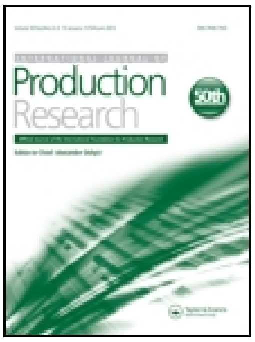

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Strategies for evaluating performance of flexibility in product recovery system

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In view of the increasing business opportunities with changing customer attitudes and stricter legislations, the handling of returns has become a daunting challenge. The need for decision models for evaluating return performance has been observed in the academia and the corporate world. To improve return system performance, integrated flexible reverse enterprise systems have attracted attention from researchers as well as practitioners. This paper addresses these critical issues and proposes a novel integrated and Flexible recovery system decision model. The proposed model aims to facilitate enterprises in assessing their product recovery system capability, and in improving overall performance. The proposed model is a natural extension of several well-grounded policies for conventional reverse supply chains and can be verified on a simulation platform.

Keywords: reverse supply chains; performance; flexibility; product recovery system

1. Introduction

Exploring the role of flexibility in product recovery is a relatively novel domain from the enterprise system perspective. A good number of researchers explore flexibility in forward supply chains and provide direction for developing product recovery, as a flexible system. In the domain of product recovery operations, Daniel and Guide (2000) and Zuidwijk and Krikke (2001) characterised complexities recovery process. Fleischmann et al. (2001), Gold, Seuring, and Beske (2010) and Guide and Van Wassenhove (2003) have addressed different issues arose in return handling and presented comprehensive inventory model. Although, when it comes to generic decisions model that determines the dynamics of returned products not much has been reported. Recently, Madaan, Kumar, and Chan (2012) suggested an initial model to manage the intricacies of product return management proposing a flexible recovery system . To proceed with FRES, firstly we examine flexibility in the conventional supply chain context and later in the product recovery system (Bottani and Montanari 2010 and Holweg et al. 2005). The detailed studies conducted by Angerhofer and Angelides (2006), He, Xu, and Hua (2012) and Zhu et al. (2007) on the influence of flexibility on supply chain performance can facilitate further work in recovery systems. Based on this track, an integrated model for flexible recovery system can be developed. On similar lines, Khoo et al. (2001) and Madaan, Kumar, and Chan (2012) used several operating alternatives concerned with recycling networks. Interestingly, Tachizawa and Giménez (2009) suggested a logistics-planning tool, which took environmental, as well as economic data, into in an integrated way. Torres et al. (2004) simulated cases where a centralised efficiency-driven reverse flow network is no longer appropriate and suggested a novel framework when return rates and recoverable product values were high. Later, Flapper, Van Nunen, and Van Wassenhove (2005) applied a simulation-based approach for evaluating recovery operations performance by including dismantlers and recyclers integrated with manufacturers and distributors. This approach evaluates recovery operations from environmental and economical aspects (cost benefit and profitability).

The model suggested by Cho, Moon, and Yun (1996) and Byrne and Bakir (1999) using hybrid simulation approach with deterministic parameters. These deterministic parameters can be acknowledged as e.g. 'Average Forward Lead Time' (AFT), 'Average Return Lead Time' (ART), 'Average Batch Size (ABS)' for carrying returns and Ordering Cost (OC) to demonstrate performance. This paper extends this study as flexible recovery process using a simulation study. It can be said that quantitative analysis gives good solutions, but it's only feasible in case of simple systems models. While modelling for complex recovery flow system simulation proves to be powerful for performing what-if analyses leading enterprises to make better and timely planning decisions. Simulations also permit the comparison of operational

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*Corresponding author. Email: f.chan@polyu.edu.hk alternatives and assist in the evaluation of operating performance prior to the system in place. Proposed simulation framework in this paper provides a good means for capturing the dynamics of product recovery system and can assist in real-time decisions.

The paper is organised as follows. Section 2 aims at developing multi-layered, multi-product generic flow architecture under various challenges facilitate developing a flexible recovery system model. Section 3 describes preliminary assumptions for modelling recovery system. Section 4 presents a simulation model with performance measures. Section 5 evaluates and analyse configured flexible RES scenarios. Finally, Sections 6 and 7 provides the conclusions with managerial implications and remarks for the future research.

2. Multilayer generic architecture for flexible product recovery system

To understand dynamics of recovery process, need for a generic framework is strongly realised by both researchers and industry. This architecture will assist in understanding product flows and establishing performance measures of recovery system; which can further led to the development of generic simulation models to demonstrate decision-making improvements.

As demonstrated in Figure 1, the proposed architecture is an enrichment to models suggested by Fleischmann et al. (2001), Goldsby and Closs (2000), Inderfurth (1997), Krikke, Bloemhof-Ruwaard, and Van Wassenhove (2003) and Wadhwa and Rao (2003). It comprises an end customer, supplier and a number of interconnected nodes from the supplier to the customer and vice versa in each layer. It comprises almost all possible product recovery scenarios. The proposed architecture takes into account the number of nodes and levels that are physically possible in a RES. It has the capability to take into account a flexible path for product and information flow through the layers. In other words, this 'flexible path' takes into account scenarios where the product and the information have flexible flow through 'n' nodes. In the inter-layer, follow products can actually reach the 'Recovery Options' after 'Gate-keeping' even without passing through the 'Regional Distribution Centers' and the 'Centralized Return Center' (CRC). Gate Keeping handles returns from both retailers/distributor as well as customers serving to the requirement of e-retailing. Here, 'flexibility' is designed to take account of flow of product and information through Reprocessing Options to the Distribution Centres, the CRCs and the customers.

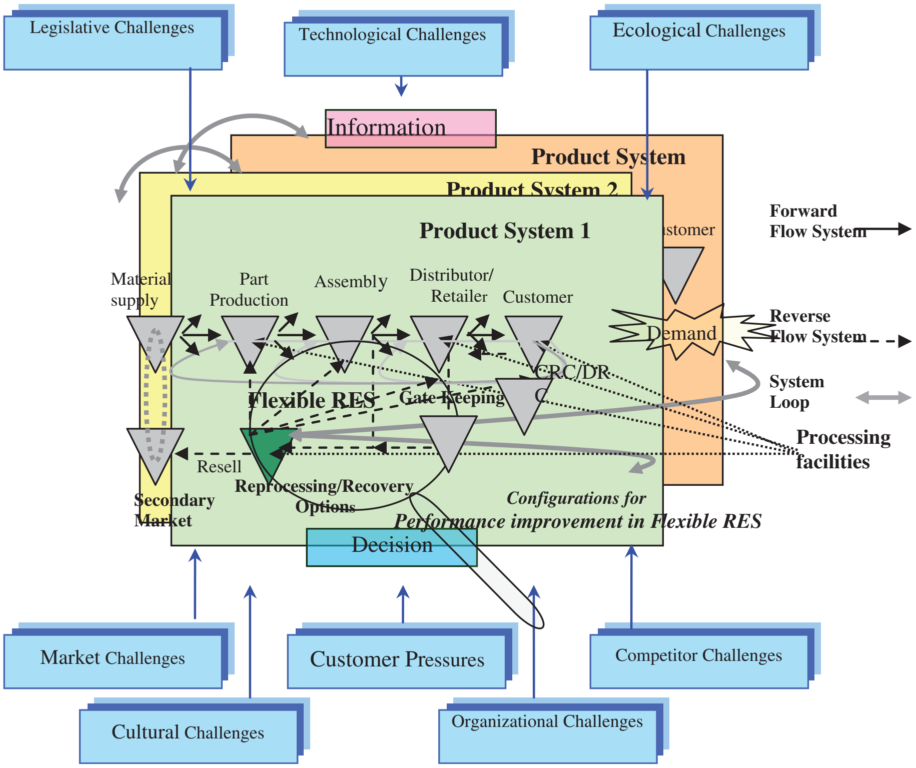

Figure 1. Multi-layered generic architecture for product recovery system.

This arrangement highlights the integrated Flexible Reverse Enterprise System (FRES) as a generic architecture that can handle inter- and intra-layer interactions for both end-of-use as well as commercial product returns. This network can be further be enriched based on the assumption that directly or indirectly, the Original Equipment Manufacturer is responsible for returns.

In this case, the proposed network emphasises the possibility of multiple layered recovery chain interactions. These layers incorporate 'product type' attributes. When we focus on layer 1, typical recovery process starts from the 'gate keeping' operation where the incoming products are checked for their eligibility. This step ensures that only deserving products traverse from the gate-keeping centre to a 'Centralized Return Center (CRC)' through a 'Regional Distribution Center (RDC)'.

From the CRC, the product can be transported to a variety of locations, like the recycling centre and the secondary market. Since we assume a flexible network, we say that it passes through the 'Recovery/reprocessing options' site that makes the disposal decision. In reality, this centre may itself host a variety of recovery options like remanufacturing, refurbishing and repair.

After the 'Recovery', the product is again transported to the appropriate node depending on its remaining value. This marks the last RES operation done on the product. Therefore, with this architecture, it is possible to model a comprehensive Reverse Enterprise System (RES) Model, comprising the recovery chain, for multi-products on multi-levels. The proposed architecture also determines interlayered information and decision requirements. It is seen that an enterprise continually strives to achieve cost savings in production processes. To consider economic benefits from product recovery, we can classify the benefits into direct and indirect gains. Direct gains are the reduction in virgin input materials, value-added recovery processes and indirect gains are in overcoming impeding legislation, market protection and green image for companies and improvement in customer/supplier relations.

It has been accentuated that recovery of resources can lead to profitable business opportunities (Andel 1997). Product recovery as 'resource recovery' operations is now being perceived by an enterprise as an 'investment recovery' as opposed to simply waste management efforts (Schmidheiny 1992). A proposed recovery system as a flexible system can bring cost benefits to organisations by emphasising flexibility in resource allocation and reprocessing options to effectively gain value.

3. Preliminary assumption for product recovery system design

Designing product recovery system for both structure and behaviour, initially it is required to have some analytical support to evaluate impact on structure. Later model behaviour can be evaluated through simulation runs as discussed in Section 5. Although, due to the inherent variability in a product recovery process purely analytical model as tool will be challenging to demonstrate recovery operations dynamics and evaluate possible solutions. Therefore, the proposed model enriched with simulation is required to demonstrate the varying levels recovery effectiveness with altered alternatives. In spite of range limitations of simulation, the model can facilitate learning to managers and decision-makers who can compare the effectiveness of the recovery process.

As discussed, proposed model has the capability to handle products in integrated forward and reverse flow situations. Here, evaluation mainly focuses on resources along with routing flexibility with following assumptions that need to be iterative in order to continuously improve.

(1) Here the forward flow chain has node limited to the Supplier, Manufacturer, Distributor, Retailer and Customer and nine recovery options clustered at different levels are in correspondence with the forward flows.
(2) The subchain of the vendors/suppliers of the manufacturer and suppliers for the reverse flow is not considered and all returned products are fit for reprocessing.
(3) The five nodes of forward flow are presented in four stages and the recovery is limited to three options with a maximum of three levels (3 × 3 = 9) at each stage based its correspondence with the forward chain. It is expected that with more members and stages, the complexity will increase.
(4) The product flow is uniform, deterministic and is produced by sole manufacturer and the returns by multiple customers are handled single retailer and then sent to the respective CRC/DRC. (Numerical assumptions will be discussed Section 4.)
(5) The model considers a one type of product. (This restriction is to ease the dynamics of the simulation and considering multi-product scenario will be scope of future research.)
(6) All processing times and costs are kept deterministic to ease result interpretation.
(7) Effect of quality attributes on the degradation of the returns as been avoided, and the recovery option is selected on the basis of time available.
(8) The results' interpretation is strictly based on the chosen continuous order (Q, s) policy.

Therefore, ‘performance improvement strategies’ are required to be modelled, considering (operational), type (qualitative and quantitative), basis (responsive or efficient), source (internal or external) and frequency (diagnostic or monitoring) perspectives of the PRS.

4. Formulation ‘performance improvement strategies’ for product recovery system

In product recovery system, flexibility in selecting recovery options can assist in improving performance and developing a competitive RES. As already mentioned, performance of the integrated Forward Supply Chain (FSC) & Reverse Supply Chain (RSC) depends upon the ‘levels’ and ‘stages’ of flexibility. Here the ‘stages’ refer to the number of members at each level of recovery chain, and if the number of stages increases flexibility also increases as demonstrated in Figure 1. Here, we consider ‘four levels’ in the conventional forward flow and ‘three levels’ in the recovery, and ‘three stages’ for the reprocessing/recovery operations. Rationale for taking less number of stages in reverse flow is due to larger return delays or recovery transit times, the value of product is reduced because of obsolescence. Thus, controlling obsolescence is vital (Angerhofer and Angelides 2006). Having a flexible value recovery levels in place can bring significant cost benefits. Therefore, the main objective of an FRES in terms of value recovery is to get the returned product available to the forward chain at the lowest possible cost and time (Bacallan 2000).

The return processing cost is usually the sum of the fixed (resources) and variable (cost of money, transportation, obsolescence, etc.) costs. Modelling FRES applies for multiple options at the recovery operation level (‘inter-level’ operations) to demonstrate reduction in the cost by selecting idle resources.

The other performance measure considered is the ‘Order Fill Rate’/‘Percentage Fill Rate of Returns’ i.e. products which enter the reverse supply chain after getting reprocessed at the respective processing facilities and reach back to the resale/fresh market. To satisfy the demand for virgin products, returned products compel the enterprise to restructure traditional product flow functions by adjusting AFT, ART, Batch Size for Carrying Returns, and OC.

Further, modelling aforementioned performance measure using (Q, s) ‘PUSH’ policy for return control is used. Here ‘s’ is the inventory level at which procurement ordering of size ‘Q’ is placed. Demand and return rates are known for an entire planning horizon. Returned items being reprocessed only once, the decision here remains only for how much to produce and reprocess. The model follows a first come, first served queuing system. As soon as the inventory level at the collection centre reaches the ‘s’ level, modules are pushed to the reprocessing operation, thus reducing the inventory level to zero and increasing the serviceable inventory of Q_s modules. Thus, the flow in the forward supply only takes place in batches of Q_s modules.

We have subdivided models into forward/rigid, partially flexible and fully flexible recovery models as depicted in Figure 1. The Rockwell ARENA® 7.0 simulation packages have been utilised to build these models based on analytical approach developed by Inderfurth (1997), which addressed optimal policy parameters for our ‘Push’ policy.

We consider a multi level reprocessing facility without flexible routing i.e. Non Flexible Reverse Enterprise System (NFRES) that receives returns at a rate corresponding to R_t. The collection facility maintains an inventory of returns and in-recovery process inventory. Retailer maintains an inventory of fresh/virgin and serviceable products (Serviceable products are commonly defined as new or reprocessed finished goods that are ready for sale). Here, serviceable products are sourced from RSC with lead-time (LT) $\mathrm{ART}_{\mathrm{RSC}}$ and fresh products from FSC with LT $\mathrm{AFT}_{\mathrm{FSC}}$. If we assume FSC as a special case, the rate of return ($R_t = 0$) and demand arrives at retailers at D_t rate, and any unmet demand is backordered and charged with penalty C_b per unit.

Using (s, Q), policy also allows to consider flexibility in order and batch size. At the small ‘scale’, the batch size of FSC is $Q_{\mathrm{FSC}} = (100, 150, 200)$ takes in Small Incremental variation (SV) in interval of order level $O_r = (10, 25, 50)$. On higher interval variation (HV), the parameters (O_r, Q) take the higher values from ($O_r = (75, 100)$; $Q_{\mathrm{FSC}} = (250, 300)$).

It has been observed that SV performance variables have a tendency to result in static results, whereas for HV performance variable shows fluctuation in results. These observations facilitated us to analyse the effect of flexibility on parameters like LT ($\mathrm{ART}_{\mathrm{RSC}}$, $\mathrm{ALT}_{\mathrm{FSC}}$), time of consumption ($C_t$) and the rate of returns in time t (R_t) by choosing suitable SV and HV intervals. Further, average inventory of saleable products per period (S_t) rises with the batch size O_r. Therefore, the average number of penalties per period will be continuously reduced as O_r and Q_{FSC} are increased. Table 1 shows the parameter values of each variable.

Further, the FSC inventory level having NFRSC has element of on-hand inventory (S'_t) − backorders (B_t) + batch size (Q_{FSC}) of the forward supply chain and the batch size (Q_{RSC}) for the recovery chain for which orders have not yet realised, refer Equation (1).

Table 1. Variables under 'Push' policy approach.

Variables	Acronym
Average stock of saleable product per period	S_{FSC}, t
Average number of penalties per period	Ft
Average stock of originals/fresh/virgin products per period	Q_t
Average number of periods by cycle	P_F, t
Average rate of returns	R_t

$$I_t = S'_t - B_t + \sum_{t=1-\mathrm{LT}_{\mathrm{FAB}}+1}^{t} Q_I + \sum_{j=t-\mathrm{LT}_{\mathrm{PFU}}+1}^{t-\mathrm{LT}} Q_{\mathrm{RSC},J} \tag{1}$$

+ = attributes with increasing behaviour over time.

− = attributes with decreasing behaviour over time.

For changing flexibility to level 1 (i.e. NFRES to PFRES), varying LTs for the FSC ($\mathrm{ALT}_{\mathrm{FSC}}$) and the recovery chain ($\mathrm{ART}_{\mathrm{RSC}}$), the inventory level can be considered as:

1. If $\mathrm{ALT}_{\mathrm{FSC}} \geq \mathrm{ART}_{\mathrm{RSC}}$: Reprocessing orders will be received before or at the same time as the forward flow orders released for the period 't'.
2. If $\mathrm{ALT}_{\mathrm{FSC}} \leq \mathrm{ART}_{\mathrm{RSC}}$: when $\mathrm{ART}_{\mathrm{RSC}}$ is 'higher' than $\mathrm{ART}_{\mathrm{RSC}}$, for e.g. $\mathrm{ART}_{\mathrm{RSC}} = 50$ and $\mathrm{ALT}_{\mathrm{FSC}} = 5$, we need to consider whether to keep the inventory level of the returns to satisfy fresh demand or not. If we choose the earlier condition, then we have to include the orders that will enter from returned stock after the new products from the FSC arrive. This presents a simple case of building extra stock in period *t*, and generating benefits from returns, to some extent.
3. If the difference between $\mathrm{ALT}_{\mathrm{FSC}}$ and $\mathrm{ART}_{\mathrm{RSC}}$ is significant, the inventory level will be determined by the net stock including orders satisfied by the FSC, + Orders replenished from the recovery chain which are received before the orders from the forward supply chain in the period *t*, as shown in Equations (2) and (3).

$$I_t = S'_t - F'_t + \sum_{t=1-\mathrm{LT}_{\mathrm{FSC}}+1}^{t} Q_I + \sum_{j=t-\mathrm{LT}_{\mathrm{RSC}}+1}^{t-\mathrm{LT}} Q_{\mathrm{REF},J}; \tag{2}$$

When the LT conditions are:

$$LT = \begin{cases} 0 & \text{if} \rightarrow \mathrm{ART}_{\mathrm{RSC}} \geq \mathrm{ALT}_{\mathrm{FSC}} \\ \mathrm{ART}_{\mathrm{RSC}} - \mathrm{ALT}_{\mathrm{FSC}} & \text{if} \rightarrow \mathrm{ART}_{\mathrm{RSC}} \geq \mathrm{ALT}_{\mathrm{FSC}} \end{cases} \tag{3}$$

+ = attributes with increasing behaviour over time.

− = attributes with decreasing behaviour over time.

Thus, model is capable of demonstrating flexibility in LT. The Equations (2) and (3) seems to be reasonable if $\mathrm{ART}_{\mathrm{RSC}}$ is 'much greater' than $\mathrm{ALT}_{\mathrm{FSC}}$. However, when the difference between the LTs is not so considerable, e.g. $\mathrm{ALT}_{\mathrm{FSC}} = 5$ and $\mathrm{ART}_{\mathrm{SRC}} = 4$, the return order will arrive after the order is released during time period *t* from FSC. This lag will be important, when the batch size for the return processing is significant as compared with the available stock from the FSC. In this particular case, modified inventory forecasting would be more useful to estimate the arrival of returned units.

Initially, test simulation assumes LT ($\mathrm{ALT}_{\mathrm{FSC}} = 5$; $\mathrm{ART}_{\mathrm{RSC}} = 2$) in a non flexible integrated RES where flexibility level = 1 and modification in the stock level due to returns is not included. The time period (C_t) between sale and recovery is called 'Consume Time' or 'Market Time' and assumed constant. Still being unrealistic, the results will not be affected, since demand is considered constant.

Further, assuming the number of returned products (R_t) to be random is more realistic and provides scope for further examination. The returned products are added to the serviceable stock after the $\mathrm{ART}_{\mathrm{RSC}}$ period, so the serviceable stock at the beginning of period *t* (S_t) can be calculated as in Equation (4):

$$S_t = \max(0, S'_{t-1} - F_{t-1} + Q_t - \mathrm{ALT}_{\mathrm{FSC}}) \tag{4}$$

The Inventory level (I_t) can also be defined as serviceable inventory − backorders (B_t), + orders in the forward supply chain released but not yet received, + the returned products in the process, plus, if any, 'expected returns'. In this case, it is important to take into account the dynamics of product returns until they are added to the serviceable inventory. Let us consider a situation when cycle period (n) = 10; $\mathrm{ALT}_{\mathrm{FSC}} = 2$; $\mathrm{ART}_{\mathrm{RSC}} = 5$. We will consider this for calculating the value of inventory I_t at the end of the period (S'_t). FSC orders (Q_t and Q_{t-1}) and product returns received but not added to the available inventory for the period (R_{t-4}, R_{t-3}, R_{t-2}, R_{t-1}, R_{t-0}). With regard to forecasting the returns flow, we must specify:

(1) Forecasting 'on' and 'before' $t - 10$ at period t: i.e. in that period, how many products have actually been returned according to the sales on period $t - 10$ and the previous ones.
(2) Forecasting at period $t - 4$ to t is combined in some period after $t + 5$.
(3) ($t + \mathrm{ART}_{\mathrm{RSC}}$): This will not affect the inventory level at period t. A case when the market time (C_t) is 'higher', for example, $C_t = 100$; and our returns arrive after a period of '$t + 100$'. This information does not affect the inventory level at period t, but affects the inventory level at period $t = 100$.
(4) Forecasting made between $t - 9$ and $t - 5$ is added. We refer to this forecasted inventory level as the Expected Inventory level.

If $C_t > \mathrm{ART}_{\mathrm{RSC}}$, the value of the expected inventory level can be calculated as Equation (5):

$$I_t = S'_t - B_t + \sum_{j=t-\mathrm{ALT}_{\mathrm{FSC}+1}}^{t} Q_i + \sum_{j=t-\mathrm{ART}_{\mathrm{RSC}+1}}^{t} \mathrm{ART}_j + \sum_{t}^{t-(n-\mathrm{ART}_{\mathrm{RSC}})} e_k; \quad \forall n > \mathrm{ART}_{\mathrm{RSC}} \tag{5}$$

+ = attributes with increasing behaviour over time.
− = attributes with decreasing behaviour over time.

On the other hand, if $C_t < \mathrm{ART}_{\mathrm{RSC}}$, the expected inventory level value can be determined as Equation (6):

$$I_t = S'_t - B_t + \sum_{j=t-\mathrm{LT}_{\mathrm{FAB}+1}}^{t} Q_i + \sum_{j=t-\mathrm{LT}_{\mathrm{PFU}+1}}^{t} \mathrm{PFU}_j + \sum_{k=t-n+1}^{t} e_k; \quad \forall n > \mathrm{LT}_{\mathrm{PFU}} \tag{6}$$

+ = attributes with increasing behaviour over time.
− = attributes with decreasing behaviour over time.

Here Q_{FSC} is released if the inventory level at the end of the previous period is less than the reorder level i.e. $I_{t-1} < O_r$. Therefore, we examine an RSC system with a forecasted make to stock policy and assume that there is no difference between newly produced and reprocessed products, i.e. returns are 'in virgin condition'. Analytical work further narrows the simulation search and helps to develop limits. This facilitates understanding of the recovery system when the push policy is employed and helps to gain insights into the effect of return rates, backorder costs and LTs on recovery system performance.

Later, we set flexibility for products in choosing the reprocessing station based on the availability of reprocessing station and the inventory level at these stations. For further explanation of this model, we use the following variables as shown in Table 2.

The novelty of managing stock for fully flexible FRES is the assumption that the returned products come to a system having all levels and types of flexibility. In this process of selection of alternatives for reprocessing i.e. repair, reselling, disassembling, cleaning, cannibalization, refurbishing, re-assembling returns, etc. The current inventory level is

Table 2. Variables to demonstrate stock position in flexible recovery scenario.

Variables	Acronym
Average stock of saleable per period	S_{FSC}, t
Average number of penalties for stock-outs per period	Ft
Average number of returns	R_t
Average stock of returns per period	S_r, t
Average number of original/new products per period	Ot
Average number of periods by cycle of FSC	P_{FSC}, t
Average number of periods by cycle of RSC	P_{RSC}, t

first determined on available recovery stations. The returned products arrive at the reprocessing nodes and after following the steps in the recovery chain, they go back to the forward chain in 'as good as new' condition. Reprocessing operations like 'cannibalization' and 'refurbishing' are considered to have no link to the forward chain. Recycling, repair and reselling have direct link to the forward chain. Therefore, available stock for the forward link RSC is the sum of the stock at the end of the previous period plus the return flow in the period, as shown in Equation (7).

$$\begin{aligned} S_{\mathrm{RSC},t} &= S'_{\mathrm{RSC},t-1} + R_t \\ S_{\mathrm{RSC},t} &= S'_{\mathrm{RSC},t} - Q_{\mathrm{RSC},t} \end{aligned} \tag{7}$$

$+$ = attributes with increasing behaviour over time.

$-$ = attributes with decreasing behaviour over time.

Here if the inventory level is equal to or greater than Q_{RSC}, an order is released from the reprocessing station. One batch (or more) from reverse flow is added to the serviceable stock after the $\mathrm{ART}_{\mathrm{RSC}}$ periods. For Q_{RSC}, t specifies the number of reprocessed products in period t i.e. stocked in the period t + $\mathrm{ART}_{\mathrm{RSC}}$. The recovered stock at the beginning of period t is determined as Equation (8):

$$S_t = \max(0, S_{t-1} - F_{t-1} + Q_{t-\mathrm{ALT}_{\mathrm{FSC}}} + Q_{\mathrm{RSC},t-\mathrm{ART}_{\mathrm{RSC}}}) \tag{8}$$

$+$ = attributes with increasing behaviour over time.

$-$ = attributes with decreasing behaviour over time.

Further, inventory level in this FRES can be similarly determined as in the case of NFRES by including the forward supply chain (Q) and the recovery chain (Q_{RSC}) orders. The demand generated in each period is in synchronisation with past sales. Expected inventory level (E_t) is combined if they sum up a quantity sufficient for releasing reprocessing order during the period C_t + $\mathrm{ART}_{\mathrm{RSC}}$. When C_t < $\mathrm{ART}_{\mathrm{RSC}}$ and C_t > $\mathrm{ART}_{\mathrm{RSC}}$, then I_t is calculated as shown in Equations (9) and (10).

Therefore, when C_t < $\mathrm{ART}_{\mathrm{RSC}}$, I_t can be considered as:

$$\begin{aligned} I_t &= S'_t - F_t + \sum_{J=t-\mathrm{LT}_{\mathrm{FAB}+1}}^{t} Q_i + \sum_{J=t-\mathrm{LT}_{\mathrm{PFU}+1}}^{t} Q_{\mathrm{RSC},j} + E_t \\ E_t &= \begin{cases} \sum\limits_{k=t-n+1}^{t} e_k si \sum\limits_{k=t-n+1}^{t} e_k \geq Q_{\mathrm{RSC}} & \\ 0 & \text{otherwise} \end{cases} \end{aligned} \tag{9}$$

$+$ = attributes with increasing behaviour over time.

$-$ = attributes with decreasing behaviour over time.

When C_t > $\mathrm{ART}_{\mathrm{RSC}}$, I_t is calculated as:

$$\begin{aligned} I_t &= S'_t - F_t + \sum_{j=t-\mathrm{ALT}_{\mathrm{ASC}+1}}^{t} Q_i + \sum_{j=t-\mathrm{LT}_{\mathrm{PFU}+1}}^{t} Q_{\mathrm{RSC},j} + E_t \\ E_t &= \begin{cases} \sum\limits_{k=t-n+1}^{t-(n-\mathrm{ART}_{\mathrm{RSC}})} e_k si \sum\limits_{k=t-n+1}^{t-(n-\mathrm{ART}_{\mathrm{RSC}})} e_k & \\ 0 & \text{otherwise} \end{cases} \end{aligned} \tag{10}$$

$+$ = attributes with increasing behaviour over time.

$-$ = attributes with decreasing behaviour over time.

Thus, when $I_{t-1} < O_r$, an order is released from the forward supply chain and for S_{RSC} when $t \geq Q_{\mathrm{RSC}}$ an order will be released to the return chain. The units from the reverse supply chain are added to the serviceable inventory after $\mathrm{ART}_{\mathrm{RSC}}$ periods. We develop a closed form of the aforementioned expression for the best possible production, reprocessing, disposal rates, time intervals for different flexibility levels. These findings enable us to analyse the simulation experiment and sensitivity of these performance variables can further be understood with the help of simulation results described in Section 5.

5. Experimenting performance parameters for flexible RES

With the model established in Section 4, the problem is reduced to determine an appropriate level of flexibility. To conduct 'what-if' analysis and determining the best possible performance parameter values by means of simulation appear to be attractive in a practical setting. Therefore, we conduct experiments, which can easily be implemented either on a spreadsheet or using an off-the-shelf discrete event simulation package.

First of all, we set a value for O_r and find the total cost of the system. We then adjust the value of O_r and find the total cost, searching for the best value of O_r. We will use the analytical understanding described in the previous sections to narrow the simulation search. As reiterated, results obtained in these experiments are deterministic as a set of parametric values. For testing, we employ the experimental set of value as depicted in Table 3.

To test flexibility of LT settings, we first vary the FSC LT and the individual reprocessing LT in RSC. Likewise, to test a wide range of backorder/holding cost ratios, we alter the backorder level. We have selected for flexibility in backorder on the basis of past behaviour.

Due to time limitation, model runs for 1000 units under all scenarios. The operational/routing flexibility varies from RF = 1 to RF = 3. At return rate $R_t = 0$ and RF = 1, when RF = 1 we consider it as a FSC model and there is no role of RES. Later, the flexibility levels at RF = 2 and RF = 3 are considered to demonstrate the performance at various recovery scenarios. In general, results indicate that (a) at RF = 2 and 3, we get the significant impact in terms of time. However the greater benefit is obtained at RF = 1 in terms of lower cost. Flexibility at RF = 2 and RF = 3 for the defined parameter is therefore required to be set. To demonstrate, this, we choose the parametric set, e.g. $Q_{\text{FSC}} = 200$; $Q_{\text{RSC}} = 25$; $R_t = 0.4$; $O_r = 50$; $C_t = 2$; $\text{ALT}_{\text{FSC}} = 2$; $\text{ALT}_{\text{RSC}} = 2$. We generate a demand as a normal distribution function (Teunter and Vlachos 2002). Again due to time limitation, planning horizon is kept for 10,000 periods. For each period, we calculate S_t, V_t, S'_t and B_t. The backorders ($B_t > 0$) are met as soon as possible. Sales volume (V_t) generates expectations (E_t) about the return of products in the future that can also be simulated as random variables. If $I_{t-1} < O_r$ an order is released and these original products arrive after ALT_{RSC} periods.

If the inventory level of the returns at the beginning of period t (S_r, t) $\geq Q_{\text{RSC}}$, then a recovery orders are released. Only after ART_{RSC} periods order is added to the serviceable stock. The corresponding to fresh/virgin and recovery product order generates an 'inventory cycle' to meet demand. Here inventory cycle is defined as the number of periods between two consecutive (P_{FSC}) orders and reprocessing (P_{RSC}) orders.

For each cycle, value of S_f, S_r, R_t and B_t is to be calculated. After, at least 150 cycles runs for each simulation are completed, we determine

1. The mean value of number of periods per cycle in forward chain (P_{FSC}, m) and per reprocessing cycle (P_{RSC}, m),
2. mean level of serviceable units in stock per cycle (S_f, m),
3. mean quantity of returns in stock per cycle (S_r, m),
4. mean number of returned products per cycle (R_t) and
5. mean number of backorders per cycle (B_m).

Finally, we evaluate the service level that indicates the capacity of the model for meeting the demand without backorders (Samar et al. 2013). The results obtained from this are deployed when flexibility is from lowest to highest level i.e. RF = 1 to RF = 3. After examining the behaviour of each one of the variables, we simulate flexibility in LT of FSC to fulfil the orders for fresh/virgin products (ALT_{FSC}) with batch size Q_{FSC}. Further, LT to fulfil orders from the returns (ART_{RSC}) with batch size (Q_{RSC}) is given with time of consumption is C_t and the return rate is R_t.

Table 3. Sample experimental design.

	FSC	RES $F = 2$	FRES $F = 3$
S_{FSC}, t	1001.39 units	1603.72 units	1777.46 units
S_{RSC}, t	–	–	51,14 units
B_m	2,97 units	5,52 units	2,49 units
R_t	–	124,15 units	24,99 units
P_{FSC}, t	10 periods	16.19 periods	16.27 periods
P_{RSC}, t	–	–	3.24 periods
Service level (%)	98.52	98.30	99.25

Interestingly, when we compare the performance with recovery system flexibility level RF = 2 shows resemblance with the model having the highest flexibility level RF = 3 with an increasing order size as shown in Figure 2. Furthermore, appealing results demonstrating the benefits of the flexible product recover model can be summarised as:

(1) When returns replenish fresh/virgin products, reduction in the requirement for new products is clearly exposed. This improves performance by increasing availability of products at the retailers in FSC, as shown in Figure 2. This can improve service level by reduction in number of stock-outs.

(2) The effect of replenishing demand by returns leads to reduction in orders size for new/virgin products from FSC. This can be clearly illustrated from Figure 3. At a large order size i.e. greater than 50, both the RF = 2 and RF = 3 graphs show equal levels of availability, interestingly average LTs ALT_{FSC}, ART_{RSC} are kept constant and its expected return rate is kept at a marginal optimistic value of 40%. Thus, when demand is high and forward and reverse LT are almost same, return rate are small then medium flexibility level will result benefit equivalent to fully flexible recovery chain in terms of P_{FSC}.

(3) When ALT_{FSC}, ART_{RSC} are equal and marginal rate of return is optimistic i.e. 40%, we observe that the higher level of flexibility i.e. RF = 3 will generate more benefits in terms of average serviceable units (S_f, t) in stock per cycle irrespective of order size as shown in Figure 4.

(4) Further, at $ALT_{FSC} = ART_{RSC}$ the availability from returns will take care of the market demand at marginal return rate of 40%. Here, major advantage is shown by highest level of flexibility RF = 3 and RF = 1 and RF = 2 are equivalent at large order level as shown in Figure 4.

(5) Under similar scenario, the availability pattern is analysed, which depicts pattern of reduction in the number of penalties as shown in Figure 5. We can interpret improved performance at higher level of flexibility i.e. RF = 3 when order size is of smaller to medium level. Later when order size increases, RF = 1 becomes equivalent to RF = 2 and RF = 3. Thus, RF = 2 is having limited advantage. Fully flexible recovery chain RF = 3 will have advantage only at smaller to medium order levels. Therefore, investments in recovery system will not be a good decision at larger order size under set conditions. Finally, Figure 6 can be utilised to analyse service level, which is mirror image to the availability conditions as shown in Figure 5. This motivates to have smaller order and fully flexible recovery system assists in improving performance. These results also verify the findings from Figure 5.

These experimental results emphasise time-dependent performance evaluation. Relation of time to cost can easily be established, as we can explicitly capture the cost of the lost product value due to time delays at each stage of the product recovery process. Further, a comprehensive cost-based benefits analysis at different levels of flexibility through numerical propositions can further be deduced as future scope of study. The experimental results are simplified and provide verification to the presented situation. When numerical formulation and experimental results are compared at the same levels, it has also demonstrated the robustness of the proposed model.

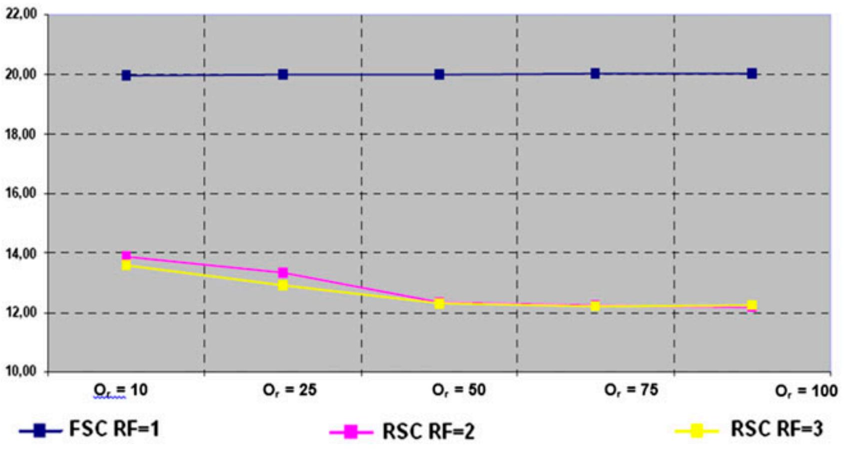

Figure 2. O_r at $ALT_{FSC} = ART_{RSC} = 2$ time units. $C_t = 2$, $Q_{FSC} = 200$, $R_T = 40\%$.

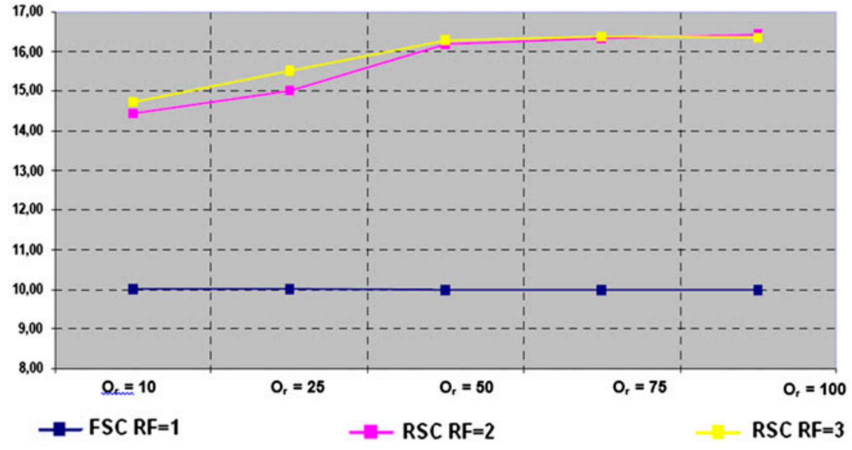

Figure 3. P_{FSC} at $ALT_{FSC} = ART_{RSC} = 2$ time units. $C_t = 2$, $Q_{FSC} = 200$, $R_T = 40\%$.

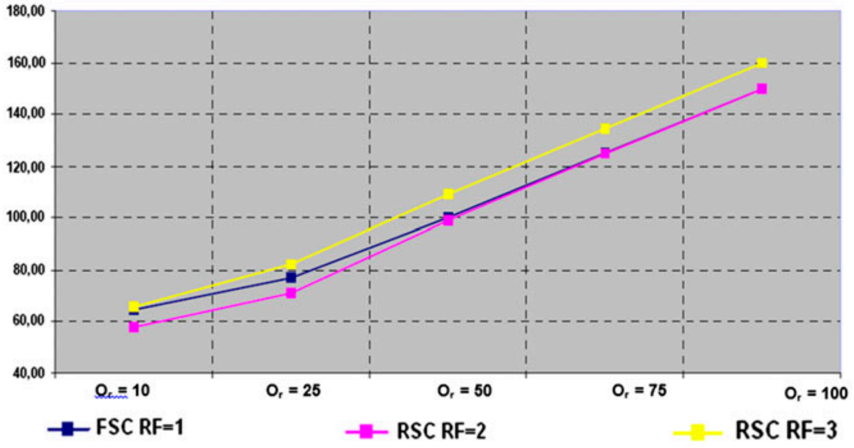

Figure 4. (S_f, t) at $ALT_{FSC} = ART_{RSC} = 2$ time units. $C_t = 2$, $Q_{FSC} = 200$, $R_T = 40\%$.

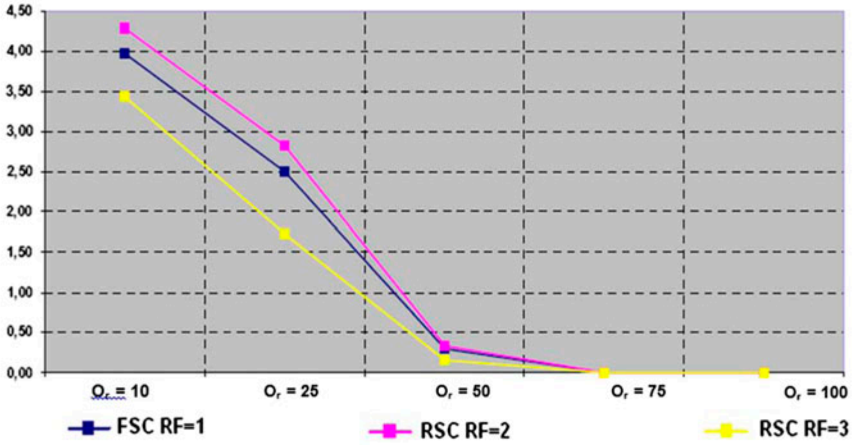

Figure 5. B_t penalty when $ALT_{FSC} = ART_{RSC} = 2$ time units. $C_t = 2$, $Q_{FSC} = 200$, $R_T = 40\%$.

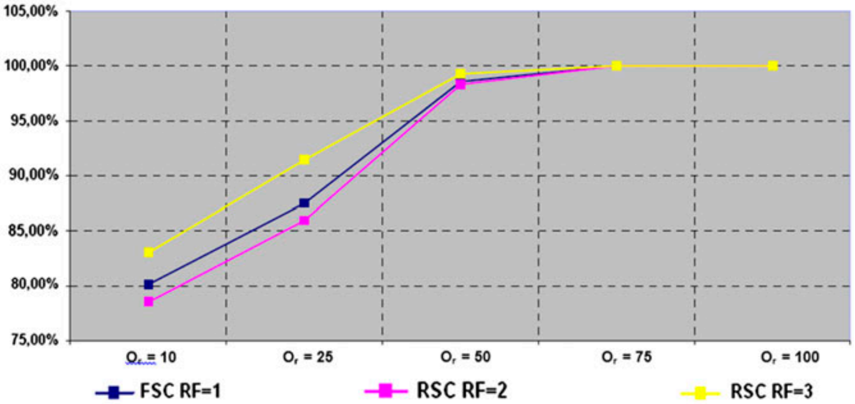

Figure 6. Service Level when $ALT_{FSC} = ART_{RSC} = 2$ time units. $C_t = 2$, $Q_{FSC} = 200$, $R_T = 40\%$.

6. Managerial implications of proposed model

The proposed model has proven to be a helpful tool for the decision-maker; it provides clear information about dynamic recovery scenarios considering variation in demand, return rates, production/reprocessing operations, as a function of LT. Furthermore, the model also considers attributes such LT, consumption time, batch size of forward chain and rate of returns on performance measures like average serviceable units in stocks per cycle for fresh products, stock-out penalties and service level, which impacts total profits. The decision-maker can use this model to analyse different trade-offs, and make good decisions related to when and how much to order, percentage quantity to reprocess, at what levels of flexibility benefits will be obtained. Under conditions when order size is substantial, it will be difficult to justify flexibility. Further, it has been observed the longer the return inventory is held in the recovery process $ART_{RSC} \gg ALT_{FSC}$, the more the product value becomes eroded, thereby losing significant opportunities to build competitive advantages. With considerable ALT_{FSC}, ART_{RSC} and marginal rate of return, we observe that the RSC model with the highest level of flexibility tends to generate a higher number of units availability to capture the market demand. Since backorder cost is quite high, we generate policies that have fewer backorders. Finally, the model emphasises flexibility impact varying range from RF = 1 to RF = 3. A comparison of scenarios with and without flexibility respectively was performed.

7. Conclusion and scope of future study

This paper proposes a generic framework that helps us to evaluate the performance of a flexible product recovery system. The performance improvement through flexibility at the operational level and through sharing stock level information is demonstrated. Considering well-known recovery operations within prescribed bounds, paper present a closed form of expression for Product Recovery System that provides the limited possible scenarios for production, reprocessing, disposal rates and time intervals at different flexibility levels. Proposed flexibility levels in product recovery operations can further be justified using performance measure such as stock-out penalties and service level.

It has been observed products with higher erosion rates lose significant opportunities to capture value from returns. To build competitive advantages in such scenario, proposed model can be of significant advantage by altering the LTs for recovery process. An interesting and more pragmatic research can be planned by the use of the proposed model in the case of electronics products that are having shorter life cycle. Furthermore, a major addition to the proposed model could be the use of an optimisation model for identifying the optimal combination of performance parameter with different level flexibility which maximises overall profits.

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