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CLOSED LOOP REPAIRABLE PARTS INVENTORY SYSTEM: A LITERATURE REVIEW

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Abstract

The paper reviews published literature related to multi - echelon inventory models for repairable items. Our objective is to understand the existing analytical models and their application in the context of the management of spare parts where repair facilities are resource - constrained. The focus of the review is restricted to the models which are suitable for practical application. A variety of models applicable to multi – echelon inventory system are reviewed and the Multi - Echelon Technique for Recoverable Item Control (METRIC) model and its variations, Level of Repair Analysis (LORA) are described. Taxonomy, showing the current position in the context of the existing research is also presented.

Keywords: *Repairable Parts Inventory System; Multi - Echelon Technique for Recoverable Item Control; queuing models; Level-of-Repair Analysis (LORA)*

JEL codes: **MO11; N60; G31**

INTRODUCTION

Repairable part inventories are particularly expensive parts of the machines which are normally repaired and replaced for the smooth working of the machines. Here failed inventory of items may go through a transformation, termed in general as repairs but the inventory is neither lost nor produced. Failure events drive the demand and dynamics in repairable item multi - echelon models. The inventory position of repairable part inventory is governed by the repair capacity which is normally assumed to be constant, repair time and number of back orders of the parts as against the finished product inventories or work in process whose stock levels are governed by production capacities and demand uncertainty and increased or decreased accordingly. Further, in addition to a small local repair activities, the members of these supply chain pools the repair activities and the spare parts to a single location for mutual benefits.

The variations in the inventory policies motivated the authors to further understand the modeling efforts done in this area and present the related

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unaddressed issues. There are few studies that summarise this work namely Pierskalla and Voelker [1976]; Nahmias [1981]; Guide Jr. and Srivastava [1997] and Kennedy *et al.* [2002]. The most recent was in 2002, hence, there is a need to update these discussions and present the gaps in the present literature.

We first categorized the literature into three categories, providing an overview of the related literature till 2002 in the first phase. In the second phase, an attempt is made to classify the related literature published till date. Parameters like solution methodology (exact or approximate), inventory policy, underlined model (deterministic or stochastic) and variations/ modifications are used for the classification purpose.

The objectives of the study are to present the published literature in above categories and provide the Taxonomy. More specifically the study will try to answer the following question related to Repairable Parts Inventory System:

(a) How has the present literature related to multi - echelon repairable parts inventory systems classified?

(b) What are the features, applications and limitations of each of these categories?

(c) Which solution methods are used in each of these categories? What types of models are used for repairable parts inventory?

(d) What are the applications of the models pertaining to repairable parts inventory systems?

This review will be a ready reference to the researcher and decision makers working in industries with heavy utilization of equipments like Chemical processing industries, Petrochemical industries, Defense systems, Mass transit systems such as airlines, Road transport etc. It will be helpful in finding the better inventory policy parameters and options/alternatives thereof, in assisting the managerial decision making for purchase of repairable items and in determining the capacity requirements at the base and depots.

The basic model studied in the literature consists of one central reconditioning unit (the Depot) and several bases. Each base requires a set of working parts and maintains an inventory of spare items. All failed items are repaired at the central reconditioning unit (although in some cases repair at the base is also possible) which also maintains an inventory of spare items. A one – for - one replenishment policy is usually adopted, which implies that an item is ordered always, i.e., the items are not batched for repair or re - supply request. Whenever an item fails at any base, there are three events that occur simultaneously: (a) Replacement of the failed item with a spare item from the inventory, if available in base inventory; otherwise, back - ordered at the base till a replacement arrives from the repair depot, (b) sending of failed item for repair to the reconditioning unit, and (c) shipment of the replacement item by central depot if available in inventory; otherwise back – ordered by the depot with the replacement request till the item is repaired and available.

There is wide literature related to multi - echelon repairable parts inventory systems published in past and can be broadly classified into three categories according to the approaches used to address them. They are:

- Multi - Echelon Technique for Recoverable Item Control (METRIC).
- Queuing based models
- Level-of-Repair Analysis (LORA)

The next part of the paper has been organized through different sections dealing with the topic. The section 2 reviews the literature related to METRIC. The section 3 presents the Queuing based models. The section 4 reviews the LORA. The section 5 presents classification of current literature on the predefined parameters and last section provides the Taxonomy and shows the future direction for the research in the area.

2. MULTI - ECHELON TECHNIQUE FOR RECOVERABLE ITEM CONTROL (METRIC)

We begin this section by reviewing the mathematical models developed under the common framework of METRIC. The basic assumptions of the METRIC model are as follows:

(a) One for one (S – 1, S) replenishment

(b) No condemnation of items (failed items are fully recoverable)

(c) Poisson failure process

(d) Large working - part population at the bases

(e) Adequate capacity at the repair facility, i.e. the repair time is independent of the present part in repairs and there is no waiting or batching of items before repair begins.

(f) Base demands for depot stock are served on an FCFS basis.

(g) No lateral supply between the bases

Sherbrooke [1968] developed the basic METRIC model. The item failure rate is assumed to be a compound Poisson process where the batches of demand (failures) follow the Poisson process and the number of demands per batch has logarithmic distribution. The number of failed items in transition from any base to the reconditioning unit as well as the number of failed items under repair at the reconditioning unit is assumed to be in the M/G/” queuing system. Due to the ample repair capacity assumption, successive replenishment lead times are assumed to be statistically independent.

In the METRIC model, the expected back - order level is used to evaluate performance. The process of estimating expected back - orders is repeated for generating table showing possible combinations of depot and base stock levels.

Then an expected back - orders vs. investment trade - off curves is plotted using marginal analysis, which helps managers in making strategic stock - related decisions.

Table 1 below gives the overview of the work done in METRIC.

Table 1
Various METRIC Models and Their Extensions

Source	*METRIC Modifications/ Improvements*	*Description*
Simon [1971]	Inclusion of non - recoverable failures	The model follows a one - for - one replenishment policy between the bases and the depot, wherein depot uses a continuous review policy for studying the stationary properties of a two - echelon repairable item system
Muckstadt [1973];	Multi – indenture	Developed the multi - indenture problem (MOD - METRIC) where each item is assumed to be of the first indenture or Line Repairable Units and composed of subcomponents or Shop Replaceable Units
Sherbrooke [1986]		
Graves [1985]	Two - parameter approximation for the distribution of outstanding orders at the bases	Assumes that aggregate outstanding orders of all the bases at any time equates to the addition of the number of back - orders in the depot for a specified target stock at the beginning of the time period and aggregate failure at all bases over the time interval equivalent to the delivery time from the repair depot to the base.
Moinzadeh and Lee [1986]	Continuous review (r, Q) policy both at the base as well as the depot	In this policy the base sends items to the depots for repair after there are Q numbers of failed items and base also places an order of same size to the depots simultaneously to replenish the stock. Upon receiving the failed items from each base, the depot sends the items to the base in batches of Q quantity if it has sufficient inventory on hand, otherwise, a back - order is made at the depot
Lee [1987]; Axsater [1990]	Lateral transshipment between bases	Pooling groups are formed by grouping identical bases. It assumes that each pool has identical bases. In case of non fulfillment of the demand from the stock on hand at a base, an emergency lateral transshipment is done from the stock – on – hand at another base in the same pooling group to fill this demand, otherwise the demand is back - ordered.
Jung [1993]	Non - homogeneous failure process at the base	The mean failure rate of items is assumed to vary with time and is based on the concept of reliability improvement. Increased usage and failures will lead

contd. table 1

Source	*METRIC Modifications/ Improvements*	*Description*
		to design or repair improvement and the mean time between failures of items is an increasing function of the total operational time. Spare stock levels at the bases and at the repair facility are estimated using the approach of Graves [1985].
Kim *et al.* [1996]	Algorithm for stock level at the base	The stock level which minimizes the total expected holding and shortage - cost function is found by the bisection method. Another stock level which satisfies the fill - rate criterion is also obtained. The maximum of these is chosen to be the optimal stock level.
Diaz and Fu [1997]	Capacity constraint and different priority classes for repair	Three cases of limited repair capacity are considered, viz., M/M/c, M/G/c single class and M/G/c – multi - class priority. It has been shown that the performance levels of spare items at bases significantly differ under the assumption of finite repair capacity.
Wang *et al.* [2000]	Base - dependent distribution of transit times from the base to the depot	The steady - state probability distribution function of transit times for each base is derived and from this the distribution of outstanding orders is estimated. Through the analytical results, it has been shown that there is a significant difference in the service levels at the bases when they differ in their transit times to the depots.
Rustenberg *et al.* [2001]	Application of VARI-METRIC on a complex - technology organization	The study observes through an extensive literature review that the VARI - METRIC method requires some modifications with respect to the capacitated systems and the hybrid product structures with both, repairable and non - repairable parts.
Wang *et al.* [2002]	Priority class of service differing in replenishment lead times	Exact steady - state probability distributions of random base delays are derived for both the services. There is a significant reduction in inventory when the service is changed from emergency to non - emergency type.

2.1. Limitations of METRIC Based Models

There are several limitations/restrictive assumption of METRIC - based models. They are following:

- These models have a complex and rigorous analytical structure, which is sometime difficult for practicing community to understand and operate. Moreover, these models may not be applicable in specific real - life situations.
- There is always a need to define the distribution for the failure process as a Poisson failure process for analytical tractability. This is due to the special properties of the Poisson process. Similarly, the service times at the repair

facility are often assumed to be exponentially distributed, again for analytical tractability.

- In the METRIC models, the distribution of replenishment lead times is captured using PALM's theorem. If there is finite capacity at the repair facility, the replenishment lead time will be a complex function of Work – in – Process (WIP) and the input flow rate of failed items to the repair facility.
- A one - for - one replenishment policy is always assumed, i.e., as and when an item fails, it is immediately sent to the repair facility and a simultaneous replenishment order is made. The other replenishment policies like continuous - review - batched replenishment (only one paper by [Moinzadeh and Lee 1986]) and periodic - review policies are not well - studied in the literature.
- FCFS priority is always assumed for the re - supply network in the literature.

3. QUEUING BASED MODELS

This section provides a brief overview of the queuing network models as they form the theoretical basis of application for the queuing approach to the multi - echelon repairable parts inventory system. After this overview, we discuss the queuing models which are developed specifically for the repairable item inventory problem.

Based on the literature, we can divide the queuing networks into three classes, i.e., open, closed and mixed queuing networks [Jackson 1963; Gordon and Newell 1967]. In an open network, the item that arrives in the system eventually departs from it. There are several arrival processes (from other nodes and outside) and departure processes (to other nodes and outside) pertaining to each node of the queuing network. In a closed network, the number of items in the system remains fixed, i.e., either there is no attrition of items from the system or if an item is removed from the system, it is replaced by a new item. Many of the METRIC - related systems resemble this type of network, where the parts are completely recoverable.

Table 2 below summarizes the various queuing network models

Table 2
General Queuing Network Models

Source	*Queuing Environment*	*Description*
Jackson [1963]	Poisson arrival, exponential service times, multi - stages, FCFS, open queuing network, exact analysis	Under the product - form structure, the system is solved by analyzing each node separately and then the results are combined. In this case, the joint probability distribution of queue lengths at each node in the system is equal to the product of the probability distribution of queue lengths at each node

contd. table 2

Source	*Queuing Environment*	*Description*
Gordon and Newell [1967]	Exponential service time, multi - stages, closed queuing networks, exact and approximate analysis.	Suggested approximate expressions for the marginal probability distribution of items in the system. An asymptotic analysis for closed systems with very large number of stages is also carried out.
Baskett *et al.* [1975]	Service time with rational Laplace transformation; open, closed and mixed network.	Joint probability distribution (steady-state) of queue lengths is derived for multi - node, multi - class items. Four cases – those of queue discipline, first – come – first - served (FCFS), processor sharing, no queuing, and last – come – first - served (LCFS) - are analyzed.
Reiser and Lavenberg [1980]	Closed networks, mean value analysis	Through - put time (when an item is processed at a node), throughput rates and queue lengths are updated sequentially according to Little's Law. The convergence of queue lengths at several nodes is used as a stopping criterion.
Whitt [1983]; Bitran and Tirupati [1988]	General arrival, general service time, multi - stages, Open networks, approximate analysis using decomposition approach.	Uses the decomposition approach for analyzing the complex open queuing networks. In the decomposition approach, the interaction between the various nodes is analyzed first. Then the network is decomposed into sub - systems of individual stations and analyzed. The results are then recomposed to obtain the network performance

3.1. Queuing Models Applied to Repairable Item Inventory Problem

The standard machine repair problem in queuing is one of the basic applications in the field. In this model there is a finite repair capacity and a finite source of population from which failures occur. The failure rate is dependent on the state of the system i.e., the number of failed items in the system.

Advances and modifications of basic queuing models for machine repair problems are summarized in Table 3 below:

3.2. Limitations of Existing Queuing Network Models

The existing queuing network models have several limitations, some of which are listed below:

- As we see, the main purpose of the queuing - based methods is to analyze the current status of a given system in terms of the steady - state probability distribution of a number of repairable items at different stages. Substantial work may be necessary to use these results to formulate an objective function and optimize it.
- These models are limited to FCFS, Poisson failure and exponential service times, similar to METRIC - based models.

Table 3
Queuing Models Applied to Repairable Item Inventory Problem

Source	*Problem Characteristics/ Solution Methodology*	*Description*
Gross *et al.* [1983]	Multi-echelon, Poisson failure, Exponential service time, FCFS, Implicit enumeration	The model consists of a system which has a single base with a base repair facility and a depot repair facility. The system here is viewed as a network with three nodes, one for operating and spare machines at the base, one for machines in base repair, and one for machines in depot repair. An optimization problem is also solved where the decision variables are the base and depot repair capacities along with the spare items. The cost is minimized subject to the constraint of operational availability
Gross *et al.* [1987]; Gupta and Albright [1992]	Multi-echelon, Poisson failure, Exponential service time, FCFS, Decomposition approach	The number of items owed by the depot to the bases (back - orders) is fixed so that the problem can be decomposed. After decomposing, problem at each base is solved using one - dimensional birth – and - death process. The problem at depot is solved using an n - dimensional birth – and - death model
Gross *et al.* [1993]	Multi - echelon, Poisson failure, Exponential service time, FCFS, Iterative procedure	The model simplifies the inversion and a solution is obtained by iterations. Methods for carrying out iterations include the Jacobi iteration, Gauss - Seidel and the bi-conjugate gradient.
Daryanani and Miller [2002]	Multi - echelon, Poisson failure, Exponential service time, Dynamic backorder filling policy, iterative procedure involving the taboo structure of state space.	The model gives computational formula for the steady - state probabilities.

- Markov chain - based models have an additional disadvantage in terms of large state space in general settings. Hence, these queuing models for the repairable item inventory system are rarely implemented in practice.

4. LEVEL-OF-REPAIR ANALYSIS

Level-of-Repair Analysis (LORA) a phrase commonly used in military jargon [Barros 1998]. It is defined as tool used to decide "not only the repair or discard location for the items that make up a system or equipment, but the extent of maintenance permitted and the resources needed to support the maintenance process." [Crabtree and Sandel 1989]. It is mostly used for complex system like Aircrafts whose non availability results in loses to the user and also needs a large number of support equipments and skilled people for maintenance [Saranga and Kumar 2006]. LORA can be used for deciding about [Basten *et al.* 2012].

(a) Components to be repaired or replaced upon failure

(b) Location where the repair and discard of failed component happens

(c) Location where the resources can be deployed for repairing, discarding or movement of the failed components

LORA is used to finds best combination of repair/reject decision and also helps to decide a level of maintenance so that total support cost for the system can be minimize [Saranga and Kumar 2006]. Table 4 below summarizes the various LORA based model models

Table 4
LORA Models

Authors	*Tools used to model LORA*	*Description*
Alfredsson [1997]	Mathematical framework using both LORA and METRIC	A mathematical framework for solving the problems related to decision about the optimizing the amount of spare part to be stocked, level of test equipment, tools and repair man power to be installed and the locations of these installations and spares using C programming.
Barros [1998]	Integer programming	This model is used for maintenance planning as a tool for deciding among the options available for level of repair. The model divides the time dependent life-cycle maintenance cost in two fixed and variable costs for getting the optimum solution.
Saranga and Kumar [2006]	Genetic Algorithm	Optimization model for maintenance of aircraft engine. This algorithm can be effectively used for deciding about allocation of repair/reject option among different echelons. This allocation will help in minimizing total maintenance cost where in total life cycle cost (LCC) will also be minimum at the design stage.
Basten *et al.* [2009]	Integer programming by removing the integrality constraints	Specific problem solved in this study is a NP hard problem. The integrality constraints on most of the variables are removed. The problem is a linear programming problem after removal of the integrality constraints and can be solved in polynomial time. The computational time is dependent on number of components in the system, indenture and echelon levels and number of fixed cost sets of the components.
Brick and Uchoa [2009]	Mixed integer programming	The model considered discrete location of facilities and installation of capacitated resources and applied to 15 real world problem which has distinct maintenance polices. This technique is considered as more comprehensive as compared to other methods and can be solved in reasonable time using any commercial solvers.

contd. table 2

Authors	*Tools used to model LORA*	*Description*
Basten *et al.* [2011]	Minimum cost flow problem with side constraints	The modeling consist of four nodes- source node, decision node, transformation node and sink node and the use of resources act as side constraints. An occurrence of failures of a certain subsystem at a certain system location as a source node is modeled. From these source nodes it is moved to Decision nodes which consists of three decisions namely, move the component to next level, repair the component or reject the component. If the repair option is chosen at decision node then parts are moved to the transformation node which represents the repair of a parent component. If the decision process end with any of the decision then parts are moved to a sink node.
Basten *et al.* [2012 A]	Integrated Algorithm for jointly solving of LORA and spare parts stocking problems	The model solves the problem of maintenance of capital goods like MRI- scanner at hospital or baggage handling system at airport. It has shown significant amount of cost reduction. It developed an integrated algorithm which jointly solved LORA and spare parts stocking problems based on Alfredsson, [1997] mathematical model. The spare part stocking problem was solved by using a METRIC method. This integrated algorithm was effective for solving two-echelon (or single-echelon), single-indenture problems

5. RECENT DEVELOPMENT IN REPAIRABLE PARTS INVENTORY SYSTEM

The literature related to Repairable Parts Inventory System in recent past is more towards the applications of base model using either METRIC or queuing based models in the different industry settings. The objective in these studies is to develop methods which will optimize the stocks so as to reduce overall cost and improve the service delivery (in terms of repair time reduction). Researcher used simulation modeling and also developed appropriate heuristics for achieving these objectives. The impact of various contract types, cooperative strategies, inventory ordering policies like batch ordering is evaluated in these studies.

Table 5 below presents the classification of the recent papers.

Source	*METRIC Modifications/Improvements*	*Problem Characteristics*	*Solution Method*	*Models*	*Inventory Policy*
Jung [2003]	algorithm to find the spare inventory level at each base so as to minimize total expected cost	Multi-echelon repairable inventory system with emergency lateral transshipments	Approximate	Stochastic	Continuous review
Caglar *et al.* [2004]	minimize the system-wide inventory cost subject to a response time constraint ateach field depot	two-echelon, multi-item spare parts inventory system; Poisson process for part failure; highly reliable and very expensive parts	Heuristic		Continuous review, base stock policy
Kilpi and Veps.al.ainen [2004]	balanced inventory pooling arrangements among various airlines	Standard statistical model of component availability showing relations between the four factors of availability (reliability, turnaround time, service level and the number of units supported)	Simulation model		
Kim *et al.* [2007]	An algorithm to find spare inventory level to minimize the total expected cost and simultaneously to satisfy a specified minimum service rate	general repair time distribution; M/G/c queuing system for both base and depots repair	Approximate	Stochastic	Continuous review
Kim *et al.* [2007 A]	Performance based contract using multitask principal-agent model	Poisson process for part failure; repair facility with infinite capacity modeled as an M/G/" queue; each supplier is compensated based on his total realized cost and realized backorder level	Exact		One-for-one base stock policy

contd. table

Source	*METRIC Modifications/Improvements*	*Problem Characteristics*	*Solution Method*	*Models*	*Inventory Policy*
Wong *et al.* [2007]	cost allocation problem in the context of repairable spare parts pooling	Game theoretic models; two games- 1) games with full cooperation; 2) games with competition	Exact	Stochastic	One-for-one base stock
Kutanoglu and Mahajan [2009]	An algorithm to find inventory level at local warehouses that meet all the time-based service level constraints at minimal costs with emergency lateral transshipments	Two-echelon distribution system with one central warehouse (depot) and large number of local warehouses (bases); infinite capacity at depots; Poisson demands; warehouses share their inventory;	Implicit enumeration	Integer non-linear program	One-for-one base stock policy
Kilpi *et al.* [2009]	Impact of various type of co-operative strategies on inventory levels and overall cost using a game theoretical setting	Four types of co-operative strategies considered namely solo, ad-hoc co-operation, co-operative pooling and commercial pooling	Simulation model		
Mirzahosseinian and Piplani [2011]	inventory model for a repairable parts system operating under Performance based contract	Poisson process for part failure; exponential distribution for repair time; $M/M/m$ queue inventory system;	Exact	Stochastic	One-for-one base stock
Jin and Tian [2012]	Trade-offs between reliability design and inventory level	Renewal equation and Poisson process for estimating the aggregate fleet failures	Heuristic		Multi-phase adaptive inventory control policy

contd. table

Source	*METRIC Modifications/Improvements*	*Problem Characteristics*	*Solution Method*	*Models*	*Inventory Policy*
Basten *et al.* [2012 A]	iterative algorithm to solve the joint problem of LORA and spare parts stocking	Poisson process for part failure; repair lead time are IID	Heuristic		One-for-one base stock
Tracht *et al.* [2013]	cost-optimal inventory levels subject to budget and inventory level limitations	Poisson process for part failure; repair time is assumed to be constant; ample repair capacity	simulation model		One-for-one base stock
Ruan *et al.* [2014]	Configuration and optimization method of partial repairable spares	Four stage process- 1) forecast spares demand rate; 2) optimize spare stock based on spares model and algorithm; 3) determine the support constraint targets; 4) calculate spares reorder point and order quantity	Exact		Combination of (s-1, s) and (R, Q) inventory policy
Tracht *et al.* [2014]	impact of varying repair capacity on a system for repairable items	Single item system; no item condemnations; the repair shop uses first-come-first-serve (FCFS) prioritization; Poisson process for part failure; exponential distribution for repair time	Simulation model	Stochastic	Continuous review

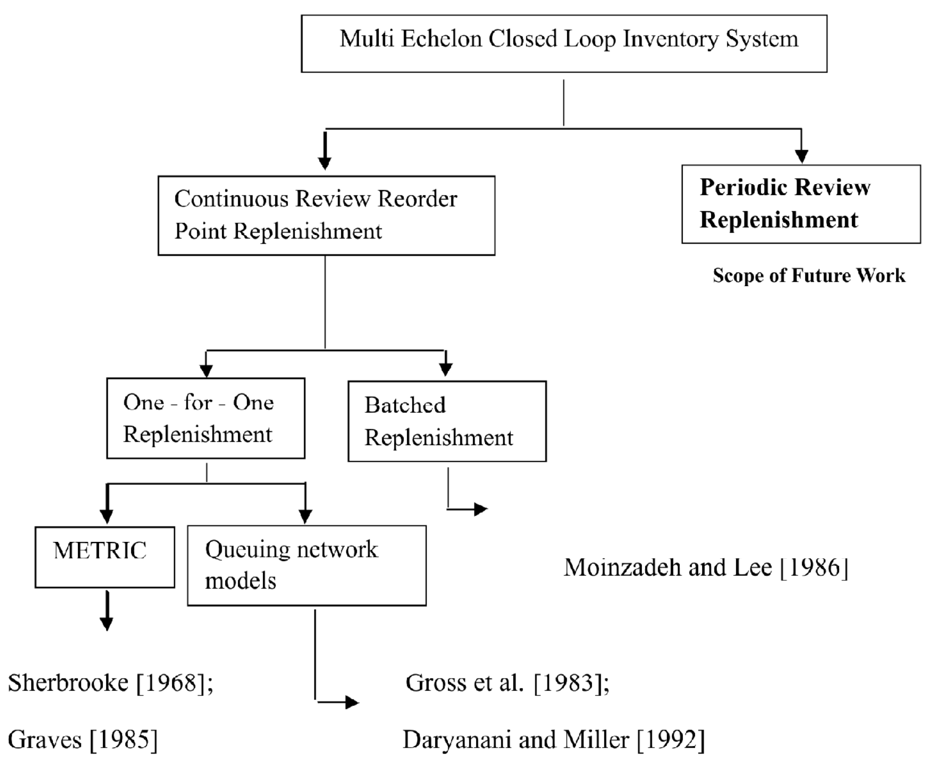
6. TAXONOMY OF THE MULTI - ECHELON CLOSED - LOOP INVENTORY SYSTEM

As we can see, not much attention has been given to periodic review replenishment in comparison to continuous review reorder point replenishment for which there are some exact results in the literature. To the best of our knowledge, there is no available analytical model or research paper addressing the periodic review policy in the context of the closed loop multi – echelon repairable inventory items.

As far as general settings are concerned, Hadley and Whitin [1963] have used the periodic review (R, T) policy in their book. Graves [1996] examines a multi - echelon system with a general system topology. In this work, an assumption regarding schedule of preset replenishment, is made at each location. It is further argued that such scheduled shipments are general practice, in order to utilize the transportation resources efficiently.

The lack of an analytical model with the periodic review inventory policy in the context of repairable items motivates us to look for other solution methodologies. Choice of the discrete – event – simulation due to its wider applicability and its flexibility in customizing the approach to a specific problem context without restrictive assumptions is promising one.

Figure 1: Taxonomical Classification of Literature



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