A System Dynamics Framework for an Integrated Forward-Reverse Supply Chain with Fuzzy Demand and Fuzzy Collection Rate under Possibility Constraints

Debabrata Das and Pankaj Dutta

***Abstract*— Reverse supply chain management has been an area of growing attention during the last decade in industry as well as in academia due to its high economic impact, increasing social awareness and strict legislations. In this paper, we develop a simulation model based on system dynamics methodology to analyze the long-term behavior of a multi-echelon forward-reverse supply chain with fuzzy demand and fuzzy collection rate by incorporating various recycling activities, namely; collection, product refurbishing, component reuse and refurbishing, and raw material recovery. The uncertainty issues associated with acquisition and collection of used product in the proposed reverse logistics network has been quantified using possibility measures. In the proposed model, it is assumed that the customer can exchange their old used product with a fresh new product in a primary market or a relatively better refurbished product in a secondary market at a discounted price. In the simulation study, we compare the bullwhip effects of different logistics participants over time with and without product exchange policy. Our results suggest that the inclusion of product exchange policy in the primary as well as in the secondary market reduce the order variation and bullwhip effect at both retailer and distributor level. Finally, sensitivity analysis is performed to examine the impact of various parameters on recovery process and bullwhip effect.**

***Keywords*— Reverse Supply Chain, Bullwhip Effect, Fuzzy Collection Rate, System Dynamics, Possibility Measures**

I. Introduction

IN a world of finite resources and disposal capacities, recovery of used products and materials is a key to support the growing population at an increasing level of consumption. Pagell *et al*. [1] pointed out that product remanufacturing is the most desirable option for end-of-life product management than a scrap or spares recovery since it minimizes the environmental impacts, results in lower loss of value, and can create new market opportunities. Refurbished products are often offered as an alternative to the original products in a secondary market to the customers those are attracted by the brand, but do not wish to pay the price of a new product (e.g. electronics and automobile) [2].

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In the present study, we address the benefits of employing product exchange (PE) policy both in primary as well as in secondary markets to increase the collection rate of used products and consequently selling of refurbished products.

Fleischmann et al. [3] provided a review of the quantitative models for reverse logistics in which they reported that most of the papers in the area of integrated reverse logistics are confined to single issues while comprehensive approaches are rare as variety of factors are involved in a general framework and the complexity of their interdependencies. System dynamics (SD) is a powerful methodology for obtaining the insights of these kinds of problems having dynamic complexity; but there are very few literatures which modeled the integrated aspects of forward and reverse supply chain using SD. Spengler and Schroter [4] modeled an integrated production and recovery system for supplying spare parts using SD to evaluate various strategies. Georgiadis and Vlachos [5] developed a SD model to evaluate the effect of environmental issues on long-term decision making in collection and remanufacturing activities.

In real supply chain problems, input data or parameters are frequently imprecise because some information is either incomplete or unobtainable. Fuzzy set theory gives a strong mathematical structure to capture such imprecise and to model a real decision-making problem. In this paper, we develop a SD framework for an integrated forward-reverse supply chain by incorporating fuzzy demand, fuzzy collection rate and fuzzy satisfaction rate of demand. The uncertainty issues associated with acquisition and collection of used product have been quantified using possibility measures.

As the quality and quantity of used products return to the collection points are uncertain in the reverse channel, the systematic distortion is inevitable and bullwhip effect may occur at retailer, distributor and manufacturer level. There are very few literatures that consider order variations and bullwhip effect in an integrated reverse supply chain ([6]-[7]), but it is yet to receive attention in the context of SD framework ([8]-[9]).

In this paper, we propose a SD framework for an integrated reverse logistics (RL) network to analyze the forward as well as backward movements of product through different stages of supply chain network with three way recovery (TWR), namely; product refurbishing, component reuse & refurbishing, and raw material recovery. We bring

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in the concept of secondary market and PE policy to make the collection and recycling process faster and better. We simulate the order variation at retailer and distributor levels and compared the bullwhip effect of the integrated forward-reverse logistics with and without PE policy. Also, sensitivity analysis is performed to examine the impact of various parameters on recovery process and bullwhip effect.

II. Problem Description

In this work, we focus on an integrated forward-reverse supply chain (see Fig. 1). Due to the high complexity of the problem; we divide the whole system into two parts:

A. Forward Supply Chain with Product Exchange

The forward supply chain comprises three echelons: producer, distributor and retailer. Specifically, the new products are first transferred from the producer to the distributor then to the retailer and finally sold to the customer to satisfy the demands. There are two kinds of demand which is generally being seen in developing countries, namely; - demand in “primary market” for fresh new products and demand in “secondary market” for refurbished products. For example, in India, due to the increasing standards of living, the concept of product exchange and secondary market are getting popularity, especially for automobile and electronics products. In this model we categorize the demand as “*demand with exchange*” and “*demand without exchange*” both in primary as well as in secondary market. The customer can exchange their old used product with a fresh new product in a primary market or a relatively better refurbished product in a secondary market at a discounted price which will effectively increase the product collection rate, market share and satisfy the customer’s need. Hence, the existence of secondary market and the incorporation of PE policy in the primary as well as in the secondary market play an important role in the process of RL.

B. Reverse Supply Chain with Three Way Recovery

In the simulation study, it is assumed that there is no constraint on the capacity of collection, inspection, sorting and restoring. After the initial inspection, if the collected products are accepted for refurbishing, then with some reprocessing, the *refurbished products* can be sold in the secondary market. If the products are not in a condition to refurbish, then it is disassembled into various components. During the process of product refurbishing, if new replacement is required for some components, then the old components are sent to reprocessing center for further recovery. In this model, we assume that the derived components can have three categories: one is *direct reusable components* that can be directly used without any further processing to increase the inventory of component in the forward channel; the second one is the *refurbished component* which require some reprocessing before adding it to the component inventory in the forward channel; the rest of the components can be used either to *recover raw material* which effectively increase the raw materials inventory in the forward channel or can be sent directly for controllable disposal as shown in Fig. 1.

III. Fuzzy Set Theory

It has been argued in a large body of recent literature that fuzzy sets theory could provide an appropriate framework for dealing with uncertainties in areas where intuition and subjective judgment play an important role. Detail reference for fuzzy sets and its applications can be found in [10].

A. Triangular Fuzzy Number

Triangular fuzzy number (TFN) $\tilde{a} = (a_1, a_2, a_3)$ (see Fig. 2) is the fuzzy number with the membership function $\mu_{\tilde{A}}(x)$, a continuous mapping: $\mu_{\tilde{A}}(x): R \to [0,1]$ such that

$$\mu_{\tilde{A}}(x) = \begin{cases} 0 & \text{for } -\infty < x < a_1 \\ \dfrac{x - a_1}{a_2 - a_1} & \text{for } a_1 \le x \le a_2 \\ \dfrac{a_3 - x}{a_3 - a_2} & \text{for } a_2 \le x \le a_3 \\ 0 & \text{for } a_3 < x < \infty \end{cases}$$

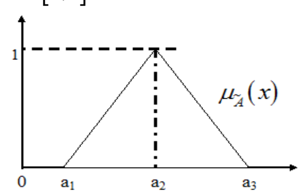

Fig. 2 Membership function of TFN $\tilde{a}$

B. Possibility Measures

There are several representations of fuzzy constraints. Here we use possibility measure concept in which fuzzy numbers are interpreted by the degree of uncertainty.

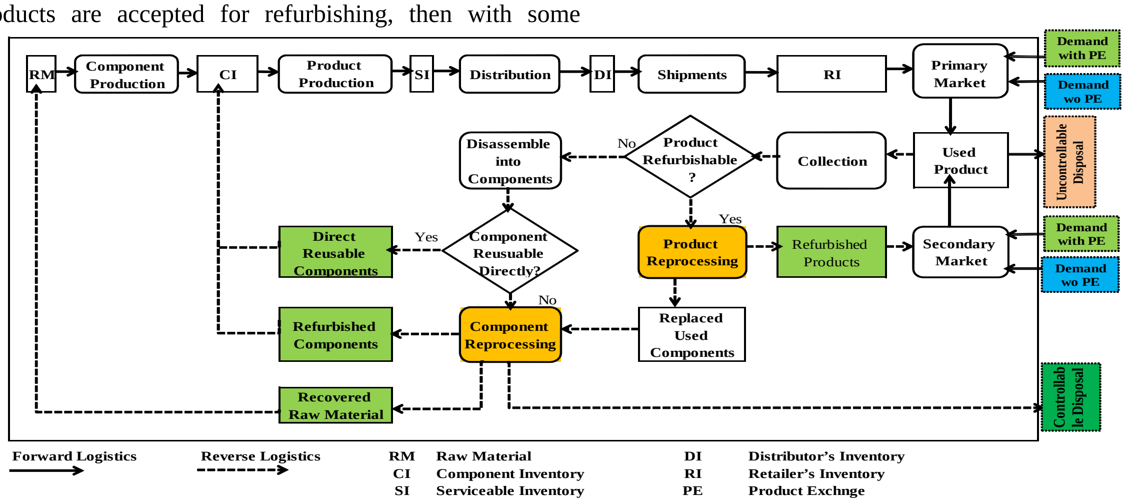

Fig. 1 Flow Chart of the integrated forward-reverse supply chain with TWR and PE policy

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Therefore, if a DM desires to impose the resource constraint in possibility sense, he/she is optimistic. According to Dubois and Prade [11], if $\tilde{A}$ and $\tilde{B}$ be two fuzzy numbers with membership function $\mu_{\tilde{A}}(x)$ and $\mu_{\tilde{B}}(x)$ respectively, then

$$Pos(\tilde{A} * \tilde{B}) = \{\sup(\min(\mu_{\tilde{A}}(x),\ \mu_{\tilde{B}}(y)),\ x, y \in \Re,\ x * y\}$$

where the abbreviation *Pos* represents possibility and * is any of the relations $<, >, =, \leq, \geq$.

Let $\tilde{a} = (a_1, a_2, a_3)$ be a triangular fuzzy number and b is a crisp number then the following lemma holds [12]:

Lemma 1: *When b is a crisp number,* $Pos(\tilde{a} \geq b) \geq \eta$ *if and only if* $\dfrac{a_3 - b}{a_3 - a_2} \geq \eta$

IV. System Dynamics Model with Fuzzy Demand and Fuzzy Collection Rate

System dynamics is a modeling and simulation methodology for framing, understanding, and discussing complex issues and problems. The structure of a SD model contains stock (state), flow (rate) and auxiliary/constant variables. Stock variables are the accumulations (e.g. inventories) within the system. The flow variables represent the flows in the system (e.g. refurbishing rate) from one stock to another. The mathematical formulation consists of a system of differential equations, which is numerically solved via simulation. Nowadays, high-level graphical simulation programs (viz. Vensim, i-think, Powersim etc) support the analysis and study of these systems. Here, we choose Vensim (version: windows 5.10 e) as a tool to simulate the model.

A. Stock-Flow Diagram

Fig. 3 depicts the stock-flow diagram of the integrated forward-reverse supply chain in which the stock variables are represented by the symbol “ ” and the flow variables by “ ”. Because of the high complexity of the closed-loop supply chain, it can be divided into the following four subsystems:

A.1. Forward Supply Chain

The forward supply chain begins from the upper left corner of Fig. 3. *Raw Materials* are furnished by external suppliers and recycling the used products (*Raw Material Recovery Rate*) from the reverse channel. *Components Production Rate* depletes raw materials and increase *Components Inventory*. The equations related to component production rate are following:

*Components Production Rate= MAX (MIN (MIN (Raw Materials/Component Production Time, (Expected Distributors Orders*Components Per Product - Expected Reusable Component+ CI discrepancy/CI Adj Time)), Component Production Capacity), 0)*

Expected reusable components= SMOOTH (Component Refurbish Rate +Components Acceptance Rate for Direct Reuse, 1)

CI discrepancy= MAX (Desired CI-Components Inventory, 0)

Components Inventory (t+dt) = Components Inventory (t) + dt(Components Production Rate +Component Refurbish Rate + Components Acceptance Rate for Direct Reuse) – dt* Components used for Product Production*

The remanufacturing process supplements the production process. Producer’s requirement for components is satisfied with a mix of new components produced by firm, and reusable/refurbished components derived from used products.

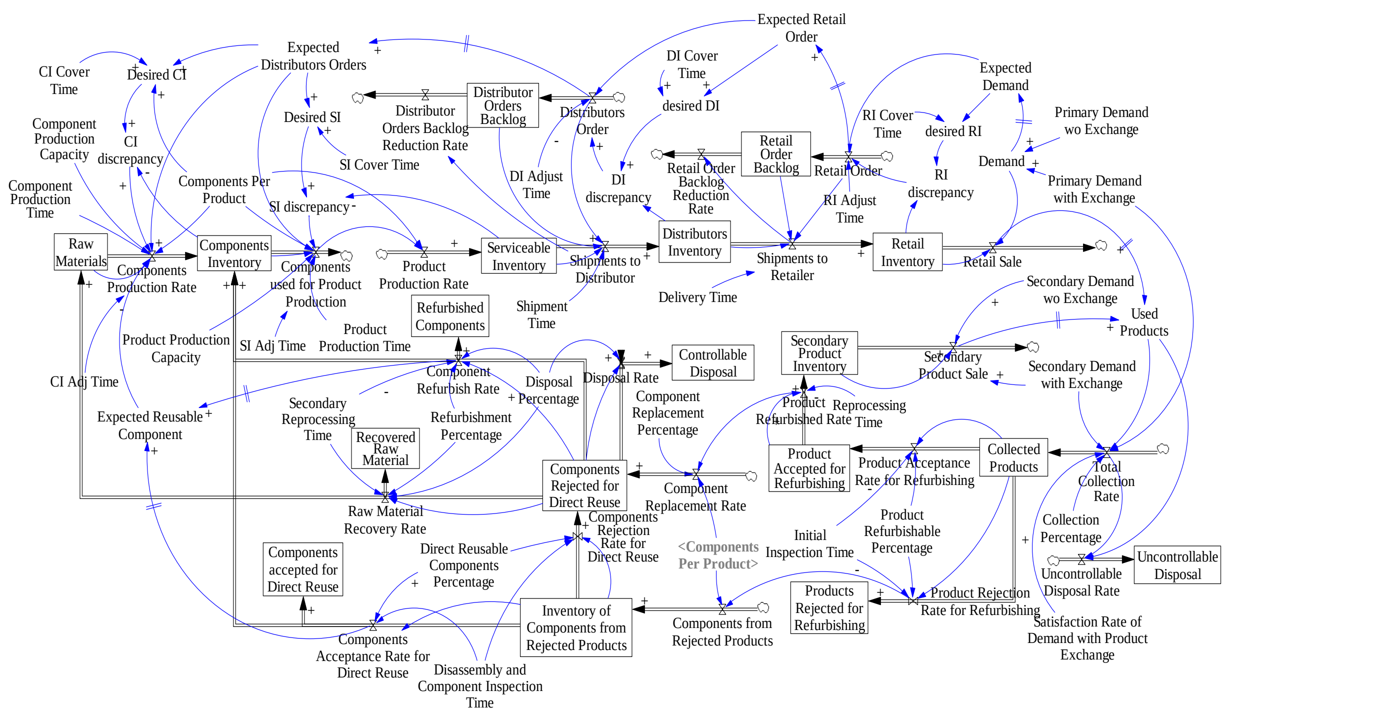

Fig. 3 Stock-flow diagram of the forward-reverse supply chain with PE policy

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The equations related to product production rate are following:

Product Production Rate = Components used for Product Production/Components Per Product

*Components used for Product Production = MAX (MIN (MIN (Components Inventory/Product Production Time, Product Production Capacity*Components Per Product) ,(Expected Distributors Orders+ SI discrepancy/SI Adj Time)*Components Per Product) , 0)*

SI discrepancy=MAX(Desired SI-Serviceable Inventory, 0)

Serviceable Inventory (t+dt) = Serviceable Inventory (t) +dt Product Production Rate –dt*Shipments to Distributor*

Product production rate depletes *Component Inventory* and increase *Serviceable Inventory*. *Shipments to Distributor* deplete *Serviceable Inventory* and increase *Distributors Inventory*. In the same way, products delivered from the upper stream increase the inventory of retailer, which can satisfy the demand of end-users. The equations related to distributor's inventory, transportation and order are presented below:

*Distributors Inventory (t+dt) = Distributors Inventory (t) + dt*Shipments to Distributor –dt*Shipments to Retailer*

Shipments to Distributor= IF THEN ELSE (Serviceable Inventory - Distributors Order -Distributor Orders Backlog >=0, Distributors Order +Distributor Orders Backlog, Serviceable Inventory)/Shipment Time

*Distributor Orders Backlog (t+dt) = Distributor Orders Backlog (t) + dt*Distributors Order – dt*Distributor Orders Backlog Reduction Rate*

Distributors Order= Expected Retail Order +DI discrepancy/DI Adjust Time

Distributor Orders Backlog Reduction Rate= Shipments to Distributor

A.2. Demand with Product Exchange Policy in Primary and Secondary Market

Demand in primary as well as in secondary market has been categorized as "*demand with exchange*" and "*demand without exchange*". The product exchange policy has been described in details in "Problem Description" section. In this paper, we assume that both primary and secondary demand is lost if it is not satisfied in the current period. Although, *Distributor Orders Backlog* and *Retailer Orders Backlog* are satisfied in a future period.

Table I Demand at various markets with and without PE

Market	Policy	Demand (Products/week)
Primary	Without PE Policy	Random Fuzzy (400,500,600)
	With PE Policy	Random Fuzzy (180,200,220)
Secondary	Without PE Policy	Random Fuzzy (115,150,185)
	With PE Policy	Random Fuzzy (85,100,115)

In the proposed SD model, we assume that all the demands are triangular fuzzy number which is shown in Table I.

A.3. Reverse Supply Chain

The recycling process which we incorporate into our SD framework consists of collection, product recovery, and component and material recovery. Sold products after their uses turn into used products. Then, Used Products are either uncontrollably disposed (*Uncontrollable Disposal*) or collected for reuse (*Collected Products*). Total Collection Rate depends upon the collection of used products directly from the end-user plus the rate at which the used products get collected from the customers through the PE policy in the retail market. The equation related to collection rate is following:

*Total Collection Rate= (Secondary demand with exchange +primary demand with exchange)*Satisfaction Rate of Demand with Product Exchange + used products*Collection Percentage*

Out of the *Product Accepted for Refurbishing*, refurbished products (*Product Refurbished Rate*) are sold to the secondary market and the components that are replaced (*Component Replacement Rate*) during product refurbishing by new components are processed further for raw material recovery and component refurbishing.

Product Refurbished Rate= Product Accepted for Refurbishing/Reprocessing Time

Product Accepted for Refurbishing (t+dt) = Product Accepted for Refurbishing (t) + dt Product Acceptance Rate for Refurbishing – dt* Product Refurbished Rate*

In the model, it is assumed that the disassembled components can have three categories: one is direct reusable components (*Components Accepted for Direct Reuse*) that can be directly used to increase the *Components Inventory* in the forward channel; the second is the part of *Components Rejected for Direct Reuse* which requires further reprocessing. After reprocessing, the *Refurbished Components* can be used to increase the *Components Inventory* in the forward channel.

Component Refurbish Rate= (Components Rejected for Direct Reuse)(1-Disposal Percentage)*Refurbishment Percentage/Secondary Reprocessing Time*

The third is rejected components that does not survive the first two screening levels but can be used either for raw material recovery (*Recovered Raw Material*) to increase the *Raw Materials* inventory in the forward channel or sent directly for *Controllable Disposal.*

Recovered Raw Material (t+dt) = Recovered Raw Material (t) + dt Raw Material Recovery Rate*

Raw Material Recovery Rate= Components Rejected for Direct Reuse(1-Disposal Percentage)*(1-Refurbishment Percentage)/Secondary Reprocessing Time*

*Controllable Disposal (t+dt) = Controllable Disposal (t) + dt*Disposal Rate*

*Disposal Rate = Components Rejected for Direct Reuse*Disposal Percentage*

A.4. Possibility Constraints on Collection and Satisfaction Rate

In the proposed SD framework, the uncertainty issues associated with *collection of used products* and *satisfaction of customers willing to exchange their used products for a fresh new product* have been quantified using the possibility constraint programming approach.

Collection Rate

It is always expected that the DM would like to maintain a predefined threshold value of collection rate in every period to increase profitability in remanufacturing and to satisfy the legislations requirements. In the proposed SD model, it is assumed that the collection rate (CR) is a triangular fuzzy distribution, $\widetilde{CR} = (a_1, a_2, a_3)$ with a

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constant deviation of 0.20 from the central value i.e. $a_2 - a_1 = a_3 - a_2 = 0.2$ and that the CR should be more than or equal to 50% of used product with at least 95% probability. But, as CR is a fuzzy number, the following possibility constraint has to be satisfied to fulfill DM's requirement: $\mathrm{Pos}\left(\widetilde{CR} \geq 0.5\right) \geq 0.95$

Now, from lemma (1) of section (3), it is clear that

$$\frac{a_3 - 0.5}{a_3 - a_2} \geq 0.95 \text{ i.e. } \frac{a_3 - 0.5}{0.2} \geq 0.95 \text{ i.e. } a_3 \geq 0.69$$

So, $a_2 \geq 0.49$ and $a_1 \geq 0.29$.

Hence, from the above calculation we can say with 95% possibility that collection percentage will be more than or equal to 50% if $\widetilde{CR} = (0.29, 0.49, 0.69)$.

Satisfaction Rate of Demand with Product Exchange Policy

The incorporation of PE policy plays an important role in the process of integrated forward-reverse supply chain as discussed in earlier sections. Therefore, it is always expected that the DM would like satisfy almost all the customers who are interested to exchange their used products to buy a fresh new product from primary market or refurbished products from secondary market. In the proposed model, it is assumed that the satisfaction rate (SR) is a triangular fuzzy distribution $\widetilde{SR} = (c_1, c_2, c_3)$ with a constant deviation of 0.10 from the central value i.e. $c_2 - c_1 = c_3 - c_2 = 0.1$ and that the SR should be than or equal to 85% of used product in that period with at least 95% probability. But, as SR is a fuzzy number, the following possibility constraint has to be satisfied to fulfill DM's requirement: $\mathrm{Pos}\left(\widetilde{SR} \geq 0.85\right) \geq 0.95$

Now, from lemma (1) of section (3), it is clear that

$$\frac{c_3 - 0.85}{c_3 - c_2} \geq 0.95 \text{ i.e. } \frac{c_3 - 0.85}{0.1} \geq 0.95 \text{ i.e. } c_3 \geq 0.945$$

So, $c_2 \geq 0.845$ and $c_1 \geq 0.745$.

Hence, from the above calculation we can say with 95% possibility that collection percentage will be more than or equal to 85% if $\widetilde{SR} = (0.745, 0.845, 0.945)$.

V. Result and Discussion

Before analyzing the performance of the integrated system, we set the important parameters as follows: *components per product=3*, *component production time*=1.2 weeks, *product production time*=2 weeks, *shipment time* from producer to distributor=1.5 weeks, *delivery time* from distributor to retailer=1.5 weeks, cycle life of product=50 weeks. We assume that 80 % of collected products are accepted for refurbishing after initial inspection, 15 % of the components get replaced by the new ones from the product which accepted for refurbishing, 65% of the components are reusable immediately from the collected products which rejected for refurbishing. The length of the time horizon is 300 weeks for the simulation.

A. Effect of Product Exchange Policy

We analyze the behavior of the integrated forward-reverse supply chain over the time periods using SD simulation. The incorporation of PE policy in the primary as well as in the secondary market increases the collection rate which is shown in Fig. 4.

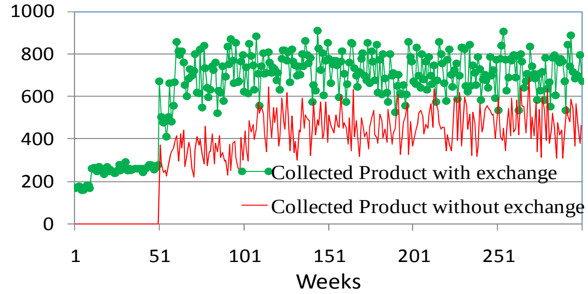

Fig. 4 Comparison of collection rates with and without PE policy

B. Effect of Recovery Policy

Fig. 5 shows the rate at which used products get refurbished; this in turn helps to satisfy the demand in secondary market. The rate at which components get refurbished from the returned products is shown in Fig 6, and Fig 7 shows the amount of components accepted per week for direct reuse from the collected products. These components are supplied to the manufacturer to increase the component inventory in forward channel and helps in reducing the fresh production of components. Fig 8 represents the raw material recovery rate. These raw materials are used in the forward channel to produce the new components, thus reducing the use of new raw materials.

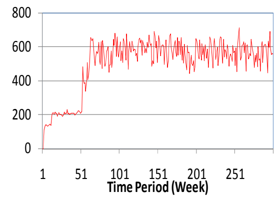

Fig. 5 Product refurbished rate

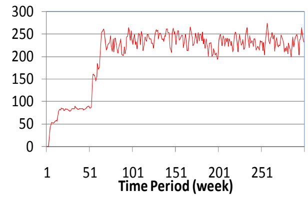

Fig. 6. Component refurbished rate

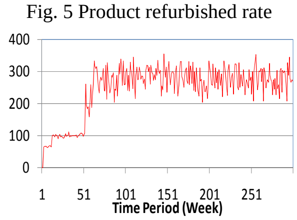

Fig. 7 Direct reusable components

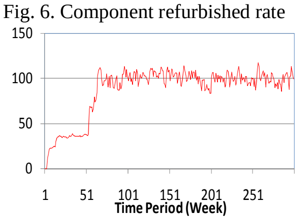

Fig. 8 Raw material recovery rate

C. Bullwhip Effects and Order Variations

We simulate the bullwhip effect of the integrated forward-reverse supply chain and compared the result with and without PE policy. Fig. 9 and Fig. 10 show the actual demand at retailer and order placed by retailer and distributor over the time periods with exchange and without exchange policy respectively.

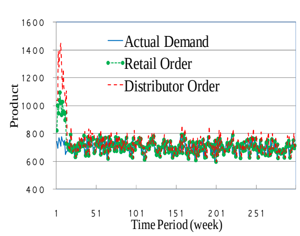

Fig. 9 Bullwhip Effect with PE

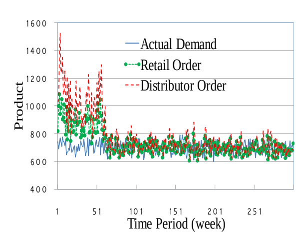

Fig. 10 Bullwhip Effect without PE

We compute the bullwhip effect of the systems using the following formulation given by [13]: Bullwhip = Var (Order Rate) / Var (Demand) and make a comparison of bullwhip

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effect at retailer and distributor for the integrated RL with and without PE policy.

Table II Comparison of bullwhip effects at two different stages of supply chain

	Retailer		Distributor	
	With Exchange	Without Exchange	With Exchange	Without Exchange
Variance of Order	4,555	8,331	13,749	24,787
Bullwhip	2.72	4.98	8.21	14.81

It can be observed that the bullwhip effects of the retailer, distributor without PE is bigger than that of with PE in the integrated RL. So the results indicate that remanufacturing with PE policy in the integrated reverse supply chain can reduce the bullwhip effect.

D. Sensitivity Analysis

Product Refurbishable Percentage assumes how much percentage of collected products is accepted for refurbishing after initial inspection. From Fig. 11, it is clear that if we increase the refurbishable percentage then the average refurbished products per week increases but the component and raw material recovery rate decreases.

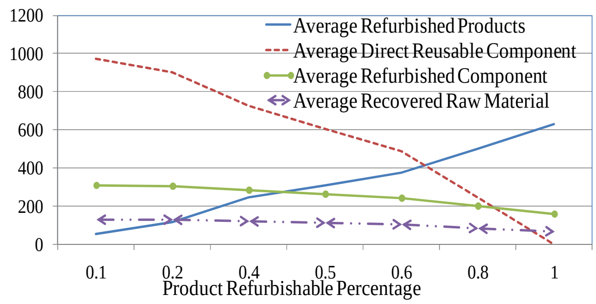

Fig. 11 Sensitivity analysis of recovery process

Inventory cover time determines the safety stock for the inventory. *Inventory adjustment time* represents how quickly a firm tries to correct the discrepancy between desired serviceable inventory and actual serviceable inventory. From the first graph of Fig. 12, it is clear that bullwhip effect increases both at retailer and distributor level as the retail inventory (RI) cover time increases; but the bullwhip effect decreases at both levels as the retail inventory (RI) adjustment time increases. The main reason is that if a firm adjusts the discrepancy between desired serviceable inventory and actual serviceable inventory very quickly, then the variations in order increases. From the second graph of Fig. 12, it can be seen that the changes of cover time and adjustment time in distributor level has almost no impact in determining the bullwhip effect at retailer level. But the bullwhip effect increases at distributor level with the increment of distributor inventory (DI) cover time and decreases with the increment of distributor inventory (DI) adjustment time.

VI. Conclusion

In this paper, we have proposed a SD framework to analyze long-term behavior of a multi-echelon forward-reverse supply chain with fuzzy demand and fuzzy collection rate under possibility constraints by incorporating various recycling activities, namely; collection, product refurbishing, component reuse and refurbishing, and raw material recovery. The behavior analysis of the developed model has indicated that collection rate increases by incorporating PE facility in both primary and secondary market. The simulation results showed that the inclusion of PE facility can reduce the order variance and bullwhip effect both at retailer and distributor levels of the integrated forward-reverse supply chain. Also, sensitivity analysis is performed to examine the impact of inventory adjustment time, cover time on the order variance and bullwhip effect.

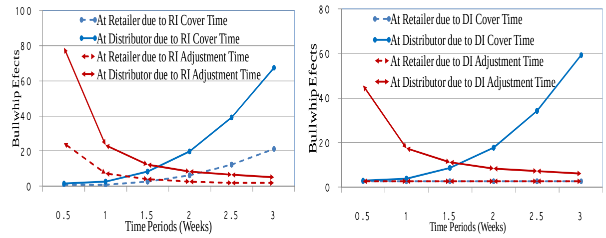

Fig. 12 Sensitivity analysis of bullwhip effect at retailer and distributor

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