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A STUDY OF REMANUFACTURING SYSTEM IN PRESENCE OF UNRELIABLE SUPPLY OF NEW PRODUCTS

Suman Niranjan

College of Business Administration
Savannah State University
3219 College St.
Savannah, GA 31404, USA

ABSTRACT

We analyze a two-echelon remanufacturing system which utilizes a mix of new components as well as remanufactured old components to produce a new product. We find the optimal mix of new and old components that minimizes inventory and overall costs of the system for a fixed service level. Additionally, this system is investigated assuming unreliable suppliers for new components. The system performance is analyzed using a series of dynamic equations that is developed to describe the system. A simulation-based optimization approach is used to analyze various scenarios as the demand and capacity under consideration is stochastic in nature. ARENA and OptQuest is used for updating the equations and optimizing the system, respectively. Several cases considered for computational evaluation in order to understand the impacts.

1 INTRODUCTION

Closed Loop Supply Chain (CLSC) has garnered a great deal of interest over last two decades. Remanufacturing forms a small portion of CLSC, and it is sometimes also referred to as reverse logistics. CLSC and reverse logistics have been studied by many corporate companies as well as academia over the course of the last two decades. CLSC focuses on several business models such as refurbishing, reusing, remanufacturing, recycling, upcycling, downcycling, etc., depending on the nature of the product and its specific use to the market. In the case of remanufacturing, the products after their end-of-useful life is either returned by the customers, or collected by certain companies, which eventually get to the original manufacturer or an original equipment manufacturer (OEM). Any such product is then checked for its functionality, when a particular component (or components) from the used product is extracted and used either as a spare part or integrated into a new product, which sometimes can be sold as a new product or refurbished product. Remanufacturing has a massive financial prospect. According to a report from the European Commission - European Remanufacturing Network, the current remanufacturing market in Europe alone is close to €30 billion and is expected to reach an annual value of €70bn to €100bn with the direct and indirect employment reaching 600,000. In the United States, according to a USITC (United States International Trade Commission) report in 2012, the remanufacturing has a market to $43 billion. In addition, conforming to a recent report from KPMG Inc., 90-95% of all automobile starters and alternators in the U.S. are sold as replacements and remanufactured. U.S. Auto Parts Remanufacture Association estimates that remanufactured parts form a $36 billion market. Globally, customers buy and return $642.6 billion of goods annually (KPMG International 2017). This manuscript focuses on the products returned prior to their useful life completion. For example, out of many possible situations, a couple of them could be: (i) the product is returned before its useful life finishes, and components of that product is used in making a new product, and (ii) the product useful life has completed, but few components in the product have useful life beyond the product itself, and these components can be used in making a new product (Guide and Van Wassenhove 2009).

Nike reuses and recycles 100% of its material that is returned through their program to make sports surfaces. Xerox, CAT Reman (Caterpillar Inc.), and John Deere Corporations are utilizing remanufacturing programs (Kerr and Rayan 2001). Xerox has always collected its components since 1960's, but the remanufacturing unit turned profitable only in 1980's. The products returned are inspected, and components from these products are extracted and used in making new products, or sold as spare parts. CAT Reman also works similar to Xerox, where the equipment is brought back to life after the end of lease-term or end-of-product life cycle, sometimes only certain components can be brought back to original condition, these components are used in new products. IBM's also has a similar model of business through their server lease program where more than 35% of components that go into making an IBM's new product contains hardware extracted at end-of-life products (Fleischmann, Van Nunen, and Gräve 2001). More than 80% of the mobile phones in the United States are upgraded after their two-year period although the useful life extends far beyond that, and this is also a perfect situation for remanufacturing/recycling. Working components of a used cell phone or end-of-life cell phone can be substituted for new components in new mobile phone manufacturing or other electronic devices.

Although several examples of CLSC described earlier, the primary motivation of this research is Kodak's single-use camera, where lenses are reused. The important research questions that arises from component reuse are: (i) optimal inventory levels for reused and new components for a given service level, (ii) impact on total cost when shortage to reused or new components occurs resulting in last minute changes to orders, and (iii) uncertainty in new and reused components supply impact the total cost. If a firm decides to use higher proportions of new components or remanufactured components to satisfy end-product demand, it may not necessarily be efficient. Thus, striking a balance between the two is important.

Suppliers of a new component are assumed to be unreliable in this research. Supply mismanagement has severe impact on a firm's financial performance, and it is critical for a company to have reliable supply. On average, a firm spends 55% of the earned income on procuring materials (Leenders and Fearson 1998), which suggests that supply disruptions have a tremendous impact on the firm's financial performance. Hendricks and Singhal (2003) show that a firm suffering with glitches from suppliers typically experience about 12 % reduction in shareholders return, further Hendricks and Singhal (2005) show that firms suffering from disruption problems have a negative impact on their stock price. There are three key decisions a firm has to make for sourcing material (Burke, Carrillo, and Vakharia 2007): i) list of criteria for selecting a supplier, ii) selecting suppliers from the list for order placement, iii) order quantities to be placed from each of the selected suppliers. In our paper, we assume that the first two steps have been already taken care by the firm and we focus on the last step. If a supplier is unreliable, having a dependence on single-supplier has a greater risk of interruption (Burke, Carrillo, and Vakharia. 2007). Operationally, multiple-suppliers provide greater flexibility, increased chances of timely delivery, and fewer disruptions. Two suppliers are considered in this research under varying reliability conditions.

Ketzenberg, Wee, and Yang (2006) study a single-echelon model and determine the production amount of new product, where both recovered product and new product is sold. The model does not consider capacitated production environment or neither it considers yield loss in recovery as in this research. Ketzenberg (2009) study the value of information when demand, product returns, capacity utilization, and recovery yield are stochastic in nature. Ketzenberg (2009) determine the quantity of new product to produce, product return quantity that gets disposed of, and recover quantity. The aforementioned problem is not multi-echelon, does not consider lead-time, and suppliers ae not uncertain. Chung, Wee, and Yang (2008) consider a multi-echelon inventory system with remanufacturing capacity using simulation-optimization approach. The authors develop a closed loop supply chain inventory model which results in optimizing the profits for the manufacturer, supplier and recycle dealer. The model considered by Chung, Wee, and Yang (2008) is similar to this research, but does not involve the supply uncertainty/disruptions considered in the present model. A follow-up research is conducted by Yuan and Gao (2010) where a closed-loop supply chain (CLSC) system is investigated using simulation optimization approach. Where authors report if one or more cycles of manufacturing followed by one or more cycles of remanufacturing can be performed to minimize the overall cost and maximize the profits and find that it is very much sensitive to return rates, based on the return rate policy is determined. Yuan et al. (2015) extend the previous research by considering various CLSC system profit-maximization models using (1, R) and (P, 1) policies by elimination theory, and deduce several managerial insights. A recent article published by Govindan et al. (2015) provide a comprehensive review of reverse-logistics and CLSC. The article cites gaps in the literature, and among the gaps presented, one of the gaps in CSLC literature is related to the study of CLSC under uncertain supply conditions. The brief literature described earlier focuses on several aspects of demand, capacity and inventory policies, but does not focus on supply uncertainty and disruptions which is one of the primary focus of this research. This study aims to fill the gap with advance research in the area of uncertain supplies for new product in conjunction with remanufactured product.

A two-echelon remanufacturing system with a single end product, dual component sourcing, and finite horizon (multiple periods), fixed lead-time is considered in this research. The supply source is analyzed under reliable and unreliable scenarios. Supplier delivers less than the required quantity with a certain probability, specifically these new components are used in the assembly of a new product. The component can be either a new component or remanufactured. The remanufactured part is assumed a perfect substitute for the new product. The demand for the final finished product is stochastic, each echelon in the supply-chain has stochastic supply, between the nodes lead time is fixed, the arrivals of the remanufactured product are stochastic in nature and follow a probability distribution. The two-echelon system utilizes a base-stock policy. A fraction of the end-products is assumed to be returned as remanufactured product. Due to many stochastic parameters, it is difficult to have a tractable closed form solution, so we use simulation as a means to get a near-optimal solution. A simulation-based optimization approach is used to analyze the performance of the system, specifically using OptQuest (optimization tool provided by ARENA). A design of experiments consisting of aforementioned variables will be utilized to conduct computational experiments. The computational experiments will achieve the following: i) near optimal total cost of the supply chain under different scenarios, and ii) optimal order-up-to level and safety-stock for the remanufactured and new components under a given service level. The paper is organized as follows, in section 2 we introduce the model, in section 3 we describe the proposed numerical analysis, in section 4 preliminary results are discussed, and conclude in section 5.

2 MODEL

Figure 1 demonstrates the representation of the two-echelon remanufacturing system. Node 2 is where remanufacturing takes place, which is assumed to acquire returns from various sources. Returns are processed as a function of the final finished product. A yield is related with node 2, we expect that not all items that are returned are effectively usable, because of two reasons i) components are not always usable, as they are sometimes damaged, ii) remanufacturing cost exceeds the cost of utilizing the component in the final product. The warehouse is represented by node 1, which holds the new and remanufactured components, which are then supplied to node 0 for assembly. The new components are acquired from two suppliers, the nature of the supply is stochastic and unreliable. Node 0 fabricates the last item, each final product incorporates one basic part which can either be the remanufactured from node 2 or new component acquired from node 1. A deterministic lead time exists between node 2-node 1, node 1-node 0, the lead time can be assumed as lead time for ordering or assembling. The cost at which the new component can be procured from the two suppliers changes dynamically each period.

To describe the operations through the rest of the paper the following notations are used:

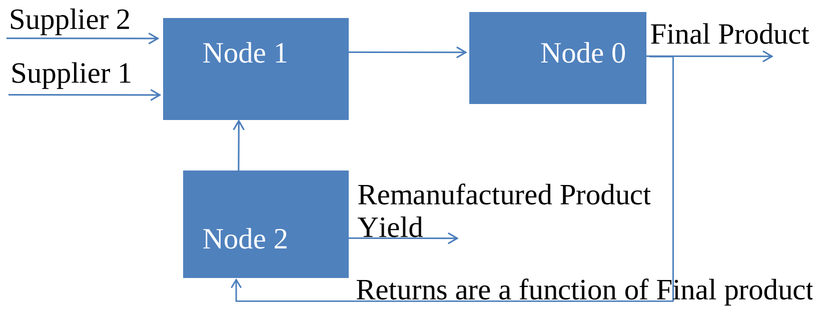

Figure 1: Two-echelon remanufacturing system.

η_n^i : Capacity realized in period *n* at stage *i*

ξ_n^j : Demand in period *n* for Product *j*

c^i : Unit cost of item *i*

s^i : Target stock (order up to or base-stock) level for item *i*

Y_n^i : Shortages of orders in period *n* for item *i* for which the delivery has not been made

IL_n^i : Inventory level in period *n* for item *i* prior to demand being realized

I_n^i : Physical (On-hand) inventory level in period *n* for item *i* prior to demand being realized

DS_n^i : Shortage downstream in period *n* at node *i*

INU_n : Initial new units in period *n*

IRU_n : Initial recycled units in period *n* ENU_n : Excess new units in period *n*

ERU_n : Excess recycled units in period *n*

ρ : Fraction of demand coming from the recycled products

α^i : Required service level (type-I) at node *i*

ε_n : Remanufacturing yield in period *n (represents a portion of returned products which are unusable)*

r_n : Arrival rate in period *n*

ϕ : Proposition of new component order to supplier 1

AUD: average units disposed due to manufacturing yield

2.1 Operations and Assumptions of System

The system considered in this research operates under a periodic base-stock policy. Inventory position is computed as: *orders + on-hand inventory – backorders*, as the inventory level falls below the base-stock level, an order is placed to bring the inventory to target stock level. The orders that are not fulfilled are backordered. The expected value of demand is assumed to be lower than capacity: $E\lfloor \xi_n^i \rfloor < E\lfloor \eta_n^i \rfloor$. The capacity constraint is only present for node 0. Only a fraction (ρ) of the demand for components is considered as returning products. The objective function (1) directly penalizes holding more inventory at each location, as higher s^i indicates more inventory of item *i*.

Node 1 corresponds to the warehouse which contains both, new and remanufactured components. Two super-script notations for node 1 are considered, which correspond to *1n* and *1s* for new and remanufactured components respectively. The volume of remanufactured product distributed from node 1 to node 0 corresponds to Initial Recycled Units (IRU_n) in a specific period *n*. IRU_n can be further defined as: *minimum remanufactured components available or remanufactured components demand* in a given period *n*. ENU_n is the amount of new components in period *n* when proportion of demand from remanufactured components is not met. Initial New Units (INU_n) corresponds to the amount of new components that is supplied from node 1 to node 0 in period *n*. ERU_n (excess remanufactured units in period *n*) is the amount of remanufactured product when proportion of demand from new components is not met.

The cost of the new components supplied by two of the suppliers changes dynamically each period. The lower cost supplier is selected to receive the majority of the demand. The two-echelon problem formulation is stated below:

$$\begin{aligned} &\min_{s^i \geq 0} \sum_i c^i s^i + \overline{ENU} * c^{ENU} + \overline{ERU} * c^{ERU} + AUD * c^{disp} \\ &s.t.\ P\left[IL_n^i \geq 0 \right] \geq \alpha^i, \text{where } i \in \{2, 1s, 1n, 0\} \end{aligned} \tag{1}$$

The objective function is a simple linear equation; the constraints are nonlinear in nature. The costs are minimized in the objective function, subject to a certain amount of predetermined service level (α) being achieved at every node. The objective function indirectly influences the holding cost as greater the base-stock level implies higher overall holding cost. The constraints are formulated on the basis of a type-I service level. $\overline{ENU}$, and $\overline{ERU}$ are the average extra new and remanufactured units, the values represent the average over the several periods used in simulation. c^{ENU} and c^{ERU} is the cost for extra new units and extra remanufactured units respectively. The average units disposed (*AUD*) is the average of the number of units disposed every period during the remanufacturing process due to some kind of defect in the critical component which cannot be fixed. c^{disp} is the cost of disposing the returned products, this is multiplied to *AUD*, which results in the total cost of disposed products.

The outstanding order equations for node 2, 1n, 1s and 0 is described in equations (2) to (5), the outstanding orders for *1n* and *1s* do not have capacity constraint, capacity for the warehouse (node 1) is assumed to have no limit. The outstanding orders for node 0 are shown below in equation (2).

$$Y_{n+1}^0 = Y_n^0 + \xi_n - \min \left\{ \begin{array}{l} Y_n^0 + \xi_n, S^{1s} + S^{1n} - \left\lfloor Y_{n-2}^{1s} + Y_{n-2}^{1n} \right\rfloor - \xi_{n-1} \\ + \left[DS_{n-1}^{0s} + DS_{n-1}^{0n} + ERU + ENU \right], \eta_n^0 \end{array} \right\} \tag{2}$$

The outstanding orders in equation (2) is either zero, or limited by the available critical component from node 1, or could be determined by the node 0 capacity η_n^0. Where DS_{n-1}^{0s} and DS_{n-1}^{0n} represent downstream shortage for remanufactured and new components. Downstream shortages at node 0 occur due to insufficient manufacturing capacity, in spite of the ability of node 0 to supply the complete requirement to node 1. We assume either the excess components which cannot be used at node 0 are sent back to node 1, or does not get shipped to node 0 at all.

$$Y_{n+1}^2 = Y_n^2 + (\rho * \xi_n) - \min \left\{ Y_n^2 + (\rho * \xi_n), (1 - \varepsilon_n) * (r_n * \xi_n) \right\} \tag{3}$$

The outstanding orders for node 2 is shown in equation (3). The outstanding orders can be zero, or can be further constrained by the combination of arrivals and yield for the remanufactured component $(1-\varepsilon_n)*(r_n*\xi_n)$. In certain numerical cases we consider no yield, when there is no yield, and in those situations ε_n are equal to zero.

The equations for node 1, depending on two different conditions is defined as follows: (i) $IRP_n \geq \rho * \xi_n$; $INP_n \geq (1-\rho) * \xi_n$, (ii) $IRP_n + INP_n < \xi_n$. Further under condition (ii) we have three cases based on where the shortage exists (i.e., due to remanufactured components, or new components), and check if we can substitute it from another source where shortage did not occur: *Case 1:* shortage occurred due to remanufactured components, and excess new components available, *Case 2:-* shortage occurred due to new components, and excess remanufactured components available, and *Case 3:-* shortage occurred due to both remanufactured and new components.

Let us initially consider condition (ii), equations (4) and (5) represent the outstanding orders for remanufactured component as well as new component under the first condition. We are either able to satisfy the required components for the current period (zero outstanding orders) or constrained by the amount of initial product for remanufactured or new component.

$$Y_{n+1}^{1s} = Y_n^{1s} + \rho * \xi_n - DS_n^{0s} - \min\left\{Y_n^{1s} + \rho * \xi_n - DS_n^{0s}, IRP\right\} \tag{4}$$

$$Y_{n+1}^{1n} = Y_n^{1n} + (1-\rho) * \xi_n - DS_n^{0n} - \min\left\{Y_n^{1n} + (1-\rho) * \xi_n - DS_n^{0n}, INP\right\} \tag{5}$$

where $IRP_n = min\left(S_n{}^R, \rho * \xi_n\right)$; $INP_n = min\left(S_n{}^N, (1-\rho) * \xi_n\right)$. $S_n{}^R$ is the amount of supply for remanufactured component from node 2, we can mathematically represent $S_n{}^R = \left(1-\varepsilon_n\right) * \left\lfloor I_n^2 \right\rfloor + ERI_n$, where ERI_n is defined as excess recycled inventory, which is a result of unused recycled units in node 2, equation (16) describes ERI_n. $S_n{}^N$ is the amount of new component from the two suppliers. $S_n{}^N$ is the amount of new component from the two suppliers, the mathematical equations for $S_n{}^N$ are described in the next sub-section.

For condition (ii), case 1 the outstanding orders for new and remanufactured component can be described as in (6) and (7). There are two sub-cases under case 1: i) when the excess new components will only be able to satisfy a portion of the deficit demand $\left(\xi_n - \left[IRP_n + INP_n\right]\right)$ in a given period, equation 6 shows the outstanding order for the remanufactured component under the first sub-case, ii) when the excess new components will completely able to satisfy the deficit demand, equation (7) shows the outstanding orders for the remanufactured component under the second sub-case. The outstanding order for the new component under both the sub-case will be same as described in equation 5.

$$Y_{n+1}^{1s} = Y_n^{1s} + \rho * \xi - DS_n^{0s} - \min\left\{\begin{array}{l} Y_n^{1s} + \rho * \xi - DS_n^{0s}, \\ IRP_n + \left\{\xi_n - \left(IRP_n + INP_n\right) - \left[S^N - \left(1-\rho\right) * \xi_n\right]\right\} \end{array}\right\} \tag{6}$$

$$Y_{n+1}^{1s} = Y_n^{1s} + \rho * \xi - DS_n^{0s} - \min\left\{Y_n^{1s} + \rho * \xi - DS_n^{0s}, IRP_n + \left\{\xi_n - \left(IRP_n + INP_n\right)\right\}\right\} \tag{7}$$

For condition (ii), case 2 the outstanding orders for new and remanufactured component can be described as in (8) and (9). We have two sub-cases under case 2: i) when the excess remanufactured components will only be able to satisfy a portion of the deficit demand in a given period. Equation 8 shows the outstanding order for the new component under the first sub-case, ii) when the excess remanufactured components will completely be able to satisfy the deficit demand, equation (9) shows the outstanding orders for the new component under the second sub-case. The outstanding order for the remanufactured component under both the sub-case will be same as described in equation (4).

$$Y_{n+1}^{1n} = Y_n^{1n} + (1-\rho) * \xi_n - DS_n^{0n} - \min\left\{\begin{array}{l} Y_n^{1n} + (1-\rho) * \xi_n - DS_n^{0n}, \\ INP_n + \left\{\left(\xi_n - \left(IRP_n + INP_n\right)\right) - \left(S^R - \rho * \xi_n\right)\right\} \end{array}\right\} \tag{8}$$

$$Y_{n+1}^{1n} = Y_n^{1n} + (1-\rho) * \xi_n - DS_n^{0n} - \min\left\{Y_n^{1n} + (1-\rho) * \xi_n - DS_n^{0n}, INP_n + \left\{\xi_n - \left(IRP_n + INP_n\right)\right\}\right\} \tag{9}$$

For condition (ii), case 3 the outstanding orders for new and remanufactured components remain the same as described in (4) and (5). The inventory level for Node 0, 2, 1s and 1n are described in equations(10) to (14) respectively; the subscript to the demand (*l*) represents *l* periods of lead time:

$$IL_n^0 = S^0 - Y_{n-l^i}^0 - \left(\xi_{n-1} + \xi_{n-2} + \ldots \xi_{n-l}\right) + ERU_n + ENU_n \tag{10}$$

$$IL_n^2 = S^2 - Y_{n-l^i}^2 - \left(\xi_{n-1} + \xi_{n-2} + \ldots \xi_{n-l}\right) * \rho \tag{11}$$

$$IL_n^{1s} = S^{1s} - Y_{n-l^i}^{1s} - \left(\xi_{n-1} + \xi_{n-2} + \ldots \xi_{n-l}\right) * \rho + DS_{n-1}^{0s} \tag{12}$$

$$IL_n^{1n} = S^{1n} - Y_{n-l^i}^{1n} - \left(\xi_{n-1} + \xi_{n-2} + \ldots \xi_{n-l}\right) * \left(1-\rho\right) + DS_{n-1}^{0n} \tag{13}$$

The on-hand inventory for node 0, 2, 1n, and 1s are given as $I_n^0 = \max\lfloor 0, IL_n^0 \rfloor$; $I_n^2 = \max\lfloor 0, IL_n^2 \rfloor$; $I_n^{1s} = \max\lfloor 0, IL_n^{1s} \rfloor$; $I_n^{1n} = \max\lfloor 0, IL_n^{1n} \rfloor$ respectively.

The inventory level equation for node 0 has the outstanding orders for node 0 that were not satisfied in period $n - l^i$, the demand for period's *n-1* to l^i (which indicate the demand during the lead time), subtracted from the base-stock level of node 0, whereas the excess recycled and new units are added to the inventory level. Similarly the inventory level of node 2 has the outstanding orders for node 2 in period $n - l^i$ and the demand that is due to the remanufactured product (the actual final product demand multiplied by the fraction of demand due to remanufactured product) subtracted from the base-stock level for node 2. Equation (12) and (13) also follow similar structure, except that both the nodes have downstream shortages added to their equation which is explained below.

Downstream shortages:

$$DS_{n-1}^0 = \max\lfloor 0, \xi_{n-1} - \eta_{n-1}^0 \rfloor; DS_{n-1}^{0s} = d_{n-1} * DS_{n-1}^0; DS_{n-1}^{0n} = (1 - d_{n-1}) * DS_{n-1}^0 \tag{14}$$

The downstream shortage is the shortages that are caused as a result of insufficient capacity at the downstream node, the only node with a capacity constraint is node 0. We assume that the shortage at the downstream node 0 due to constrained capacity are either never shipped to the downstream node or returned back due to insufficient capacity. The units are sent back from node 0 to the warehouse or node 1 will have units from both the remanufacturing and new components (represented as DS_{n-1}^{0s} & DS_{n-1}^{0n} respectively), and they have to be split appropriately according to the proportion of remanufactured and new components used in a given period. This ratio (*d*) is expressed in equation (15).

$$d_{n-1} = \frac{IRU_{n-1} + ERU_{n-1}}{INU_{n-1} + ENU_{n-1} + IRU_{n-1} + ERU_{n-1}} \tag{15}$$

The equation for excess recycled inventory is described in (16). The Excess Recycled Inventory (*ERI*) when added to the on-hand inventory for node 2, will result in the upper limit on the supply for the recycled units. It is possible that node 2 can have more recycled units available than actually required to satisfy its portion of demand. This depends on the rate of return and the yield at node 2, if the rate of return is so high that even after the yield and demand in a given period are accounted, if there are units still remaining, this could be used to satisfy shortages due to a new product. If node 2 has excess units, it can be used to satisfy the final product demand when there is an insufficient supply for the new components, but at a cost higher than the regular recycled products.

$$ERI_n = \max\left\{0, \left[(1-\varepsilon_n)*(r_n * \xi_n)\right] - \left[Y_n^2 + (\rho * \xi_n)\right]\right\} + \left[\max(0, ERI_{n-1} - ERU_{n-1})\right] \tag{16}$$

$\lfloor Y_n^2 + (\rho * \xi_n) \rfloor$ in equation 16 represents the actual requirement of recycled product at node 2 in period *n*, $\lfloor \varepsilon_n * (r_n * \xi_n) \rfloor$ represents the total recycled products that will be available in period *n*, $\lfloor Y_n^2 + (\rho * \xi_n) \rfloor$ of which will be used to satisfy the actual requirement at node 2. The second part of equation (16) represents the excess units that were unused in the previous period, either because the demand was satisfied with the initial new and recycled product, or there was more than required excess recycled units that were used to satisfy the demand of the critical component in the final product assembly at node 0. A positive value of ERI_n represents that there is an unused portion of the recycled units which can now be used to satisfy if a shortage occurs in the new product supply in future periods.

Equation (17) below represents *AUD*. The average units disposed are obtained by averaging number of units disposed in each period, the numerator of equation (17) shows the number of units disposed in each period.

$$AUD = \frac{\sum_n \lfloor \varepsilon_n * (r_n * \xi_n) \rfloor}{periods} \tag{17}$$

2.2 New Component Supply

A portion of the demand for the final product has to be satisfied via new component procurement from the suppliers for new product. Two new component suppliers is assumed, and the total amount of supply for the new product depends on the two factors, the proportion of demand for new product in the current period, and the outstanding orders for the new product (if any). We assume that for each supplier the firm does not have exact information on the cost per unit $\left(c^{1n}\right)$ until the beginning of the period, but has the information about approximate range of cost for the new product before the start of the period. Depending on the cost of the new product in a given period the firm decides which supplier will receive a larger order among the two. We assume that quality of the new component supplied by both the suppliers is same, and the cost is the only factor that would decide which supplier receives a larger order, a supplier with lower cost receives a higher proportion of the new components order. Moreover, we also assume that the suppliers are completely unreliable, and we model the unreliability in the supplier using two models i) all-or-nothing supply, and ii) supply yield. In an all-or-nothing supply the firm receives the entire supply or receives nothing in a given period, whereas in a supply yield, the supplier might be unable to satisfy the entire order and certain amount of yield associated with the order. The supply of new components from supplier 1 and 2 under all-or-nothing supply is given as show in equation (18) and (19).

$$Supply\ from\ supplier\ 1 = \left\lfloor Max\left(Order1, Normal\left(Order1, CV * Order1\right)\right)\right\rfloor * \beta_1 \tag{18}$$

$$Supply\ from\ supplier\ 2 = \left\lfloor Max\left(Order2, Normal\left(Order2, CV * Order2\right)\right)\right\rfloor * \beta_2 \tag{19}$$

In equation (18) and (19) order 1 and order 2 correspond to the amount of order that is placed with supplier 1 and supplier 2 respectively. The all-or-nothing supply modeled by the use of random variable $\beta_1, \beta_2 \in \{0,1\}$ which can take up a random value equal to zero or one. We also assume that approximately 50% of the time when the supplier supplies everything, the supplier has more new components than the required order, although the excess units are used only when a need arises (shortage due to recycled components), and at an additional cost per unit. In order to model this assumption, a normal distribution with a mean equal to the supplier order, and a standard deviation defined by the CV (coefficient of variation) is used. The term *Max* in equations (18) and (19) ensures that only the values greater than mean (order 1 or order 2) are used, since this is an all-or-nothing we cannot have quantity less than the order. Equation (20) describes order 1 and 2, where ϕ is fraction (value between 0 and 1) dependent on the suppliers cost for the new component, if supplier 1 quotes a lower price, then a higher value of ϕ is used.

$$Order1 = \left\lfloor (1-\rho) * \xi_n + Y_n^{1n} \right\rfloor * \phi; Order2 = \left\lfloor (1-\rho) * \xi_n + Y_n^{1n} \right\rfloor * (1-\phi) \tag{20}$$

The supply of new components from supplier 1 and 2 under supply yield is given as show in equation (21) and (22). The value of $\beta_1, \beta_2 \in uniform\{a,b\}$ where the value of *a* and *b* is a value between 0 and 1.

$$Supply\ from\ supplier\ 1 = \left\lfloor Normal\left(Order1, CV * Order1\right)\right\rfloor * \beta_1 \tag{21}$$

$$Supply\ from\ supplier\ 2 = \left\lfloor Normal\left(Order2, CV * Order2\right)\right\rfloor * \beta_2 \tag{22}$$

3 SIMULATION AND COMPUTATIONAL SET-UP

ARENA, a discrete-event simulation tool is used to update the dynamic equations on a periodic basis. The objective function and the constraints are defined in OptQuest (optimization engine part of ARENA), along with all the decision variables defined in OptQuest. Lower and upper bound values of all the decision variables are defined in OptQuest. A numerical analysis with three-period fixed lead time is assumed between the echelons. The values for capacity and demand are based on a normal distribution (Ciarallo, Akella, and Morton 1994; Bollapragada, Rao, and Zhang 2004; Niranjan and Ciarallo 2011; Niranjan and Ciarallo 2014). Node 2 and 0 is defined 90% service level. A design of experiments with varying coefficient of variability of demand, capacity, costs of remanufactured components, cost of new components, dynamic pricing, and beta will be considered to find the optimal inventory level under each scenario.

This section briefly discusses set-up for numerical results, simulation, various cases used in analysis, and validation based on the results. As mentioned earlier, we use ARENA as a tool to update the equations every period. Each period the following sequence of activities occur: i) the outstanding orders are updated (i.e., shortages), ii) on-hand inventory is updated (i.e., the actual physical inventory), iii) demand is realized, and iv) capacity is realized. The simulation software is used to simply update the equations every period in the aforementioned sequence. The lower and upper bound values of base-stock levels (decision variables) are defined in OptQuest. Each simulation run starts with a randomly selected base-stock value selected by OptQuest based on the upper and lower limit values selected. The simulation is run for a minimum of 500 periods (selected based on observation) or until no further improvement (based on the tolerance value set-up in ARENA) in the objective value is found, whichever arrives later. The best base-stock values for the nodes are determined if no improvement in the objective function is found (total cost) after meeting all the service level constraints. Figure 2 provides the details on how simulation is conducted.

The following base values/assumptions are used for numerical computation: (i) a three-period ordering/manufacturing/supply lead time is assumed, (ii) the values of demand yield and capacity are normally distributed, (iii) Node 0 and 2 uses a service level of 90%, and (iv) remanufactured component cost < ERU cost < new component cost < ENU cost. For the numerical analysis we consider the following design of experiments: 4 instances x 3 varying values of yield probability x 3 varying values of fraction of demand coming from recycles products x 2 cost values of ERU x 2 cost values of ENU x 2 cost values of remanufactured components x 2 cost values of new component, a total of 576 unique simulation runs are considered for the initial analysis. Table 1 lists all the considered instances, capacity denoted as average implies a utilization between 65% and 75%, whereas a tight capacity would imply utilization between 85% and 95%. The average demand value is 21 units. If the demand and capacity CV is 0.2 it is defined as low variability, 0.4 CV is considered as high variability. The capacity utilization determines the average capacity, based on the fixed demand value. We consider that both the suppliers are all-or-nothing, which means they would either supply everything or nothing.

4 VALIDATION-VERIFICATION AND RESULTS

As a part of ongoing research, we were able to run several simulation runs but have not completed the 576 unique scenarios. For all the results discussed, a cost of 1 per unit is assumed, we also assume cost of disposal as 0.25, cost of remanufacturing is 1, cost of ERU and ENU same at 1.5. The results that we present here sufficiently validate and verify the model. We use basic inventory theory principles to validate and verify the model. For instance when all variables are fixed and the CV for demand changes we should be able to see the overall cost go up, and safety-stock go up as well, similarly as the capacity utilization increase the overall cost should go up as a result of optimal stock level on each node go up as well. The preliminary results are provided in Table 2. Table 2 provides results on the basis of the following parameters: Table 2 can also be considered as the base situation. For the random value of demand and capacity the following is considered under four instances discussed in table 1: (i) average yield of 10% with a CV value as 0.2, (ii) average yield of 25% with a CV as 0.4, (iii) average yield of 10% with a CV value as 0.4, (iv) average yield of 25% with CV as 0.2.

Based on the results in table 2 we can observe that as the CV increases the yield under each instance we see an increase in average safety stock as well as total cost increase. Additionally, we also see as the yield increases under a given instance, we find an increase in safety stock as well as total cost. Also across instances under a given column we see an increase in safety stock and overall cost, which clearly indicates that high variance results in higher safety-stock and increased overall total cost.

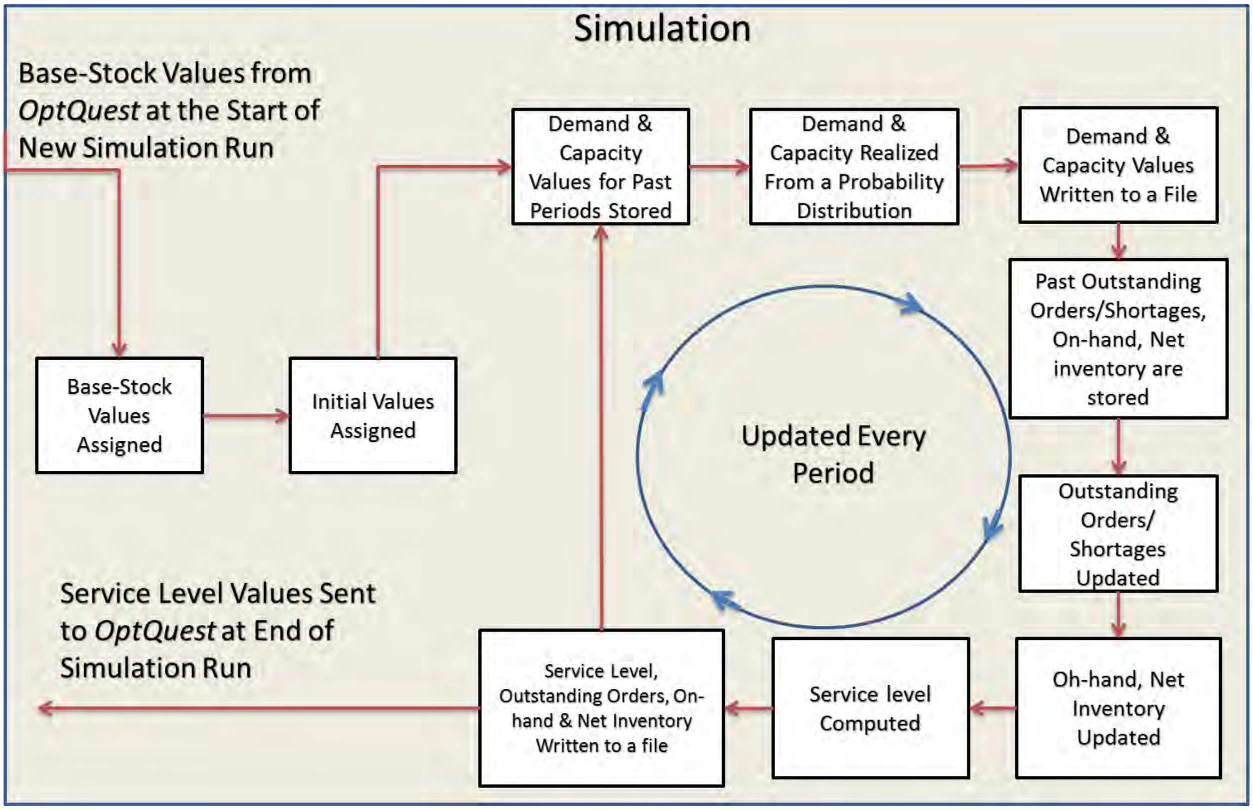

Figure 2: Simulation in ARENA within the OptQuest Framework.

Table 1: Instances for two-echelon system.

Instance #	Name of instance	CV for Capacity	CV for Demand
1	Average Capacity (AC)	0.2	0.2
2	Tight Capacity	0.2	0.2
3	High Demand Variance with Average Capacity (HDVAC)	0.4	0.4
4	High Demand Variance with Tight Capacity (HDVTC)	0.4	0.4

Additional analysis was conducted with *situation 1*-zero yield, *situation 2*-80% of the new component demand is satisfied from supplier 1 and rest from supplier 2 (we assume unreliable supplier 2 resulting in lower proportion of demand), *situation 3*-60% of the new component demand is satisfied from supplier 1 and rest from supplier 2 we assume unreliable supplier 2 resulting in lower proportion of demand), *situation 4*-Both the suppliers are unreliable as a result we have an all-or-nothing situation for demand with a 50% chance of demand being satisfied fully or unable to satisfy any. Table 3 has these results. The zero yield situation has demand split evenly between the two suppliers and considered to be reliable. Situation 2-4 have at least one supplier unreliable with zero yields for the remanufactured product.

Table 3 offers an interesting insight into the problem as the results were not as expected. We can observe from the table 3 that under instance 1 and 2, which is low variability, we find situation 4 (unreliable suppliers) has an average total cost lower than situation 2 and 3. This can be attributed to the low variability and lower capacity utilization which did not have much impact on the unreliable suppliers. Additionally, the average probability of 50% of the time when the orders are not fulfilled seems to also be another reason.

Whereas in instance 3 and 4, we do not see any counter-intuitive results, and the results show that the simulation has valid results.

Table 2: Preliminary results for two-echelon system.

	0.1 Yield 0.2 CV	**0.25 Yield 0.2 CV**	**0.1 Yield 0.4 CV**	**0.25 Yield 0.4 CV**
INSTANCE 1				
Average Safety Stock (SS)	37.18	38.01	38.84	39.68
Average Total Cost (TC)	742.44	743.02	744.38	747.94
INSTANCE 2				
Average SS	39.04	40.62	41.37	44.12
Average TC	732.78	735.62	743.47	747.74
INSTANCE 3				
Average SS	67.36	69.63	70.02	72.63
Average TC	906.7	921.83	914.91	926.18
INSTANCE 4				
Average SS	76.29	78.63	79.46	80.63
Average TC	978.05	989.38	988.5	999.6

Table 3: Special situations.

	Situation 2	**Situation 3**	**Situation 4**	**Situation 1 - Zero Yield**
INSTANCE 1				
Average Safety Stock	52.56	52.23	53.73	36.68
Average Total Cost	831.97	828.28	804.98	733.6
INSTANCE 2				
Average SS	70.91	65.78	69.74	38.99
Average TC	961.46	945.62	938.02	728.53
INSTANCE 3				
Average SS	118.44	123.46	126.56	67.22
Average TC	1182.36	1190.62	1205.66	899.7
INSTANCE 4				
Average SS	199.03	199.33	200.73	74.79
Average TC	1724.42	1725.54	1751.11	978.86

5 ONGOING RESEARCH AND CONCLUSION

In this paper, we developed dynamic equations for a two stage remanufacturing system in the presence of unreliable suppliers for new components. Initial validation and verification based on numerical analysis have been conducted. Currently, numerical analysis is being conducted for 500 plus unique simulation scenarios with managerial inferences that will be deduced from the results.

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AUTHOR BIOGRAPHY

SUMAN NIRANJAN is an Associate Professor of Operations Management at Savannah State University, College of Business Administration. He is also the director of transportation studies and coordinator of G-LIB program. His research interests include supply chain optimization, service operations management, inventory control, strategic management, multivariate statistical analysis, simulation optimization. His email address is niranjans@savannahstate.edu.