ PCBs also travel from higher to lower echelons without bypassing any echelon in between.

3.1 Observations/Comments Specific to the Case Study

Following are the observations/comments on the existing flow in the case study:

- Maintenance scales are prepared in consultation with OEMs/field trials and authorisation of modules/PCBs remain static throughout the life cycle of the equipment. It must be dynamic in nature instead, based on consumption pattern/exploitation under different user conditions.
- The emphasis in the present flow is on reduced recycling time and is facilitated only through personal monitoring by maintenance technicians.
- The status of a work order placed by store sections on higher echelons is not available instantly. The status is presently known through personal liaison or routine reports received from the higher echelons.
- Performance of any two links or the entire chain is not available to any level of the monitoring cell. These cells are not able to quantify the performance of the echelons above/below them.
- Monitoring of modules/PCBs for which equipment is ‘out of action’ is through personal monitoring by maintenance technicians but the system does not support it.
- In few organisations technicians are transferred periodically from their present set-ups. The expertise/knowledge accumulated by a technician over this period are carried away by him and go waste.
- Echelons at times report only deficiencies and not surpluses of modules/PCBs held with their store sections for achieving a false sense of security. Present system does not guard against such tendencies.
- Inordinate delays at all levels occur when equipment is not exploited for longer durations.
- An operational unit using the equipment looks forward to maintenance echelons for status of his ‘out of action’ modules/PCBs.
- The system lacks transparency.

3.2 Observations/Comments for General Interest

Following are the observations/comments on the existing model of general interest:

- No model is available to determine the stock levels at each location to achieve optimum inventory-system performance for minimising backorders.
- Flow of information using information technology is lacking.
- Physical flow of repairable items using information technology is valuable than mere information flow, which is also lacking.

- No proper Performance Measurement System (PMS) exists in the present model.
- Multi echelon repair inventory chain in the present model is not flexible as flexibility provides more options, quicker change mechanisms and enhanced freedom.
- Knowledge management needs to be strengthened with the help of an effective information system.

These improvements, though generic in nature, must be undertaken in the existing model.

4. PROPOSED MULTI-ECHELON REPAIR INVENTORY SYSTEM

Based on the above observations, the desirable features of the proposed system include :

- Inventory authorisation at every echelon may be dynamic in nature to reduce inventory costs.
- In the present system no echelon can be bypassed by any of the lower echelons even if serviceable stocks are not available at the immediate higher echelon. When an effective information system is established to view the serviceable inventory stock status at all levels, this problem can be overcome.
- Effective information system to view serviceable and repairable inventory status by monitoring cells at various echelons must be incorporated.
- An effective performance measurement system of one or more echelons in the chain may be established.
- System must work effectively with less monitoring.
- There must be improved transparency at all levels.
- Better management of expertise/knowledge acquired by repair technicians in their tenure must be incorporated.

A suggested framework incorporating above desirable features is given at Figure 4 in which various issues and desirable outcomes are highlighted.

4.1 Optimisation Model Objectives

The objective here is to determine the optimal number of modules/PCBs to be kept at various echelons so as to minimise the expected total system cost. This requires the development of a mathematical model with broad optimisation model objectives as follows:

- How many modules/PCBs in total should be stocked for a particular telecommunication equipment at all echelons?
- What should be the distribution of these modules/ PCBs at various echelons and levels?
- Should a periodic review be undertaken for lateral transshipment between same/different level echelons on regular intervals?

Optimal stocking of recoverable spares, i.e., modules/ PCBs is a key issue for most maintenance organisations. A stock of module/PCBs at the various repair echelons, both in range a depth, represents an assurance of their availability when required, but, the increase in inventory cost with assurance level is exponential and not linear. The spare parts management, therefore, necessitates a judicious balance between the cost of stocking spares and the cost of non-availability of operational equipment.

There are a number of methods for calculation of spare parts quantity. One of the methods for working the requirements of expendables is to undertake replacements at a fixed periodicity. The other method is to use cumulative poisson distribution for spare parts for which failure rates are known or can be estimated with reasonable accuracy using FNS, VED, HML analysis etc. Another method is a packaged approach based on the cumulative Poisson distribution formula and the incremental analysis.

The present system in the above case study deals with static inventory scales pertaining to modules/PCBs. There is a requirement of stocking of spares at various

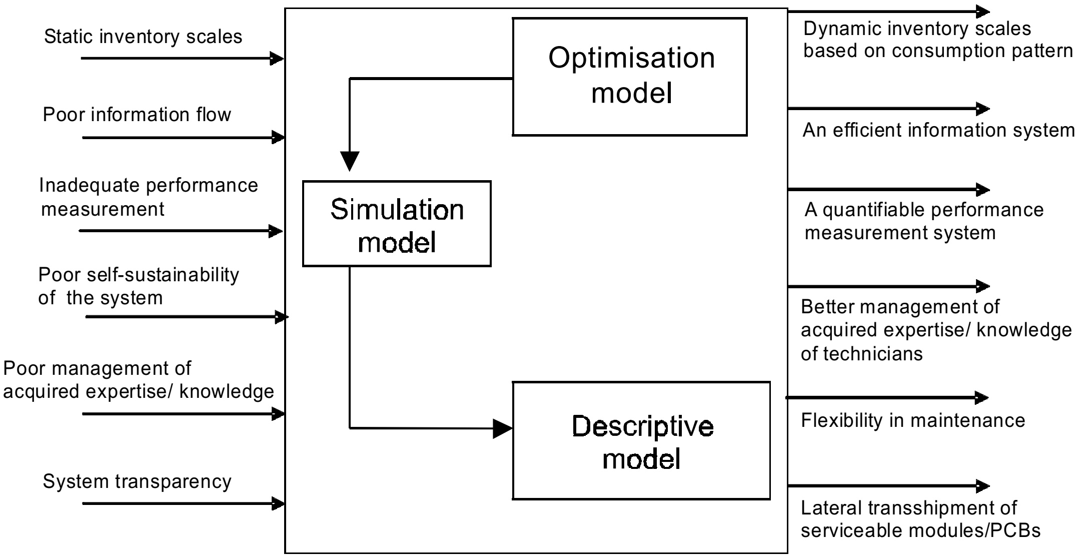

Figure 4. Modelling framework for the proposed system.

echelons on dynamic scales, i.e., stocking must match with the consumption of modules/PCBs with minimum cost and with no compromise on the assurance levels. A mathematical model based on cumulative Poisson distribution formula or the incremental analysis may be designed to arrive at optimum stock levels at various echelons.

4.2 Simulation Model Objectives

The simulation model developed must be able to consider all the activities occurring between at least two consecutive echelons and determine the system cost by considering all the costs relevant to the system. The broad objectives of this model include:

- To cope up with the complexity and uncertainty of real inventory flow in the existing system by creating physical operation of an echelon with enough accuracy.
- Extending the model to permit cannibalisation of serviceable modules/ PCBs and their lateral transshipments between echelons.
- What should be the optimum lead-time between various echelons?
- Lateral transshipment of modules/PCBs to meet emergent demands or to undertake rationalisation of stocks.

A simulation model can be developed to suggest optimal inventory policy to minimise the expected total system cost, to evaluate the performance of the system for various levels of spare stocks at different levels of echelons. Using simulation, a large number of alternate scenarios from the base model discussed in Fig. 1 having different number of echelons, may be generated. The lead time and inventory cost due this reduction can be compared with the base model using the simulation model. The overall cost involved in such a system can be compared with varying number of echelons.

Similarly, an effective flow of information between various echelons is an important output of the suggested model. The information sharing may help managers to review the stocks periodically for inventory optimisation with minimum lead time/ inventory cost.

4.3 Descriptive Model Objectives

Broad objectives of this model include:

- Vertical and lateral rationalisation of surplus/deficient modules.
- Developing an effective performance measurement system.
- An effective knowledge management system (KMS) for acquired expertise by technicians.
- Information sharing between various echelons.
- Flexibility in maintenance and stocking actions.

An effective performance measurement system (PMS) is one of the key objects of the description model. Measuring performance of repairable inventory system is very important as it quantities the efficiency and effectiveness of various repairs actions in the inventory system. Performance measurements of such chains have also not been adequately covered in the literature so far.

A suitable PMS out of the above for a multi-echelons repair inventory chain needs to be developed. The PMS must contain performance objectives and accordingly select performance indicators (PIs) for supply chain parameters, i.e., maintenance and stocking actions individually. An effective PMS can therefore quantify each of the echelons, compare them, identity weak links in the chain and push the entire performance inventory loop to the desired mission of the organisation.

An effective PMS along with information system for a multi-echelon repair inventory system shall also bring in the concept of flexibility in the entire repair loop.

The above three models may be developed with broad objectives as mentioned against each with overlap between these. There are a number of approaches for development of above models which can be adopted..

4.4 Desired Benefits of the Proposed System

The desired benefits of the proposed system include:

- In practice, most of the spare parts management is done by a series of ad hoc 'seat-of-the-pants' approaches. The proposed system may be aimed to provide dynamic inventory scales based on consumption pattern.
- It is desired to quantify the performance of an echelon in a multi-echelon inventory system setup. The system may thus be aimed to develop various performance parameters quantifying performance of one or more echelons for reasons of objective comparison and efficiency assessment.
- Better management of acquired expertise/knowledge of technicians for use at same or higher levels of echelons is an essential requirement for effective functioning of any multi-echelon inventory system.

4.5 Methodology and Likely Approaches

Methodology for this proposed system may be as under:

- Literature is examined extensively and reviewed for various models reported so far.
- All models are examined for practical utility in industry and the ones close to the above application be identified for further development.
- The model is developed with aim to achieve desired benefits as discussed above keeping in view its generalisation for use in various other applications.

Each of the models mentioned in the previous section contains objectives which can be achieved through a large number of approaches. Following are some of the approaches for development of the proposed model:

- *Extension of base model (METRIC):* Many repairable inventory theory models are based on Sherbrooke's METRIC (Multi-Echelon-technique-for- recoverable-item-control) model for setting repairable inventory levels and allocating these units so as to achieve some desired level of service, measured by expected backorders Sherbrooke,[24]. MOD-METRIC (Muckstadt[1]), VARI-METRIC (Sherbrooke[25]), DYNA- METRIC (Pyke[26]) are some of the extensions of this base model providing for multiple levels of indenture, more accurate estimate of number of backorders and addressing problem of surges in the demand during war time in military applications, respectively.

- *Queuing models:* Queuing models allow for the relaxation of assumptions in METRIC based models such as infinite parts population and incapacitated repair facility (Diaz and Fu[8]). While these are more realistic than METRIC model, they are also more difficult to solve (Guide and Srivastava[9]). In literature, queuing related analysis falls in to two main types i.e. decomposition in to individual queues and Markov chain representation of the entire system.
- *Simulation-based Models:* Babu[2] infers that surprisingly simulation methodology has not been used adequately which can certainly fill in the gap of analysing most of the real life situations effectively. Nahmias[27] and Gross[28] call for the use of hybrid models that involve simulation. Discrete even stochastic simulation is commonly used for benchmarking purposes and is in principle a perfectly flexible tool in that almost real life conditions can be modeled. Its use for multi–echelon inventory models dates at least as far back as Clark[29]. Multi- echelon simulation based models therefore can be another approach, which this proposed model may follow.

In Section 5, one of the specific problems out of the various issues discussed earlier has been casted in detail to generate more interest on the case study for the benefit of researchers working in the area of OR/IE modelling.

5. DEVELOPMENT OF THE MODEL

As a first step, the objective was to develop a large number of alternate scenarios from the base model discussed in Fig. 1 and to reduce total number of repair echelons including the lead time. These scenarios or analytical models so developed may be compared for advantages accrued out of the base model and subsequently examined for arriving at the most feasible option. Presently, following analytical model is suggested and a comparison has been made with the base model.

5.1 Three-echelons Model with One Repair Centre

A suggested model with an operating base, maintenance centre, and stocking depot consisting of three echelons is given in Fig. 5. According to this model, faults in the failed electronic equipment are identified at the operating base. Repairs to external components are undertaken on priority and repaired equipment is sent out immediately. Alternately, defective modules are replaced from the base module stock. The replacements for failed modules are received from maintenance centre stocks. Failed modules are replaced at the repair facility of maintenance centre and stocks replenished. Depot continues to have the dual responsibility as hither-to-fore. Operating base is mobile in nature while maintenance centre and depot are static.

5.1.1 Salient Features

Salient features of proposed model over the base model include:

- Total number of echelons reduced from five to three.
- Maintenance base module stock merged with operating base stock.
- Scope of maintenance activity at operating base increased by strengthening the maintenance personnel.
- Maintenance base removed; maintenance depot deleted by merging its module stocks with maintenance centre stocks.
- Strength of maintenance personnel and facilities accordingly augmented at the maintenance centre.
- Condemnations continue to be permitted.
- Basic performance measure continues to be the lead time.

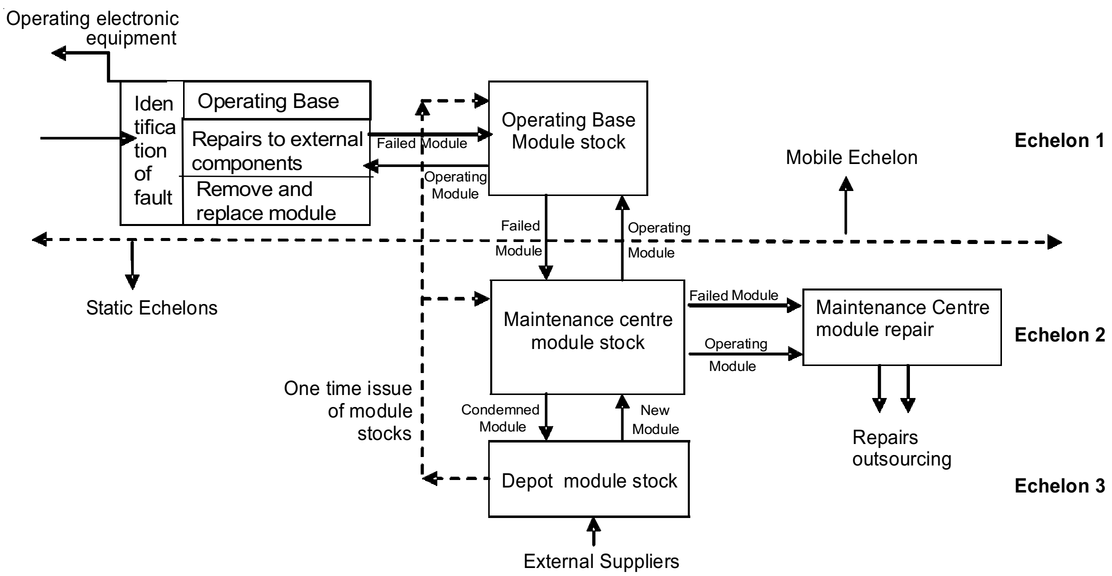

Figure 5. Three-echelons model with one repair centre.

5.1.2 Advantages

Advantages of proposed model over the base model include:

- Reduced mean time to repair (MTTR) for failed electronic equipment due to merger of maintenance base with operating base.
- Reduce recycle time of modules due to merger of maintenance depot with maintenance centre.
- Reduction of number of echelons from five to three.
- Reduction in number of backorders due to increased availability of modules at operating base.
- Reduction in depth of inventory due to reduction in number of echelons.
- Reduction in strength of technicians due to merger of repair echelons.

5.1.3 Disadvantages

Disadvantages of proposed model over the base model include:

- Since operating base is mobile, enhancing scope of maintenance activity may have to be examined in detail.
- A failed module will have to travel larger distances due to reduction in number of echelons.
- Repair infrastructure at maintenance centre will have to be re-enforced to take on depot maintenance tasks.

Similarly, these two models (base model and the proposed model) and their more variants can be validated through simulation and comparison drawn. Simultaneously, few performance measures can be taken for these two models and validated through simulation. Concept of balanced score card (BSC) as a performance measure for effective maintenance of repairable inventory system can be examined. Further, feasibility study of re-engineering the maintenance organisation of the Indian Army may be undertaken.

6. CONCLUSIONS

Shortcomings in multi-echelon repair inventory system pertaining to modular electronic equipment for a large maintenance government organisations have been critically examined through a case study. Suggested improvements in the existing model have also been identified. Subsequently, a number of approaches for development of the proposed model have been discussed. This paper clearly identifies the improvement areas in the selected case and lays down a road map for the identification and selection of the new model.

It is expected that the above research gaps will offer opportunities to study multi-echelon repair inventory systems in detail, especially for large maintenance organisations having modular electronic equipment on their repair responsibility. Suitability of available models for these organisations may be analysed and a new system attempted suiting the applicability of the selected organisation. Subsequently, generalisation of this system may be examined for application in various other situations. For technical reasons, name of the organisation and the equipment have not been revealed.

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