ABSTRACT
Reverse logistics (RL) is concerned with reverse flow of the products from consumer to the original equipment manufacturers. The development of the network for collection, storage, inspection, remanufacturing and redistribution are important RL activities that need to be carefully planned.

RL is characterized by uncertainty in terms of the receipt of the used products from the consumer. A good returned product can be reused or remanufactured with lower inputs. However, a defective product can either be disposed or recycled. On the other hand, it is also difficult to predict as to what the demand for the remanufactured or reusable products would be. Thus RL has uncertainty as to receipt (of used products) and their processing. Therefore, while designing a network, companies have to consider not only the allocation of capacities for warehouse, transportation but also the stochastic nature of supply and demand. Remanufacturing not only requires the used parts but it also needs to be supplemented by new modules.

In this work, we propose a model that considers stochastic supply of return products and stochastic demand for the remanufactured products. The network also considers the sale of reusable modules and materials in the secondary market and the requirements for new modules for remanufacturing in case of higher demand for the remanufactured products. The attempt is to establish a network incorporating the above randomness for strategic decision involving huge capital investments. The network is illustrated by a numerical study.

KEY WORDS
Reverse Logistics Network, Facility Location and Allocation, Stochastic Demand, Stochastic Supply

1. Introduction
Legislative actions, social responsibility, corporate imaging, environmental concern, and economic benefits are forcing original equipment manufacturers (OEMs) to take back the products after its end of life. With increasing concerns on landfilling by recyclable or reusable products, “take back” actions are becoming a norm [1,2,3]. Environmental concern is also spreading among the consumers who have recognized the importance of waste reduction and resource conservation [4,5]. This has resulted in the concept of ‘extended producer responsibility’ (EPR). Also, OEMs are using environmentally friendly inputs in terms of purchased raw materials or finished products to facilitate resource reduction, reuse or recycling of products [3]. This concern for the environment has credible implications on the logistics activities related to product recovery. It encompasses all activities used in handling used and discarded products to capture the latent economic (and ecological) value embedded in them and to ultimately reduce wastes.

Implementation of reverse logistics (RL) requires setting up of appropriate cost effective and efficient logistics infrastructure to handle the return flow of products [6]. The design of such a network is strategic as it involves a decision on the number, location and capacities of various facilities and allocation of material flows between them [7,8,9]. Therefore, design of a RL network needs to consider the network spectrum from the locations for the acquisition of used products to the locations for secondary markets and sale of remanufactured products. This transport-storage network must also match the availability and location of used products. A properly designed network can also enhance dealing with remanufacturing activities [10].

In this paper, a mathematical model for the design of a RL network is proposed. The model assumes stochastic supply of used products and stochastic demand for remanufactured products. It also considers storing, reprocessing, remanufacturing facilities and new module suppliers in the network. If the recovered modules are not sufficient to remanufacture the products to meet the demand, then certain quantities of certain new modules need to be purchased.
2. Literature Review

Guide et al. [11] and Flapper [12] discuss the difference between forward and reverse supply chains in terms of the difficulty in forecasting product returns as compared to forward distribution which works on a fixed quantity and schedule. This uncertainty in the quantity, quality and timing of product returns and also in the demand for remanufactured products has been highlighted by several researchers. RL operations are complex and prone to high degree of uncertainty, affecting collection rates, the availability of reprocessing production inputs, and capacities of facilities in the reverse channel [13]. Uncertainty also looms over the quality of the returned product and the demand for the remanufactured product in the re-use markets. Also, there is large uncertainty over which recovery option can be used for the returned product. Underestimating uncertainty and its impact can lead to planning decisions that neither safeguard a company against the threats nor take advantage of the opportunities that higher levels of uncertainty provide. Thus, the strategic design of a product recovery network in particular the logistics infrastructure, needs to take the above mentioned uncertainty into account [14].

Gupta and Maranas [15] analyze the impact of demand uncertainty in the traditional supply chain. The authors propose a two-stage stochastic model for facility location and flow allocation in forward logistics. The model attempts to minimize the cost of the network which assumes a demand with normal distribution and multi-product, multi-site supply sources in a multi-period horizon.

Fleischmann et al. [16] reviewed several cases in RL and highlight that uncertainty is a characteristic of product recovery management. For example, the availability of used products on the disposer market or the demand for recovered products is identified as major uncertain factors. Inderfurth et al. [17], proposed a periodic review model for product recovery in stochastic remanufacturing systems with multiple reuse options. Listes and Dekker [14] proposed a two-stage stochastic model for recycling sand; a case reported by Barros et al. [18]. The authors develop a two-stage stochastic model for varying demand and supply scenarios and find that the number and location of newly opened facilities is influenced by the amount and quality of incoming flows and also by the sources and demand points. Biehl et al. [13] develop a model assuming stochastic collection (having lognormal distribution) and demand (normal distribution) for the US carpet industry. The model is used to determine the quantity of virgin nylon to be ordered by the manufacturers based on the supply of recycled nylon (carpet) to meet the market demand.

Listes [19] presents a generic two-stage, capacitated model for stochastic supply and return network design. The author proposes a decomposition approach to the model based on branch and cut procedure (known as the integer L-shaped method). Duque et al. [20] study the recovery of residual products that originate at industrial plants. The authors propose a MILP model to suggest the optimal processing and transport routes, which is modeled using a maximal state task network representation. It also takes environmental impacts as constraints into considerations and demand is assumed to have normal distribution. A stochastic feasibility index is proposed as a measure of the robustness of the optimum solution generated by the model. Lieckens and Vandaele [21] extend a facility location-allocation MILP model in RL with queuing relationships to incorporate product life cycle and inventory holding costs, as well as to deal with the uncertainty in RL networks. The authors formulate a mixed integer non linear programming (MINLP) model to solve the problem of single-product returns.

Our contribution to the above work is in the form of a stochastic model for RL network design. We have considered the modular architecture of returned products which has not been discussed in the literature reviewed so far. The focus is on deciding the number of facilities, their locations and allocation of corresponding goods flow with stochastic supply and stochastic demand conditions.

3. Model Background

The network under consideration involves 9 echelons which contribute actively in the respective functions of RL. The multi-layer RL chain includes retailers, warehouses, reprocessing centres (RPC), remanufacturing factories, recycling centres, disposal sites, new module suppliers, spare part markets, and secondary markets. The conceptual framework used for the development of the mathematical model is shown in Figure 1.
The retailers act as collection centres for used products. Customers return their used products to the retailers. An infinite source of used products is assumed. The products collected at the collection points are transported to the warehouses. The warehouse is only a centre for storage and consolidation to minimize the transport cost. No value added activity is carried out in the warehouses. From the warehouse, the collected products are transported to the reprocessing centres. The products are dismantled to their modular form in the RPC. These modules are cleaned, tested and sorted for reuse, remanufacture, spare and recycle.

A certain percentage of modules may be disposed, as prescribed by the manufacturer. Also, a certain percentage of modules may be sent for recycling, as prescribed by the manufacturer. The demand for modules from the spare markets and the remanufacturing factories is met by the remaining modules. The remanufacturing factories cater to the demand for remanufactured products via a distribution centre (DC). The DC collects all the demands for remanufactured products from the secondary markets. In case the demand at either the spare market or the factories can not be met by the recovered used modules, the balance demand is met by procuring additional modules from the new module suppliers. However, if the stock of recovered used modules is more than the demand, the excess modules can either be sent for recycling (incurring transport cost) or can be stored in the RPC’s till the next period (incurring inventory cost). Similarly, if the total products transported to the DC’s are excess to the demand from the secondary markets, the excess products are stored till the next period (incurring inventory cost).

The warehouse, RPC and factory are assumed to incur fixed monthly costs. They also incur different inventory holding cost for each product and module. The final assembly of the product with used and new modules, if any, is done inside the factory. The factory has inventory holding costs only for the used modules while it operates on Just-In-Time (JIT) inventory strategy to acquire new modules. The transport cost varies with distance and size of product and modules. It is also assumed that remanufactured products are transported to distribution centres immediately after production.

The objective of the modeling process is to determine the optimal location of the facilities and the allocation of goods flow between them that minimize the total cost of the network. The linear optimization model is formulated in the form of linear programming and has the following structure:

Minimize:

\[
\text{Total costs} = \text{product acquisition cost} + \text{transport cost} + \text{inventory cost} + \text{fixed cost} + \text{reprocessing cost} + \text{new module cost} + \text{assembly cost} + \text{disposal cost}
\]

Subject to:

- Demand constraints of spare markets for modules
- Stochastic demand constraints of secondary markets for remanufactured products
- Storage capacity constraints of the facilities
- Processing capacity constraints of the facilities
- Stochastic supply constraints

When demand and acquired quantities differ, the given choice of locations and capacities for the warehouses, remanufacturing facilities and other entities in a RL network also differ. One of the ways to deal with this type of situation is the use scenario analysis where probability of each scenario can be ascertained to some extent.

Figure 1: Generic RL Structure
4. Analysis

The proposed model is implemented in a case which involves 5 retailers, 4 warehouses, 3 return processing centres, 5 spare market locations, 3 remanufacturing factories, one disposal and recycling centre each, 6 suppliers of new modules, and 6 distribution centres. The network is as shown in Figure 2. A scenario based stochastic programming method is used to solve this model.

Figure 2: Assumed RL Structure
Figure 3: Proposed RL Structure (Base Case)
The model is tested for three scenarios (low, medium, high) of returned products and three scenarios (low, medium, high) of demand for remanufactured products. Figure 3 shows the network which is developed for supply scenario with returns ranging between 9,300 (low) and 10,500 (high) units as shown in Table 1. The demand for remanufactured products ranges between 13,800 (low) and 18,600 (high) units. The optimal cost of the network is about $1,839,850. It is seen that the total returns can be allocated to only two warehouses (W_1 and W_4), thus making the additional warehouses unnecessary for the given scenarios. Factory F_1 receives most of the recovered modules from the RPC’s. However, under same scenarios of supply and demand, when the transport costs between the RPC’s and the factories change and the reprocessing cost of factory F_1 decreases the network changes considerably. This changed network is shown in Figure 4. The optimal cost of the network is to $1,839,000 but the flow of goods between the facilities changes significantly. It is seen that the recovered modules at all RPC’s are sent to factory F_1. The other factories (F_2 and F_3) receive no supplies of recovered modules from the RPC’s. Also, the demand for new modules from the factories F_1 and F_3 are easily met by only four suppliers. Flow of new modules from the suppliers also changes. For example, supplier S_3 which supplied 3070 modules to F_1 in the base case now supplies 670 modules to F_1 and 2400 modules to F_2.

It can be seen that factory F_1 caters 40% of the demand of remanufactured products whereas factories F_2 and F_3 supply new products to the markets. Hence, factories F_2 and F_3 can be treated as traditional manufacturing facilities used to meet the demand. Thus, based on the structure, the demand for remanufactured products cannot be met and has to be supplemented by new products. This makes the strategic location of remanufacturing facilities important to meet the demand.

Table 1 shows network and new module costs for the base case with changes in the probability of product returns at the retailers.
Table 1: Network and New Module Cost Variation which Change in Return Probabilities

<table>
<thead>
<tr>
<th>Probability of Low Return</th>
<th>Probability of Medium Return</th>
<th>Probability of High Return</th>
<th>Network cost</th>
<th>New module cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>.25 (9300)</td>
<td>.5 (10000)</td>
<td>.25 (10500)</td>
<td>$1,839,850</td>
<td>$833,743</td>
</tr>
<tr>
<td>.2</td>
<td>.6</td>
<td>.2</td>
<td>$1,838,591</td>
<td>$833,148</td>
</tr>
<tr>
<td>.1</td>
<td>.7</td>
<td>.2</td>
<td>$1,835,693</td>
<td>$828,982</td>
</tr>
<tr>
<td>.1</td>
<td>.8</td>
<td>.1</td>
<td>$1,837,763</td>
<td>$831,958</td>
</tr>
</tbody>
</table>

5. Conclusion

A model is proposed to design a network for product recovery under stochastic supply and demand conditions. Both, the returns and the demand of remanufactured products are considered to have a probabilistic distribution to represent various supply and demand scenarios. The implementation of the model shows that depending on the probabilistic distribution, a facility may not be required to operate the network. Scenarios have been analyzed to show the variations in the network structure and network cost. The scenarios show the importance of citing the remanufacturing facilities. This type of model can be used to establish a RL network for stochastic supply and demand conditions.

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References
