Simulation-based Optimization of Multi-indenture and Multi-echelon Inventory Systems

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The problem that we address is to determine the inventory stockage levels in a multi-echelon inventory system for repairable items in a multi-indenture system. We propose the simulation optimization approach to determine the stockage levels at each echelon, where a simulator for the underlying system is combined with an appropriate optimization tool, Genetic Algorithm (GA).

1. Introduction

Technically advanced systems play an ever more important role in society. as a consequence, the availability of such systems may strongly affect daily operations. This applies to, e.g. heavily automated production processes, computer systems, medical equipment, and military systems. Downtime of critical equipment may have serious consequences, e.g. in terms of loss of production, quality reduction in health care or ineffective military missions. Various measures can be taken to reduce the amount of system downtime, such as system redundancy, appropriate preventive maintenance and effective corrective maintenance. Especially with respect to the latter, fast supply of the service parts required is essential.

This characteristics cause that service parts management is an increasingly important, yet complex task. A key challenge is to attain high availability of the installed system at low supply costs. Effective and efficient spare part management means the several design choices have to be made and a suitable logistical control structure has to be developed

One way to influence the relation between customer service (high availability of the installed system) and supply costs is by appropriate *stock allocation* [2]. That is, decisions have to be taken about which parts to stock at which storage locations in the network in which amounts. This well-known *stock allocation problem* for service networks is different from traditional inventory models, because the relevant performance measure is availability of the installed echelon rather than part fill rates.

Many models for these kinds of stock allocation problem have been developed in the past decades. Already in the 60s, Sherbrooke [10] developed the famous METRIC model for repairable item inventory control of the multi-echelon system. An overview of the most important models based on the METRIC approach is given in Sherbrooke [11]. Slay [12] devised an improvement to METRIC that he called VARI-METRIC, and Graves [5] more recently published a simple derivation of this approximation.

The service network model considered in this article describes the process in which operating units are sent to repair after failure, and after repair they return as good as new. Since the repair process in this model has several echelons of supply, and takes into account the product structure of failed units (assemblies, subassemblies), the model will be referred to as a *Multi-Indenture*, *Multi-Echelon* (MIME) model.

In the literature, various approaches to solve such MIME models are described. The basic reference in this area is the METRIC method of Sherbrooke [10]. Practical applications using METRIC method are described in various military systems in the air force, the navy and the army [11] and various commercial settings, such as aircrafts [3], the Venezuelan metro-system [4] and electronic testing equipment [1]. For a general review of these kinds of models, we refer to Guide and Srivastava [6], Rustenburg et al. [9], and Kennedy et al. [7].

The existing literature on MIME inventory systems is extremely voluminous. Nevertheless most of the investigated models suffer from one or more restrictive assumptions like Poisson demand process, zero or constant transportation, lead times, and infinite repair capacity. Relaxing these assumptions we cannot expect to get an analytical solution.

To surpass some of these limitations a simulation model is developed in this work. We propose the simulation optimization approach to determine the stockage levels at each echelon, where a simulator for the underlying system is combined with an appropriate optimization tool, Genetic Algorithm (GA).

This paper is arranged as follows. Section 2 gives an overall description of the problem for the simulation. In section 3 the simulation optimization approach including the simulation model and genetic algorithm is described in detail. Finally we present a brief summary of conclusions and possible directions of further research in the Section 4.

2. Model Description

In this section, the system to model and the assumptions considered are described.

2.1 Multi-Indenture, Multi-Echelon (MIME) system

Multi-indenture structure menas that every item (assembly) may consist of other items (subassemblies), see Figure 1. This paper looks at three levels of indenture within an end-item: LRUs, SRUs, and Piece Parts. The indenture breakdown of a home audio system is depicted in Figure 1, for an example. Piece part is considered in an aggregate manner.

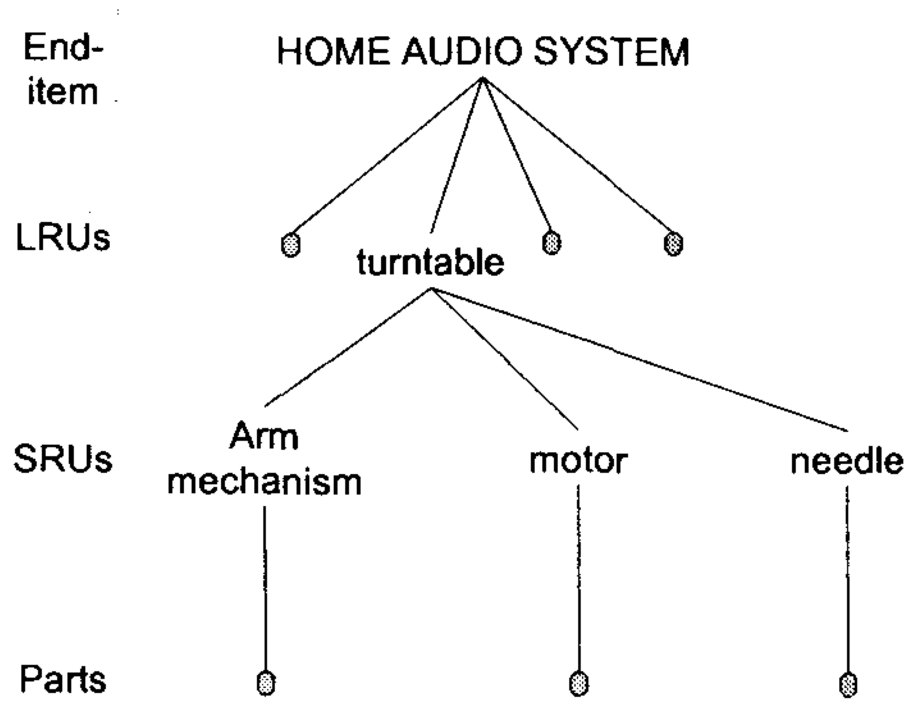


Figure 1. An example of 3-indenture system

A *multi-echelon* system is the hierarchical network of which level has a repair and storage facility. We consider 4-echelon system, see Figure 2. It is assumed that the echelon structure is symmetric. In addition, we assume that same number of end-items are assigned to each ORG (1^{st} echelon).

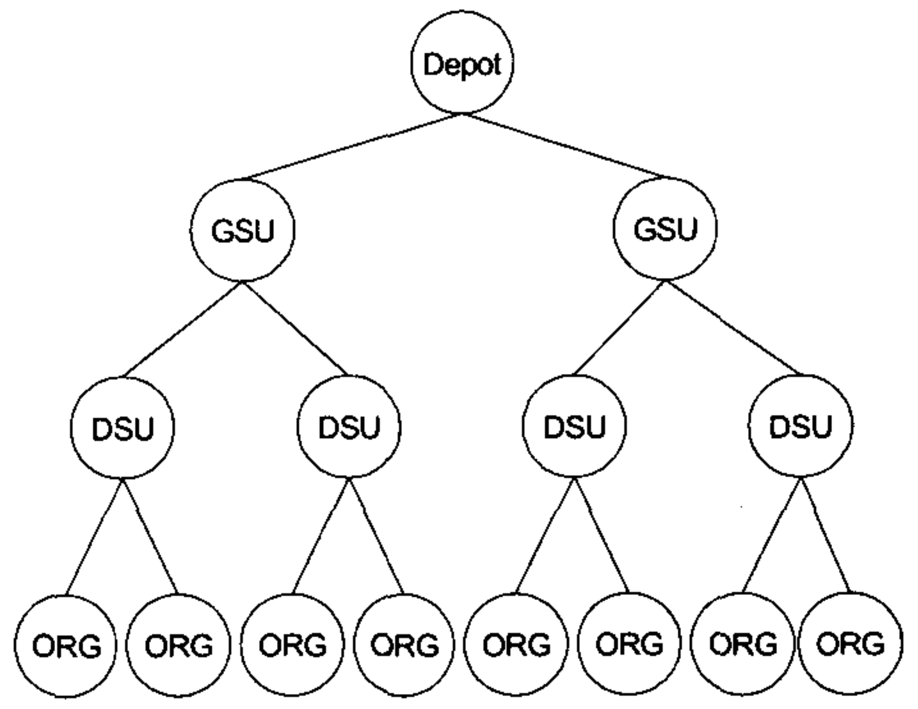


Figure 2. An example of 4-indenture system

2.2 Failures

If a SRU has failed, a specific LRU, then, fails immediately. As a result, the end-item fails. We assume that the failure of a SRU follows the Weibull process.

It is assumed that LRU failures which result in washouts do not generate SRU failures. An inherent washout rate is input for each item except end-item. And it is assumed the washouts are moved to it's repair echelon and discarded.

Removals include failures plus *false* removals. A false removal occurs when an LRU or SRU which is perfectly good is removed due to an error or ambiguity in diagnosis. We assume that false removals occur according to stationary Poisson process.

When a end-item fails, the failed LRU is transported to a repair shop and all the remaining LRUs are switched off, which implies that there is no demand of those LRUs until the end-item has been restored. This phenomenon called passivation [8] is hold in this paper.

2.3 Maintenance

If an assembly fails, we assume either the failure is caused by the failure of exactly one of its subassemblies, or there is no specific subassembly causing the assembly failure, say there is washout. If by the failure of a subassembly, then the replacement of this subassembly is sufficient to repair the assembly. If by the washout of assembly, hence the assembly is discarded and it does not generate a demand of a subassembly. In the case of a subassembly failure, the repair procedure is as follows: the item is disassembled and the failed subassembly is sent to the subassembly repair shop, where the procedure is similar to assembly.

The stockage levels at each echelon depends on what the maintenance allocation decisions are. We assume that maintenance policies for all failure modes of the end-item is given as shown in Table 1.

Table 1. Maintenance Policies

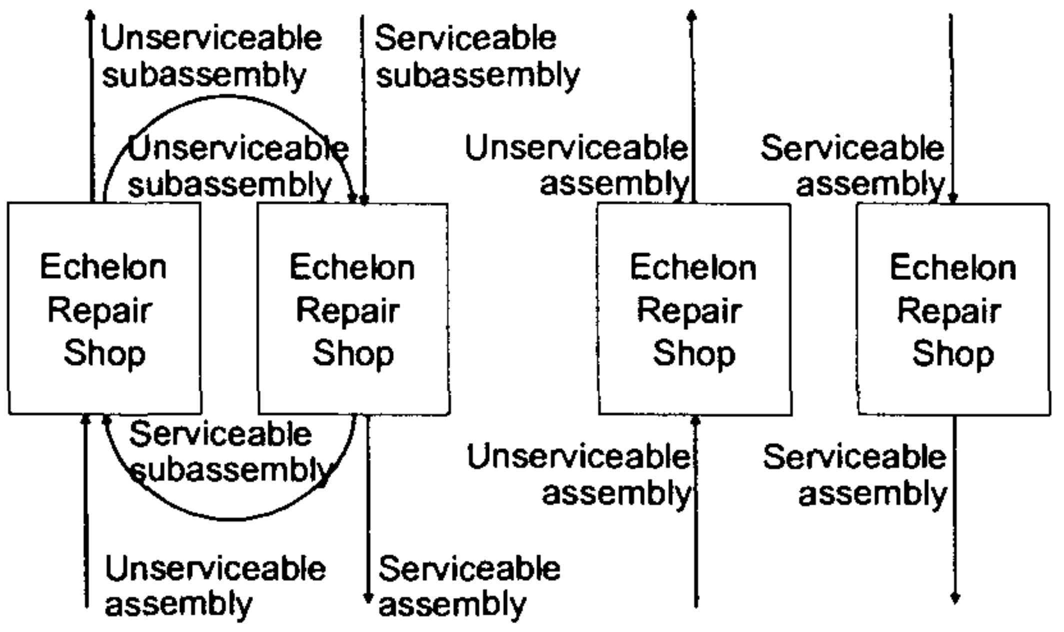
HOME AUDIO SYSTEM			
Failure Mode	Audio Repair	Turntable Repair	SRU Repair
Arm mechanism	ORG	DSU	Throw Away
Motor	ORG	GSU	Depot
Needle	ORG	ORG	Throw Away
⋮	⋮	⋮	⋮

We define a repair shop as a part of a echelon that has its own finite repair facilities. The repair shops handle their jobs according to the FCFS discipline (i.e. no repair priorities).

We assume that the item repair times are independent, identically distributed random variable and after repair, the items are as good as new.

2.4 Supply and transportation

We consider a one-for-one replenishment, $(S, S\text{-}1)$ policy, for an requisition of either serviceable assembly or serviceable subassembly. S is decision variable. Figure 3 depicts the movement of a subassembly and an assembly of which failure does not result in washout.



(a) If echelon is the repair echelon for the failed assembly (b) If echelon is *not* the repair echelon for the failed assembly

Figure 3. An assembly and a subassembly movement

Transportation is required both to supply the user (forward movement) and to retrograde unserviceables. We assume that transportation times are *i.i.d.* and retrograde and forward are same.

3. Simulation Optimization Approach

We provide a framework that enables us to optimize the stockage levels for each echelon. We estimate the availability of the end-item by using simulation. Genetic algorithm combined with the simulation searches the optimal stockage levels to minimize the Life Cycle Cost with restriction on the operational availability.

To find a sufficiently good solution for the above mentioned complex optimization problems we will follow the simulation optimization approach as outlined in Figure 4.

3.1 Simulation model

To surpass some of the complexity previously described we develop a simulation model to manage the MIME system in this paper. The model aim is to estimate the system availability for given the stockage levels. We analyze and model the simulation system using by object-oriented method. The model is implemented by general programming language C++.

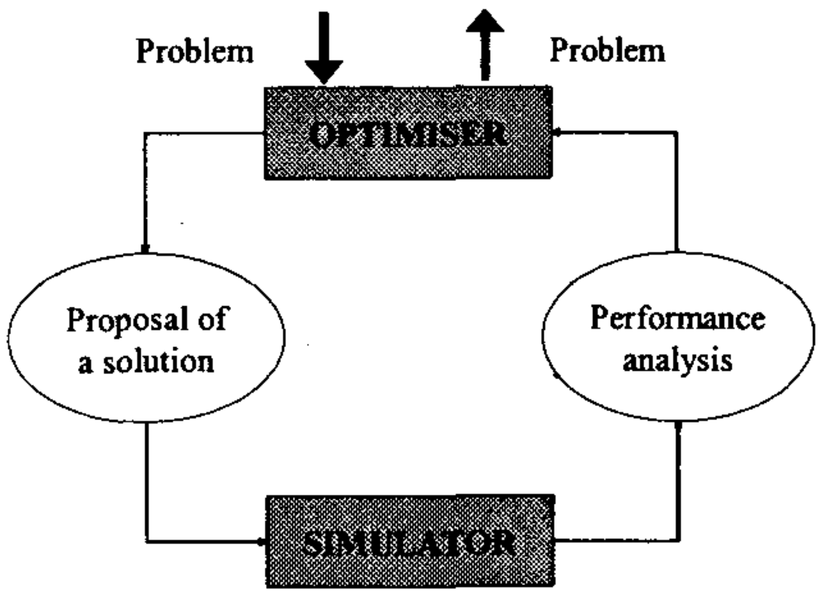


Figure 4. Scheme of simulation optimization

3.1.1 Object-oriented discrete event simulation

Process is defined as an object that operates by changing states over time. Simulations are executed based on the operations of the processes and their interactions.

Simulation executive controls the events and the time in control routine, as shown Figure 5. Main roles of the simulation executive are the time advance task and management of the event list. Since each processor has phase information as an attribute, it remembers the task information when simulation executive orders. After finishing the task, each process returns the control to the simulation executive.

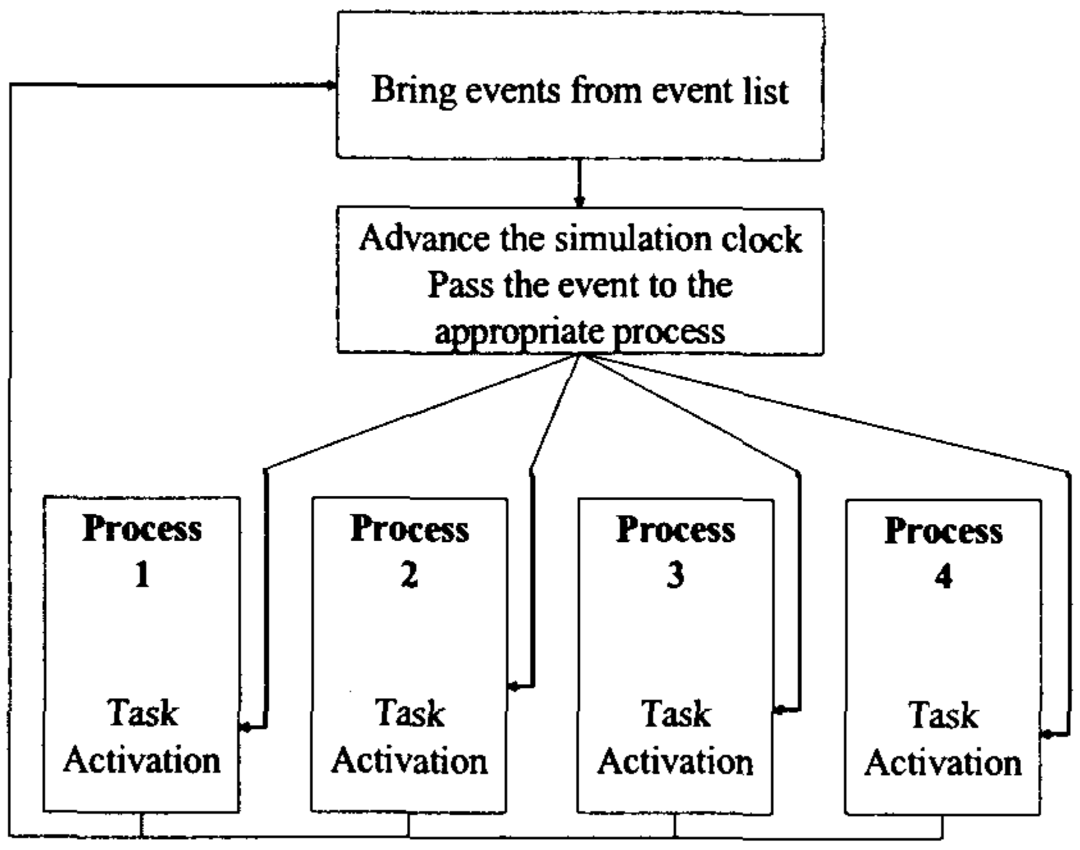


Figure 5. Roles of the simulation executive

3.1.2 Objects and events

Indenture, Echelon, and Equipment classes constitute the most important classes. Figure 6 depicts a hierarchy of the all defined object type.

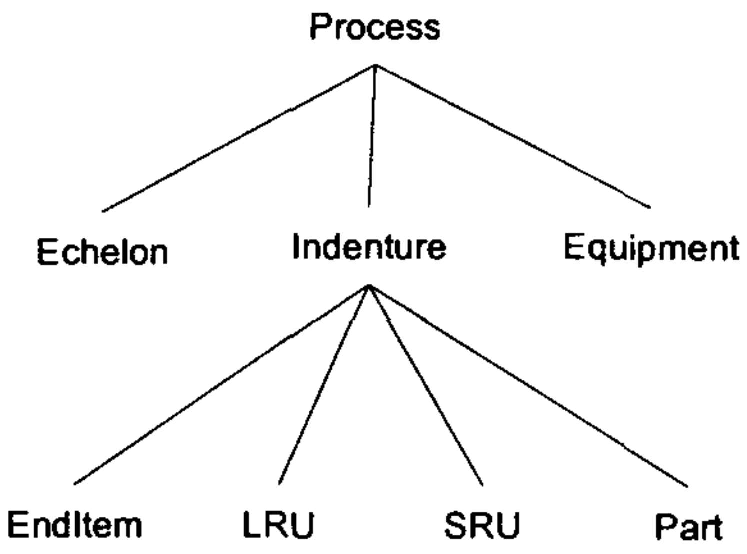


Figure 6. A generalization hierarchy of object types

An event is defined as an instantaneous occurrence that may change the state of an object. In this study, an event can be divided into two categories: global and interactive. A global event is enrolled into the event list by objects such as indenture, echelon, and equipment. When the simulation clock reaches the specified time, the event controller invokes the event (see Table 2). An interactive event is one in which an object is invoked by another one that has just finished its process, for example, Backorder, EnditemDown, LruDown, Activated, Activate, DeActivated, DeActivate, and so on.

We analyze the manner in which the state of the object changes with the help of the state transition diagram. Defined states of main objects are given in Table 3.

We also develop the event/operation diagram to represent the relationship between events and tasks resulting from the events. After analyzing events and activities, we design the simulation logic. Figure 7 depicts a outline of simulation logic.

Table 2. Global events for objects

Object	Event	Explanations
EndItem	SimEnd	terminate simulation
Indenture	ENDFIX	complete fix
SRU	BREAKDOWN	generate failure
Echelon	FORWARD RETROGRADE	arrive a serviceable arrive a unserviceable

Table 3. Definition of state of object

Object	State	Description
Indenture	RUNNING IDLE DOWN REPAIR	on working idle due to passivation failure on maintenance
Equipment	RUNNING IDLE	on working idle due to no demand

3.1.3 Availability

To reduce the point estimator bias, Each simulation run divided into two phases: warm-up period from time 0 to time T_0, followed by a data-collection phase from time to T_E (lifetime of end-item) in which data collection, is done. The point estimator for the operation availability OA is the average of availabilities in n simulation runs. Let A_i be the operational availability in the simulation run i. It can be obtained from $A_i(t)$ which denotes availability at time t in simulation run i using by

$$A_i = \int_{T_0}^{T_E} A_i(t)/(T_E - T_0) \qquad (1)$$

in which $A_i(t)$ is obtained by

$$A_i(t) = Min\{A_{i1}(t), \ldots, A_{iM}(t)\}. \qquad (2)$$

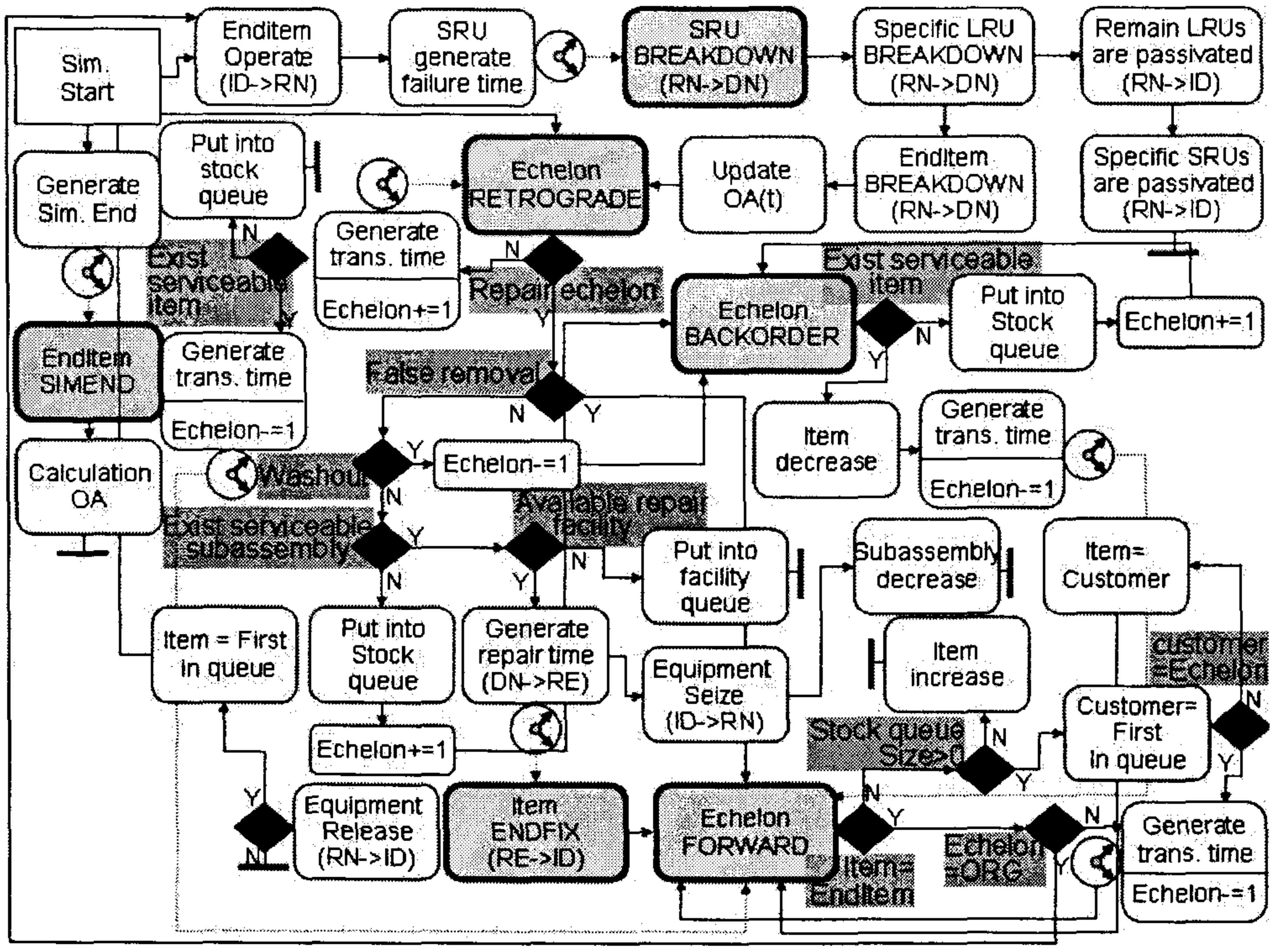


Figure 7. Outline of simulation flow

Here, M denotes the total number of ORG echelon in the multi-echelon system and $A_{ij}(t)$ denotes the availability at time t in ORG j in simulation run i and can be computed by dividing the number of operational end-item at time t in ORG j in simulation run i by the total number of end-item deployed in ORG echelon.

3.2 Genetic algorithm

To apply simulation optimization in the described form in general, we need two things - a simulator and an optimization tool. For the letter, we prefer genetic algorithm (GA).

We use two-dimensional binary string as x_{ij} which is positive integer for i=1,..., # of LRU + 2 # of SRU, j=1, 2,3,4. We use 100 population. The initial population of chromosome is randomly generated.

Crossover and mutation operators are used to generate new offspring from the parents. Simple two-point crossover is used in this article. We concerns the mutation of some bits in the population.

The new offsprings are passed to the objective function, which in case of GAs is more aptly called the fitness function for evaluation. Our objective is to minimize the Life Cycle Cost (LCC) with restriction on end-item availability. We consider the stokage cost for the LCC, as follows:

$$LCC = \sum_{All\ i} \left(\sum_{k=1}^{4} S_{ik}\right) UP(i)\,(1 + CFH \times PVFAC) \tag{3}$$

where, S_{ik} denotes stockage level of the item i at echelon k, UP(i) denotes the unit price of item i, CHF is the yearly cost of holding a stock over the life of the item, and $PVFAC$ is defined as present value adjustment factor. For given discount rate α and the lifetime of end-item T_E $PVFAC$ is calculated by

$$PVFAC = \sum_{t=1}^{T_E} \left(\frac{1}{1+\alpha}\right)^{t-0.5}. \tag{4}$$

We estimate the availability by running previously described simulation model. For given a solution, fitness function is given by

$$fitness = \begin{cases} LCC & \text{if } |TOA - OA| \le \epsilon \\ \infty & O.W. \end{cases} \tag{5}$$

where, TOA is target operational availability, OA is estimate of achieved availability by simulation, and ϵ denotes the tolerance to be input.

A new population is formed with the survived parents from the initial population and their offspring by Roulette selection rule. This iterative process will continue with limited number of generation.

4. Conclusion and Remarks

In this study, we proposed a framework to optimize the stock allocation problem in a multi-indenture, multi-echelon system. We used simulation-based optimization approach combined with genetic algorithm. For a given solution from GA, the simulation model estimated the operational availability of end-item. We defined objects, their attributes, and events in order to develop a simulation system of a MIME system. We designed the simulation logic using the discrete-event simulation and developed a simulator using VC++, an object-oriented language.

Further research can be focus on the proof of the model trough the application to the real world problem. And we can also study the effect of the various input parameters on the optimal stockage levels using the sensitivity analysis.

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