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Reverse channel selection for commercial product returns under time-to-market and product value considerations

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Abstract
The advent of mobile channels have changed retail business models, the choice of retail mix, and shopper behavior. As consumers do not differentiate among the channels where they try, purchase and/or take delivery of their product, they also expect maximum flexibility in the product returns process. On average, retailers forecasted returns to reach about 16.6% of the total merchandise that customers purchased in 2021, according to the National Retail Federation, which is an increase from an average return rate of 10.6% in 2020. The resulting cost of returns amounted to $761 billion worth of merchandise in 2021 (Repko in A more than $761 billion dilemma: retailers' returns jump as online sales grow. https://www.cnbc.com/2022/01/25/retailers-average-return-rate-jumps-to-16point6percent-as-online-sales-grow-.html. Accessed 17 June 2022, 2022). For retailers and manufacturers, integration of different reverse channels is extremely important to deliver the seamless experience demanded by today's discerning consumer while ensuring the profitable handling of the returned products as well as ensuring the environmental sustainability of the retailing operations. Regardless of which channel receives a return, the reverse logistics network should have the flexibility and the capability to remarket or to recover the value in the returned product in a cost efficient and timely manner that maximizes firm profitability. To the best of our knowledge, this paper is one of the first studies that develops a linear programming model with profit maximization objective to help determine how to optimally decide the returned product touch point(s) in the reverse logistics network. Unlike the extant literature, our model explicitly incorporates the marginal value of time for returns, product characteristics as well as the underling reverse logistics network configuration in return channel selection strategy. We present a comprehensive analysis on how and to what extent the return channel selection is dependent on the product characteristics such as time-based value decay rate, defective rates, and disposal rates as well as the network structure. Using data from HP and Bosch Power tools operations as well as real geographical US data,

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we show that our decision model can effectively help determine the reverse logistics network and the type of facility where a product is returned as a function of product characteristics and economic parameters. Our work emphasizes that product returns and waste reduction, improved firm sustainability and profitability can co-exist through effective reverse logistics planning.

Keywords Sustainability · Time-value · Commercial returns · Reverse channel selection

1 Introduction

The world of retailing has changed dramatically in the past decade. The advent of mobile channels has changed retail business models, the choice of retail mix, and shopper behavior (Verhoef et al., 2015). The scope of multi-channel retailing has broadened with the dawn of mobile channels, tablets, social media, and the integration of these new marketing channels with the online and physical retailing. Growth in online sales channels has resulted in an unprecedented increase in the number and cost of product returns for manufacturers and retailers, thus positioning returns management at the forefront of any strategic agenda. On average, retailers forecasted returns to reach about 16.6% of the total merchandise that customers purchased in 2021, according to the National Retail Federation, which is an increase from an average return rate of 10.6% in 2020. The resulting cost of returns amounted to \$761 billion worth of merchandise in 2021 (Repko, 2022). For retailers and manufacturers, integration of different reverse channels is extremely important to deliver the seamless experience demanded by today's discerning consumer while ensuring the profitable handling of the returned products as well as ensuring the environmental sustainability of the retailing operations. Regardless of which channel receives a return, the reverse logistics network should have the flexibility and the capability to remarket or to recover the value in the returned product in a cost efficient and timely manner that maximizes firm profitability. *The overarching goal of our paper is to examine how to design an optimal reverse channel strategy for a multi-product firm to maximize firm profitability taking into consideration product and logistics network characteristics in a multi-product setting in the presence of multiple return channels*.

In 2021, for every \$1 billion in sales made on-line, retailers saw \$166 million worth of goods returned, at a rate of 20.8% of goods sold through e-commerce, according to another survey by the National Retail Federation (O'Brien, 2022). Multi-channel retailing promotes not only product sales, but also product returns since customers cannot experience products' characteristics from an online purchase. In a recent study (Benson, 2020) reports that e-commerce returns rates have grown by 95 percent between 2014 and 2019, and expected to rise by another 27.3 percent in the UK alone by 2023. While in store return rates range between 5 and 10 percent, return rates reach to 40 percent for online sales, and consequently their cost and environmental impact is considerable. If not properly managed in a time-sensitive fashion, stock returned to retailers is often landfilled, considered too time- and cost-intensive to add back into inventory. In the US alone, 5 billion pounds of landfill waste is created by returns, contributing 15 million metric tons of carbon dioxide to the atmosphere, equivalent to what 3 million cars would emit in one year (Benson, 2020). Hence, a carefully designed reverse logistics network (RLN) that can feed a returned product back to the forward channel for redistribution would not only be creating economic value for a manufacturer and/or a retailer but also would be reducing environmental impact of returned products and improve sustainability of retail operations.

To this end, some retailers and manufacturers have been embracing returns management as an opportunity rather than a cost burden. For example, Nordstrom is to begin selling second-hand in their new store, "See You Tomorrow". Unlike platforms such as Vestiaire Collective and The RealReal, which rely on consumers reselling their own items, Nordstrom will stock items from their own inventory of returned and damaged merchandise (Benson, 2020). Happy Returns, a reverse logistics company, allows brands to utilize 700 "Return Bars" across the United States, where customers can drop off their returns for free, without the need for any new packaging. Manufacturers such as Bosch power tools, HP and Apple have also recognized the environmental and profit impact of integrating returns along with forward distribution operations by carefully establishing processes to collect and resell returned products. In this paper, we develop a multi-echelon, multi-product LP decision model that can guide such companies in identifying the most profitable network design choices to collect and resell returned products in a timely fashion to maximize economic value recovered, and thus minimize the environmental impact of returned units. Our analysis offers guidance to manufacturers/retailers in deciding how to structure their RLN operations as a function of product characteristics such as decay rate in product value (e.g., a product with high fashion content versus a more generic commodity type product), product defect rate, product disposal rate as well as the network structure.

More specifically, as an example of the context modeled here, consider a customer who purchases a pair of glasses from Warby Parker. The customer first tries out the product at a Warby Parker store and receives recommendations regarding the right style for his/her needs, and orders his/her glasses from the online channel, but picks up the product from the store that is the most convenient. Despite the best of salesperson's effort, suppose the product does not fully meet the customer's needs and therefore s/he returns it for a refund or to exchange. To ensure seamless returns management, Warby Parker needs to direct this customer to the optimal touch point in the reverse channel so that the returned product can be profitably and effectively recovered and redistributed in a timely fashion. We focus on developing a decision model to answers questions such as:

1. Should Warby collect the returned products at the retail store for inspection and resale, or should the glasses be sent directly to its factory for refurbishing and redistribution, or should the returned product be just disposed of so as to maximize value recovered from the product returns?
2. What should be the optimal return channel strategy of a manufacturer like Warby Parker that maximizes the product value recovered while minimizing the reverse logistics cost?
3. More generally, how should product characteristics as well as forward and RLN features shape the optimal economic value maximizing reverse logistics design decisions in a retailing environment?

To the best of our knowledge, this is one of the first studies that addresses such questions by using an LP-based decision model that is tested using product decay and cost data from two large companies (Bosch power tools and HP) as well as geographical US data . We take into consideration how the choice of reverse channel strategy would impact the value recovered from a commercial return through repair, refurbishing, reuse and redistribution. Thus, in a multi-product and multiple reverse channels setting, we focus on the trade-offs between the time spent in the RLN, the logistics cost of product returns and the economic value obtained from remarketing of the returned unit. We denote this tension between the time spent in the reverse channel and the value recovered as *the time-value trade-off.*

The concept of *time-value trade-off* for commercial product returns was first introduced by Blackburn et al. (2004) and Guide et al. (2006). While their insights derive from simple queuing type models, both studies have emphasized the importance of integrating product characteristics into reverse supply chain decision models. In our paper, we build upon these preliminary insights and present a detailed LP based decision model to characterize the multi- reverse channels strategy of a retailer for commercial returns with the objective of profit maximization under time-value trade-off considerations.

Some of the interesting insights of our paper can be summarized as follows. Consistent with Blackburn et al. (2004) and Guide et al. (2006), we find that a product of high (low) value decay rate should be collected via a responsive (cost efficient) reverse channel. Moreover, we also find that a firm's reverse channel choice for each product type is in fact a portfolio of channel formats (i.e., involves all four structures with varying utilization rates) to manage the cost efficiency versus responsiveness trade-off in the most profitable way. Especially for a high value decay product (such as an HP printer), we find that the optimal portfolio of reverse channels evolves over the product life cycle, and gravitates towards more cost efficient channels towards the end of the life cycle. Hence, it is not an either-or type of decision for a firm when it comes to determining the optimal reverse channel format, but it is about identifying the optimal portfolio of channel formats to use at different stages of a product's life cycle.

The rest of the paper is organized as follows: In the next section, we present the contribution of this paper to the extant literature on reverse logistics. In Sect. 3, we provide a detailed problem definition and a mathematical model for the optimal reverse channel selection problem of a retailer. Section 4 is dedicated to the discussion of how product and logistics network characteristics should drive reverse channel strategy of a firm. Here we develop an extensive numerical study using real geographical data based on large cities in the U.S. and product data from Guide et al. (2006). In Sect. 5, we summarize our findings and make our concluding remarks.

2 Literature review

As environmentally sustainable operations increasingly gain importance in supply chain management in response to governments' increasing efforts to encourage circular economy, research that addresses the design of reverse logistics systems for product returns has also been growing dramatically in recent years (Lechner & Reimann, 2020; Yang, 2022). These research studies address a variety of research questions and can be broadly categorized as follows: the type of product returns that are modeled (for example commercial versus end of life product returns), the overall objective of the decision model (cost minimization versus profit maximization), the type of the modeling methodology (game theoretic, optimization or simulation based) and the scope of the decision model (strategic versus tactical). To the best of our knowledge, this paper is one of the first studies that develops a Linear Programming (LP) model for commercial product returns with a profit maximization objective to help determine how to optimally decide the returned product touch point(s) in the reverse logistics network as a function of product and network characteristics. Using data from HP and Bosch power tools recovery operations and real geographical data from the US, we present a comprehensive analysis on how and to what extent the return channel strategy is dependent on the product characteristics such as time-based value decay rate, defective rates, and disposal rates as well as the network structure. Below, we highlight some of the recent as well as more seminal works in this area, while positioning our research respectively.

The reverse logistics network (RLN) design literature has a long rich history of analytical network optimization models that focus on the cost minimization objective of a firm in the design of its reverse channel strategy. A recent work in this area is by Mishra and Singh (2022) who study the problem of designing a multi-country production-distribution network that also provides services such as repairs and remanufacturing. The production-distribution model developed in the paper is a mixed-integer nonlinear program (MINLP) that is later transformed to a mixed-integer linear program to reduce the solution time. The model is validated using a randomly generated dataset. In a prior work, Mishra and Singh (2020) also examine the design of reverse logistics systems in a cost-minimization framework, when facing the random demand/supply disruptions in a disaster affected zone. In a recent paper, Govindan et al. (2020) present a hybrid approach of fuzzy analysis network process (FANP), fuzzy decision-making trial and evaluation laboratory (FDEMATEL), and multi-objective mixed-integer linear programming (MOMILP) models for circular supplier selection and order allocation in a multi-product circular closed-loop supply chain (C-CLSC). In a previous work, Govindan et al. (2019) use a newly developed decision making tool and stochastic multi-criteria acceptability analysis to address the decision to use or not to use a third party logistics provider in the reverse channel. Our work is different from these studies as we focus on the larger network design problem using an LP based modeling framework that takes into consideration the time-value trade-off for commercial returns in a multi-product and multiple reverse channels setting. Prakash et al. (2020) study a generic closed-loop supply chain network based on mixed integer programming formulation. A large number of numerical tests are carried out to test the performance of their model from a cost efficiency perspective, and therefore dramatically differ from our focus of recovered value optimization. Soleimani et al. (2016) address design and planning of an integrated forward / reverse logistics network over a planning horizon with multiple tactical periods. The collection amounts of used products with different quality levels are assumed dependent on offered acquisition prices to customer zones. Unlike our work, they resort to a simulation type analysis while we develop an LP-based decision model for commercial returns where product fit with consumer needs drives the return process rather than used product acquisition price.

A growing stream of papers in reverse logistics model incentive and contracting issues between different agents (suppliers, manufacturers, retailers, third party logistics providers, consumers, and/or the government) in the RLN. These studies use game theoretic modeling as the back-bone of their analysis. The focus of these studies is to develop an understanding of how contracts and optimal incentive management can help shape the decisions of the independent agents in a way that is optimal for the overall reverse logistics channel. Some of the remarkable work in this stream are (Heydari et al., 2017; De Giovanni, 2017; Hosseini-Motlagh et al., 2020a, b; Johari & Hosseini-Motlagh, 2019; Taleizadeh et al., 2020). In our paper, we abstract away from the incentive issues since we take the perspective of a single centralized decision maker such as a large manufacturer/retailer who manages the distribution and collection nodes. We focus on the profit maximization objective of the firm, taking into consideration the time-value trade-off for commercial returns in a multi-product and multiple reverse channels setting.

Our consideration is also apart from instances of returns caused by end-of-life issues (Majumder & Groenevelt, 2001; Savaşkan et al., 2004; Savaşkan & Van Wassenhove, 2006; Karakayalı et al., 2007; Esenduran et al., 2016), intra-channel returns (Cachon, 2003), durable goods and buy-backs (Desai et al., 2004; Shulman & Coughlan, 2007), and product-failure and warranty returns (Moorthy & Srinivasan, 1995; Balachander, 2001; Ferguson et al., 2006); instead, we focus on commercial product returns (Ofek et al., 2011; Ferguson et al., 2006) and develop a decision model to guide firms in the choice of optimal reverse channel strategy in a multi-product setting.

Our work is relevant but is also profoundly different from a stream of marketing research that study return policies for commercial returns. In a series of papers, Shulman et al. (2009, 2010, 2011) examine the role of restocking fees and information provision in the management of commercial product returns. By analyzing game theoretic models of two-echelon channel structures, authors focus on how restocking fees can be used to shape consumer's incentives to return a product and the strategic pricing interactions in the distribution channel. In the present paper, we focus on the network design aspect of the reverse channel strategy for commercial returns to maximize value for the firm in a multi-product setting. To the best of our knowledge, this is one of the first studies that develops a decision model to support firms in the design of an optimal multiple reverse channels strategy for commercial product returns in a multi-product setting by explicitly taking into consideration the time-value trade-off for commercial returns.

Design of multi-channel strategy, and more recently the omni-channel strategy in forward distribution has been a topic of research in both marketing and operations management fields. Verhoef et al. (2015) presents a very recent review of work on omni-channel research in marketing. This stream of work focuses on understanding the differences between multi-channel strategy and omni-channel strategy in terms of firm objectives and marketing-mix variables. Furthermore, this group of papers also investigate the impact of omni-channel distribution on consumer behavior and retail mix across channels. In operations management, Bell et al. (2015) present one of the first studies that examine the role of show rooms and information provision in an omni-channel retail context. While the studies in marketing and in operations focus on the changes in consumer behavior during product purchase under an omni-channel strategy, this paper studies the optimal multiple channels return strategy for a retailer when a consumer decides to return the unit after having purchased it through an omni-channel experience. Our modeling framework provides guidance to firms in determining the most profitable reverse channel format for each unit that is returned from the consumers.

In operations management literature, we also find several seminal papers on maximizing recovered value in commercial returns management. As one of the first in this stream of work, (Blackburn et al., 2004) develop a conceptual framework for the choice of optimal reverse channel design strategy, specifically emphasizing the time-value trade-off for commercial products. Authors argue that time-responsive reverse supply chains would be more appropriate for products with high marginal-value-of-time (MVT), whereas cost-efficient reverse supply chains would be more suitable for products with low MVT. In a follow up paper, (Guide et al., 2006) present a queuing model of a *single product* closed-loop supply chain (CLSC) and test Blackburn's hypothesis by considering the residual value of product in return process. In their model, authors propose two types of reverse supply chain designs: centralized design that evaluates returns at an evaluation facility and decentralized design where returns are evaluated at each retailer. They analyze the performance of CLSC (total profit from recovered returns) based on characteristics of the product and simulate the model using data from HP inkjet printer and Bosch power tool cases. Authors conclude that centralized (i.e., cost-efficient) reverse supply chain is appropriate under low product decay rate and high proportion of new product (non-defective) returns, while a decentralized (i.e., time-responsive) reverse supply chain may be more important at high product decay rate. Guide et al. (2006) focus on designing reverse supply chain, whereas this study focuses on the selection strategy of return channels. This paper builds upon and contributes to this stream of work by developing a *multi- product* and a *multiple reverse channels* decision model that incorporates MVT into a firm's optimal reverse channel strategy.

More specifically, we develop a Linear Programming (LP) model for commercial product returns with a profit maximization objective to help determine how to optimally decide the returned product touch point(s) in the reverse logistics network as a function of product and network characteristics. Using data from HP and Bosch power tools recovery operations and real geographical data from the US, we present a comprehensive analysis on how and to what extent the return channel strategy is dependent on the product characteristics such as time-based value decay rate, defective rates, and disposal rates as well as the network structure. Our findings demonstrate that environmental sustainability and firm profitability can co-exist under optimally designed reverse logistics strategy.

3 Modeling of a multiple reverse channels strategy

The reverse channel strategy choice model presented in this paper is motivated by the commercial return process of a retailer such as Warby Parker, Apple, Home Depot or Walmart. Before introducing the mathematical formulation, we first provide an overview of possible reverse channel formats and touch points for a returned product, our problem definition and assumptions.

As discussed by current research on commercial returns (Guide et al., 2006), a large share of consumer returns happens mainly for two reasons: either the customer does not find a good fit between his/her preferences and the product characteristics or the product is possibly defective or damaged during delivery. The former has nothing to do with quality issues, thus, products are assumed to be non-defective. The non-defective products can be resold at the retailer after a minor visual inspection and repackaging. On the other hand, defective or damaged products need to be repaired, refurbished, remanufactured or disposed of, based on the nature of the defect. In the following channel formats, we consider both the possibility of defective and non-defective returns.

Given the presence of four entities including customers, retailers, distribution/collection centers (e.g., a warehouse), and product recovery facilities (e.g., remanufacturing operations which can be part of an existing manufacturing facility), a company has multiple return collection/processing options. Products can be collected (i.e., shipped to or taken to by the customer) at a retailer, or a center, or a recovery facility. This constitutes the first leg of the return process. In addition, a company must also be concerned with the recovery processes, such as inspection, repackaging, refurbishing, remanufacturing, and redistribution in the forward channel. The longer the time spent in the reverse channel process, the lower the value recovered from a product, especially, if the product life cycle is short (e.g. fashion goods, electronics). We introduce four different reverse channels (Fig. 1). The challenge for the retailer is to identify the one that minimizes reverse logistics costs while maximizing the value recovered from the returned unit given product characteristics and the collection network configuration. Hence, unlike past research, we focus on *the profit maximization* objective of the firm in determining the optimal reverse channel strategy.

- *Channel I-R-C-M* Customer returns the product to a retail location. A minor inspection is performed to determine whether the product is non-defective or not. If non-defective, after minor processing such as repackaging, the product is put back on shelf for sale. Defective units are forwarded to a collection center for further processing and consolidation with

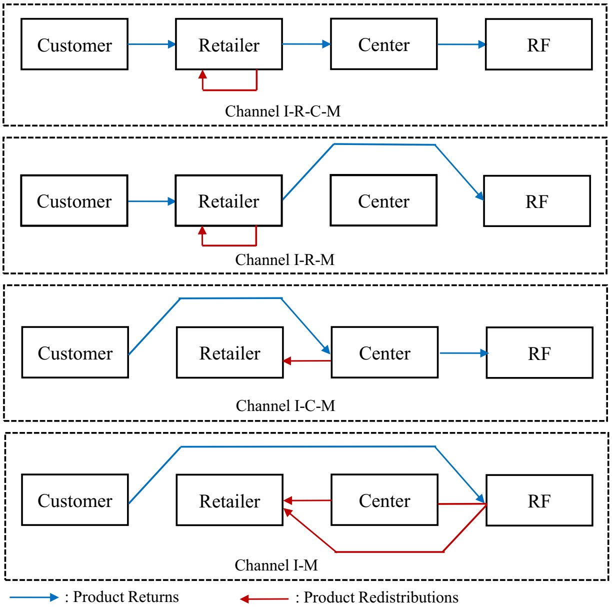


Fig. 1 Multiple return channels in the network

other returns and, eventually, are sent to a recovery facility.[1] This reverse channel format provides the fastest path for remarketing of non-defective items.

- *Channel I-R-M* This channel is similar to I-R-C-M with the exception that after minor inspection, if the product is classified as defective, it is directly sent to a recovery facility.[1]
- *Channel I-C-M* The product is sent to a distribution center from the customer. After a major inspection, the non-defective product is redistributed to retail and the defective item is sent to a recovery facility[1].
- *Channel I-M* Customer sends the product directly to a recovery facility. If the products is identified as non-defective after a major inspection, it is redistributed to retail directly or via a distribution center. If the product is found defective, it undergoes repair at a recovery facility.[1]

Based on the definition of these four channels, there are two major recovery strategies for a returned product: (a) In the case the product is classified as non-defective, it is put back on shelf for resale via redistribution in the primary retail market. (b) In the case it is not classified as non-defective after the minor inspection, it requires a major inspection either at a center (in case of I-R-C-M and I-C-M) or at a recovery facility (in cases of I-R-M, and I-M). Repairing and refurbishing activities require skilled labor and specialized equipment. The primary responsibilities of retailer and center locations are product sales and product distribution, respectively. However, it is not economically viable to have skilled labor and equipment in all retailer and center locations. Besides, most commercial product returns are convenience returns, which only require minimal testing and repackaging. Therefore, we assume that a certain fraction of defective products are ultimately repaired or refurbished at

[1] A recovery facility handles *major inspection* and repair. Once product is repaired, it is redistributed either directly or via a distribution center to a secondary retail channel, such as an outlet. After major inspection, some returned products may also be just disposed of. These activities are not a part of our study.

a recovery facility. Major inspection dictates a decision on the type of recovery (i.e., repair or refurbish) or disposal. In the former, repaired/refurbished products are redistributed to a secondary retail market such as the retailer's outlet channel. We assume that enough demand exists at the primary and the secondary retail markets so that all non-defective products and the recovered products are eventually sold.

Each channel has different operational characteristics in terms of product travel time and transportation costs. Return channel I-R-C-M provides the lowest transportation costs, due to potential economies-of-scale in transportation traveling back from distribution, but this channel has a long travel time because of multiple locations involved in the return processing. Return channel I-M provides the fastest travel time due to direct shipment, but transportation cost of this channel format is the most expensive dedicated transfer. Minimal economies of scale is attained under I-M format. Return channels I-R-M and I-C-M have shipment costs and travel time characteristics that are somewhere in between I-R-C-M and I-M.

Since the sale of non-defective and repaired products occurs at the primary and the second market channels, respectively, collecting products at the retailer or at a recovery facility can minimize the loss of value for non-defective and repaired products, respectively. Therefore, we refer to both the I-R-M and I-M channels as the *responsive return channels*. Although the return channel I-R-C-M can also resell a non-defective products at the primary retail location quickly after a minor inspection, the delivery time of the defective product to a recovery facility is long due to additional time spent at a distribution facility. Hence, the return channel I-R-C-M focuses more on minimizing transportation and product handling costs than reducing travel time. For this reason, we refer to the return channel I-R-C-M as the *cost efficient channel*. Interestingly, I-C-M channel can be either responsive or cost-efficient based on the physical locations of the retailer, the distribution center and the recovery facilities. In I-C-M, a distribution center collects a returned product first, so it may take more or less travel time to resell a non-defective product at a primary retail location depending on the physical network characteristics.

In our decision model, product travel time in the reverse channel is important. A product's price can decrease over time due to factors including physical depreciation, seasonality and/or technological advancements. Therefore, we assume that products lose value over time and we introduce a time parameter to capture product's residual value. To characterize the rate at which this value loss occurs for a particular product, we model a product value decay parameter. In particular, the longer time a product spends in the reverse channel network, the larger is the product value decay, and therefore, the lower is the profits we expect to attain from product resale. Specifically in our model, letting the decay rate be d, a product p's selling price in time $t + \Delta t$, denoted by $S^{\cdot}_{p\,t+\Delta t}$, is calculated as $S^{\cdot}_{t}\,(1 - d)^{\Delta t}$. Lastly, we assume that all activities (retailer, center, and recovery facility) have capacity limits that can be shared across multiple products.

In the following subsection, we formulate a decision model which a firm can use to determine the most profitable reverse channel format for each unit that is returned from the consumers, taking into consideration time traveled in the reverse channel, the value decay in the returned product, inspection, transportation, and recovery costs under capacity limitations in the reverse logistics process.

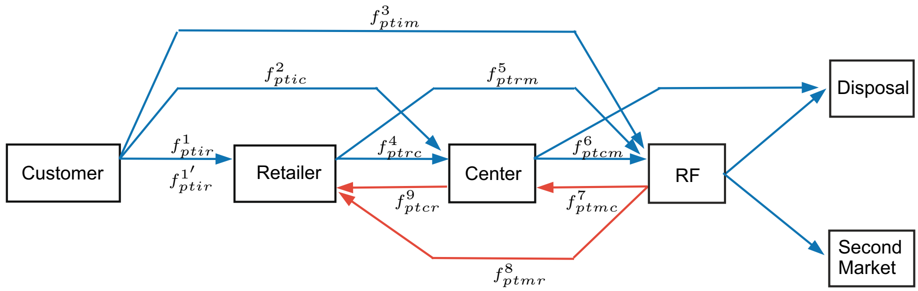


Fig. 2 Product recovery network with multiple channels

3.1 Formulation

Superimposing all the channels in a representative generic network and including the disposal and the second market nodes, the flows and associated decision variables in our decision model can be depicted as in Fig. 2.

We can summarize our underlying assumptions in building the model as follows:

- The retailer/center/facility locations are fixed.
- The demand and return rates are known as an average based on historical data.
- Returned product value is a function of the time spent by a unit in RLN and decays exponentially at a constant rate.
- Multiple return channels are considered simultaneously and one is chosen optimally for each product return.
- Each channel has different characteristics based on transportation costs and product delivery time to represent their individual cost-time trade-offs.
- The average defect and disposal rates are known and are constant over time.
- Minor defects/repackaging can be easily fixed in any location (retailer, center or RF), whreas major defect can be handled only at RF locations.

Below we provide a list of indices, parameters and decision variables used in our decision model.
Sets and indices:

$\mathcal{P}$ set of products, $p \in \mathcal{P}$.
$\mathcal{T}$ set of periods in the planning horizon, $t \in T = \{1, \ldots, T_{max}\}$.
$\mathcal{I}$ set of customer locations, $i \in \mathcal{I}$.
$\mathcal{R}$ set of retailer locations, $r \in \mathcal{R}$.
$\mathcal{C}$ set of center locations, $c \in \mathcal{C}$.
$\mathcal{M}$ set of Remanufacuting Facility (RF) locations, $m \in \mathcal{M}$.

Parameters:

d^1_p decay rate of a new product, $p \in \mathcal{P}$.
d^2_p decay rate of a repaired product, $p \in \mathcal{P}$.
R^G_p non-defective rate for a returned product $p \in \mathcal{P}$.
R^D_p disposal rate for a defective product $p \in \mathcal{P}$.
D_{pti} return of product $p \in \mathcal{P}$ at customer $i \in \mathcal{I}$ in time $t \in \mathcal{T}$.
S^1_{pt} selling price of a new product $p \in \mathcal{P}$ in time $t \in \mathcal{T}$ (i.e., $S^1_{pt} = S^1_{p0} * e^{-d^1_p t}$).

S^2_{pt} selling price of a repaired product $p \in \mathcal{P}$ in time $t \in \mathcal{T}$. (i.e., $S^2_{pt} = S^2_{p0} * e^{-d^2_p t}$).
T_{ij} travel time between nodes i and j, $i,\ j \in \{\mathcal{I}, \mathcal{R}, \mathcal{C}, \mathcal{M}\}$.
P^1_{pr} processing time of product $p \in \mathcal{P}$ at retailer $r \in \mathcal{R}$.
P^2_{pc} processing time of product $p \in \mathcal{P}$ at center $c \in \mathcal{C}$.
P^3_{pm} processing time of product $p \in \mathcal{P}$ at RF $m \in \mathcal{M}$.
G_{ij} transportation cost per unit between node i and j, $i,\ j \in \{I, R, C, M\}$.
Q^2_r redistribution capacity at retailer $r \in \mathcal{R}$.
Q^1_r return capacity at retailer $r \in \mathcal{R}$.
Q^2_c redistribution capacity at center $c \in \mathcal{C}$.
Q^1_c return capacity at center $c \in \mathcal{C}$.
Q_m return capacity at RF m.
C^1_{pr} return cost of product $p \in \mathcal{P}$ at retailer $r \in \mathcal{R}$.
C^2_{pr} redistribution cost of product $p \in \mathcal{P}$ at retailer $r \in \mathcal{R}$.
C^1_{pc} return cost of product $p \in \mathcal{P}$ at center $c \in \mathcal{C}$.
C^2_{pc} redistribution cost of product $p \in \mathcal{P}$ at center $c \in \mathcal{C}$.
C^1_{pm} return cost of product $p \in \mathcal{P}$ at RF $m \in \mathcal{M}$.
RE_p repairing cost of product $p \in \mathcal{P}$
CD_p disposal cost of product $p \in \mathcal{P}$

Decision Variables:

f^1_{ptir} return quantity of product p from customer i to retailer r at time t to use I-R-C-M
$f^{1'}_{ptir}$ return quantity of product p from customer i to retailer r at time t to use I-R-M
f^2_{ptic} return quantity of product p from the customer i to the center c at time t
f^3_{ptim} return quantity of product p from the customer i to the RF m at time t
f^4_{ptrc} return quantity of product p from the retailer r to the center c at time t
f^5_{ptrm} return quantity of product p from the retailer r to the RF m at time t
f^6_{ptcm} return quantity of product p from the center c to the RF m at time t
f^7_{ptmc} quantity of non-defective product p sent from the RF m to the center c at time t
f^8_{ptmr} quantity of non-defective product p sent from the RF m to the retailer r at time t
f^9_{ptcr} quantity of non-defective product p sent from the center c to the retailer r at time t

Firm's decision problem can be formulated as follows:

$$
\begin{aligned}
\text{Max} \quad & \sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}}\sum_{r\in\mathcal{R}}\left\{\sum_{i\in\mathcal{I}} S^1_{p(t+T_{ir}+P^1_{pr})}\, R^G_p\, \left(f^1_{ptir}+f^{1'}_{ptir}\right)\right.\\
&\left. + \sum_{m\in\mathcal{M}} S^1_{p(t+T_{mr}+P^1_{pr})}\, f^8_{ptmr} + \sum_{c\in\mathcal{C}} S^1_{p(t+T_{cr}+P^1_{pr})}\, f^9_{ptcr}\right\}\\
& + \sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}}\sum_{m\in\mathcal{M}} (1-R^D_p)\left(\sum_{i\in\mathcal{I}} S^2_{p(t+T_{im}+P^3_{pm})}\,(1-R^G_p)\, f^3_{ptim} + \sum_{r\in\mathcal{R}} S^2_{p(t+T_{rm}+P^3_{pm})}\, f^5_{ptrm}\right)\\
& + \sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}}\sum_{c\in\mathcal{C}}\sum_{m\in\mathcal{M}} S^2_{p(t+T_{cm}+P^3_{pm})}\, f^6_{ptcm}\\
& - \sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{I}}\left\{\sum_{r\in\mathcal{R}} G_{ir}\,\left(f^1_{ptir}+f^{1'}_{ptir}\right) + \sum_{c\in\mathcal{C}} G_{ic}\, f^2_{ptic}\right\}\\
& - \sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}}\left(\sum_{i\in\mathcal{I}}\sum_{m\in\mathcal{M}} G_{im}\, f^3_{ptim} + \sum_{r\in\mathcal{R}}\sum_{c\in\mathcal{C}} G_{rc}\, f^4_{ptrc} + \sum_{r\in\mathcal{R}}\sum_{m\in\mathcal{M}} G_{rm}\, f^5_{ptrm} + \sum_{c\in\mathcal{C}}\sum_{m\in\mathcal{M}} G_{cm}\, f^6_{ptcm}\right)
\end{aligned}
$$

$$-\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}}\left(\sum_{c\in\mathcal{C}}\sum_{m\in\mathcal{M}} G_{mc}\, f^{7}_{ptmc} + \sum_{m\in\mathcal{M}}\sum_{r\in\mathcal{R}} G_{mr}\, f^{8}_{ptmr} + \sum_{c\in\mathcal{C}}\sum_{r\in\mathcal{R}} G_{cr}\, f^{9}_{ptcr}\right)$$
$$-\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}}\left\{\sum_{i\in\mathcal{I}}\left(\sum_{r\in\mathcal{R}} C^{1}_{pr}\,\left(f^{1}_{ptir} + f^{1'}_{ptir}\right) + \sum_{c\in\mathcal{C}} C^{1}_{pc}\, f^{2}_{ptic} + \sum_{m\in\mathcal{M}} C^{1}_{pm}\, f^{3}_{ptim}\right)\right\}$$
$$-\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}}\left\{\sum_{r\in\mathcal{R}}\sum_{c\in\mathcal{C}} C^{1}_{pc}\, f^{4}_{ptrc} + \sum_{m\in\mathcal{M}} C^{1}_{pm}\left(\sum_{r\in\mathcal{R}} f^{5}_{ptrm} + \sum_{c\in\mathcal{C}} f^{6}_{ptcm}\right)\right\}$$
$$-\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}}\left\{\sum_{m\in\mathcal{M}}\sum_{c\in\mathcal{C}} C^{2}_{pc}\, f^{7}_{ptmc} + \sum_{r\in\mathcal{R}} C^{2}_{pr}\left(\sum_{m\in\mathcal{M}} f^{8}_{ptmr} + \sum_{c\in\mathcal{C}} f^{9}_{ptcr}\right)\right\}$$
$$-\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}}\sum_{m\in\mathcal{M}} RE_{p}\left(\sum_{i\in\mathcal{I}}(1-R^{D}_{p})\,(1-R^{G}_{p})\, f^{3}_{ptim} + \sum_{r\in\mathcal{R}}(1-R^{D}_{p})\, f^{5}_{ptrm} + \sum_{c\in\mathcal{C}} f^{6}_{ptcm}\right)$$
$$-\sum_{p\in\mathcal{P}}\sum_{t\in\mathcal{T}} CD_{p}\, R^{D}_{p}$$
$$\left(\sum_{i\in\mathcal{I}}\sum_{c\in\mathcal{C}}(1-R^{G}_{p})\, f^{2}_{ptic} + \sum_{i\in\mathcal{I}}\sum_{m\in\mathcal{M}}(1-R^{G}_{p})\, f^{3}_{ptim} + \sum_{r\in\mathcal{R}}\sum_{c\in\mathcal{C}} f^{4}_{ptrc} + \sum_{r\in\mathcal{R}} f^{5}_{ptrm}\right)$$

subject to

$$\sum_{r\in\mathcal{R}}\left(f^{1}_{ptir} + f^{1'}_{ptir}\right) + \sum_{c\in\mathcal{C}} f^{2}_{ptic} + \sum_{m\in\mathcal{M}} f^{3}_{ptim} = D_{pti} \quad \forall p\in\mathcal{P},\ i\in\mathcal{I}, t\in\mathcal{T} \tag{1}$$

$$(1-R^{G}_{p})\sum_{i\in\mathcal{I}} f^{1}_{p(t-T_{ir}-P^{1}_{pr})ir} = \sum_{c\in\mathcal{C}} f^{4}_{ptrc} \quad \forall p\in\mathcal{P},\ r\in\mathcal{R},\ t\in\mathcal{T} \tag{2}$$

$$(1-R^{G}_{p})\sum_{i\in\mathcal{I}} f^{1'}_{p(t-T_{ir}-P^{1}_{pr})ir} = \sum_{m\in\mathcal{M}} f^{5}_{ptrm} \quad \forall p\in\mathcal{P},\ r\in\mathcal{R},\ t\in\mathcal{T} \tag{3}$$

$$(1-R^{G}_{p})(1-R^{D}_{p})\sum_{i\in\mathcal{I}} f^{2}_{p(t-T_{ic}-P^{2}_{pc})ic} + (1-R^{D}_{p})\sum_{r\in\mathcal{R}} f^{4}_{p(t-T_{rc}-P^{2}_{pc})rc} = \sum_{m\in\mathcal{M}} f^{6}_{ptcm} \quad \forall p\in\mathcal{P},\ c\in\mathcal{C},\ t\in\mathcal{T} \tag{4}$$

$$R^{G}_{p}\sum_{i\in\mathcal{I}} f^{3}_{p(t-T_{im}-P^{3}_{pm})im} = \sum_{c\in\mathcal{C}} f^{7}_{ptmc} + \sum_{r\in\mathcal{R}} f^{8}_{ptmr} \quad \forall p\in\mathcal{P},\ m\in\mathcal{M},\ t\in\mathcal{T} \tag{5}$$

$$R^{G}_{p}\sum_{i\in\mathcal{I}} f^{2}_{p(t-T_{ic}-P^{2}_{pc})ic} + \sum_{m\in\mathcal{M}} f^{7}_{p(t-T_{mc}-P^{2}_{pc})mc} = \sum_{r\in\mathcal{R}} f^{9}_{ptcr} \quad \forall p\in\mathcal{P},\ c\in\mathcal{C},\ t\in\mathcal{T} \tag{6}$$

$$\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\sum_{i\in\mathcal{I}}\left(f^{1}_{ptir} + f^{1'}_{ptir}\right) \le Q^{1}_{r} \quad \forall r\in\mathcal{R} \tag{7}$$

$$\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\left(\sum_{m\in\mathcal{M}} f^{8}_{ptmr} + \sum_{c\in\mathcal{C}} f^{9}_{ptcr}\right) \le Q^{2}_{r}$$

$$\forall r \in \mathcal{R} \tag{8}$$

$$\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\left(\sum_{i\in\mathcal{I}} f^2_{ptic} + \sum_{r\in\mathcal{R}} f^4_{ptrc}\right) \leq Q^1_c$$

$$\forall c \in \mathcal{C} \tag{9}$$

$$\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\sum_{m\in\mathcal{M}} f^7_{ptmc} \leq Q^2_c$$

$$\forall c \in \mathcal{C} \tag{10}$$

$$\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}}\left(\sum_{i\in\mathcal{I}} f^3_{ptim} + \sum_{r\in\mathcal{R}} f^5_{ptrm} + \sum_{c\in\mathcal{C}} f^6_{ptcm}\right) \leq Q_m$$

$$\forall m \in \mathcal{M} \tag{11}$$

$$f^1_{ptir},\ f^{1'}_{ptir},\ f^2_{ptic},\ f^3_{ptim},\ f^4_{ptrc},\ f^5_{ptrm},\ f^6_{ptcm},\ f^7_{ptmc},\ f^8_{ptmr},\ f^9_{ptcr} \geq 0$$

$$\forall p,\ t,\ i,\ r,\ c,\ m \tag{12}$$

Note that since the flow on the link from a customer to retailer (I-R) is part of two channels, namely I-R-C-M and I-R-M, we employ two flow variables, f^1_{ptir} and $f^{1'}_{ptir}$, respectively, for this segment of flow. Thus, we can determine the flow amounts explicitly for these channels from the solution of the model.

In the above formulation, the objective function represents the total profit as the difference between the total revenues and the total costs which include transportation, material handling, and repair/disposal costs over the planning horizon. Each term of the objective function, given on a separate line above, represents a different component of the total profit function. Furthermore, each term refers to associated returns (in the first three terms) and costs (in the rest of the terms) at various locations of the network given in Fig. 1. Thus, they are represented accordingly by summing over those locations. We describe the terms of the objective function as follows:

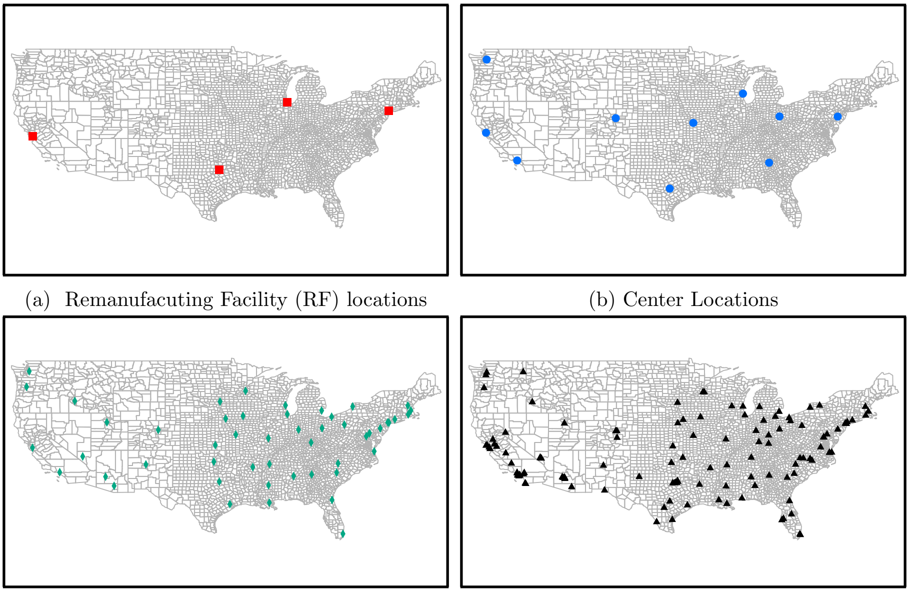
- The first term represents the revenues from non-defective products. Each location (retailer/center/RF) begins product inspection right after the arrival of returned products. If a returned product is identified as a non-defective product, then the product will be sold as a new product. Since the value of products changes over time, the sale price is determined based on the completion time of inspection. For example, suppose products collected by retailer locations using the return channel I-R-C-M or I-R-M arrive at the retailer on time $t + T_{ir}$ and the inspection time is P^1_{pr}, then the sale price will be $S^1_{p(t+T_{ir}+P^1_{pr})}$ for the non-defective products in the return channel I-R-C-M and I-R-M.
- Similarly, the second and third terms are the revenues from the sales of repaired products. We assume that the repaired products are sold in the second market and the sale begins right after repair. Thus, the sale price of the repaired product is determined based on the completion time of repair. The completion time of the defective products collected by the channel I-M is $t + T_{im} + P^3_{pm}$ including travel time, thus the sales price is set as $S^2_{p(t+T_{im}+P^3_{pm})}$ for the repaired product in the return channel I-M.
- The fourth and fifth terms are transportation costs associated with return flows.
- The sixth term gives the transportation cost associated with forward redistribution flows.
- The seventh, eighth, and the ninth terms are the product handling costs associated with both return and forward redistribution.
- The tenth and eleventh terms represent repair and disposal costs, respectively.

Constraint set (1) ensures that the returned products are collected by one of the retailers, the centers, or the recovery facilities. As mentioned above, the return flows from customer to retailer locations are split into two terms based on the return channel types, I-R-C-M and I-R-M. Constraint sets (2) and (3) represent the conservation of flows at each retailer location for return flows (blue flow lines on Figs. 1, 2) specifically in channels I-R-C-M and in channel I-R-M, respectively. Constraint set (4), on the other hand, represents the conservation of return flows at each center location, regardless of the specific channel, i.e., it conserves the return flow (flow out = flow in) at each center location. These flow conservation constraints are presented by taking into account the time components of the problem formulation, i.e., travel and processing times between the locations and at the locations, respectively. Specifically, suppose that travel time from the retailer r to center c is T_{rc} and processing time at center is P^2_{pc}. If the product p leaves from the retailer r to center c at time $(t - T_{rc} - P^2_{pc})$, in the amount $f^4_{p(t-T_{rc}-P^2_{pc})rc}$, then product p will arrive at the center c at time $(t - P^2_{pc})$. After operation at center c, for P^2_{pc} time units, the product p leaves for RF m at time t, f^6_{ptcm}. Therefore, the relation between f^4_{ptrc} and f^6_{ptcm} can be expressed as $\sum_{r\in\mathcal{R}} f^4_{p(t-T_{rc}-P^2_{pc})rc} = \sum_{m\in\mathcal{M}} f^6_{ptcm}$. Constraint sets (5) and (6) are flow conservation equations ensuring that the non-defective products (coming directly from customers) are redistributed to retailers after major inspection at the manufacturing facilities and at the centers, respectively. Constraint sets (7) and (8) ensure that the retailer capacities are not violated for return and redistribution flows, respectively. Similary, constraint sets (9) and (10) are capacity constraints for the center locations. Finally, constraint (11) ensure that the flow through manufacturing facilities are within their capacity limitations. Constraint set (12) represents the restrictions on the decision variables. Based on the developed linear programming formulation, we are able to analyze the best channel selection strategy explicitly to maximize profit from returned products. To solve our model to optimality with short runtimes in our computational study, we use CPLEX 12.4 solver.

4 Computational study and model analysis

In this section, we present a comprehensive computational study of the firm's optimal reverse channel choice problem. We focus on product related characteristics such as product value decay rate, expected non-defective and disposal (non-recoverable) rates as well as logistics network characteristics such the number, spread, and proximity of the distribution centers and product recovery facilities to customers and retail locations.

For the computational study, we use real geographical data based on large cities in the U.S. and product data from Guide et al. (2006). According to U.S. population data (2007), there are 263 cities with the population larger than one million and those cities are located in 41 states. Thus, we first pick 41 cities from 41 states, one city per state. After selecting 41 cities, there are 72 cities with over two million population. Lastly, we also add 7 more cities with the next highest population values so that we have total 120 customer locations. For the retailer locations, we again select 41 cities from 41 states and add 9 more cities from the populated areas, such as California, Texas, New York, and Florida. For distribution center locations, we select 10 cities from 7 regions, North-West (Washington-Oregon), West Coast (California), South (Texas), Midwest (Illinois-Michigan-Ohio), East Coast (New York-Pennsylvania), South-East (Georgia-Florida) and Central region (Colorado-Missouri). Lastly, for product recovery facilities locations, we select 4 cities as follows: West Coast (San Jose),



(a) Remanufacuting Facility (RF) locations
(b) Center Locations
(c) Retailer Locations
(d) Customer Locations

Fig. 3 Geographical distribution of RFs, centers, retailers, and customers in the U.S.

Midwest (Chicago), South (Dallas), and East Coast (New York). The set of locations listed above are also depicted in Fig. 3. Ranges for input parameters are shown in the below table. Parameter d_{ij} represents distance between node $i \in \{\mathcal{I}, \mathcal{R}, \mathcal{C}, \mathcal{M}\}$ and $j \in \{\mathcal{I}, \mathcal{R}, \mathcal{C}, \mathcal{M}\}$ and is calculated by using the *haversine* formula. The presented model in the paper is a type of minimum cost network flow model. Given a set of customers in the network with returned products, the model seeks a way of collecting products to maximize value from returned products. The returned products are collected together and sent to the next stage. Because of the pooling effect at retailers, centers, and RFs, different transportation costs are assumed based on the routes. For example, in the return channel I-R-C-M, the transportation costs of the route between center and RF are assumed to be lower than that of the route between retailer and center. For a similar reason, in the return channel I-C-M, the transportation costs of the route between center and RF are lower than that of the route between customers and center (Table 1).

Table 2 shows the problem size and its solution time. The decision model is implemented using C++ and CPLEX Concert Technology (CPLEX 12.10). Runs are completed on a machine with 3.6GHz Intel Core i7-4790 processor and 32 GB RAM.

4.1 Channel selection strategies based on product characteristics

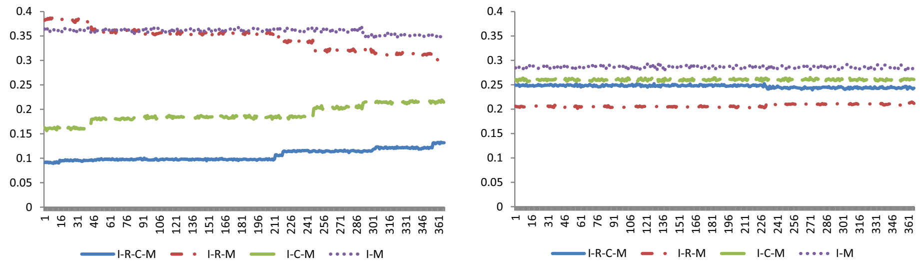
Recall that our primary goal in this paper is to develop an understanding of how the reverse channel strategy of a firm should be driven by product and network characteristics in a multi-product setting. To this end, we first test our model with product specific data from HP Printers and Bosch Power Tools case studies of (Guide et al., 2006). Using HP and Bosch product data set helps us identify how our multi-product analysis and insights compare to the findings in (Guide et al., 2006).

Table 1 Input parameters

Parameter	Value	Parameter	Value
$R_p^G, R_p^D, D_{pti}, S_{pt}^1, S_{pt}^2, RE_p, CD_p$	See Sect. 4.1	$T_{ij}, (i,j) \in \{(\mathcal{I},\mathcal{R}), (\mathcal{R},\mathcal{C}), (\mathcal{C},\mathcal{M})\}$	$\frac{d_{ij}}{400}$
$T_{ij}, (i,j) \in \{(\mathcal{I},\mathcal{C}), (\mathcal{R},\mathcal{M})\}$	$\frac{d_{ij}}{600}$	$T_{ij}, (i,j) \in \{(\mathcal{I},\mathcal{M})\}$	$\frac{d_{ij}}{1000}$
P_{pr}^1	7 days	P_{pc}^2	10 days
P_{pm}^3	21 days	$G_{ij}, (i,j) \in \{(\mathcal{I},\mathcal{R}), (\mathcal{R},\mathcal{C}), (\mathcal{C},\mathcal{M})\}$	$0.006 * d_{ij}$
$G_{ij}, (i,j) \in \{(\mathcal{I},\mathcal{C}), (\mathcal{R},\mathcal{M})\}$	$0.016 * d_{ij}$	$G_{ij}, (i,j) \in \{(\mathcal{I},\mathcal{M})\}$	$0.024 * d_{ij}$
Q_r^1, Q_r^2	$\frac{\text{RAND}[50,100]}{1000} * \sum_{p,t,i} D_{pti}$	Q_c^1, Q_c^2	$\frac{\text{RAND}[150,200]}{1000} * \sum_{p,t,i} D_{pti}$
Q_m	$0.5 * \sum_{p,t,i} D_{pti}$	C_{pr}^1, C_{pr}^2	$0.02 * S_{p0}^1$
C_{pc}^1, C_{pc}^2	$0.015 * S_{p0}^1$	C_{pm}^1	$0.01 * S_{p0}^1$

Table 2 Problem size and solution time (s)

Network size	Single product ($\|\mathcal{P}\| = 1$)			Multiple products ($\|\mathcal{P}\| = 2$)		
	Constraints	Decision variables	Solution time	Constraints	Decision variables	Solution time
N-S	65,394	2,411,920	180			
N-M	89,184	5,533,400	221	178,244	11,066,800	274
N-L	91,014	5,788,900	253			



(a) HP printer (b) Bosch power tool

Fig. 4 Channel selections for two individual products

HP printer case

According to (Guide et al., 2006), HP collects 1668 units of printers per day in North America. Thus, we compute daily return quantities at customer locations by multiplying 1668 with the corresponding population percentages. For example, population of New York City (NYC) is 8,323,732, which is 14.29 percent of the total population. Therefore, daily printer return quantities at NYC is obtained by multiplying 1668 with 14.29 percent. The price of an HP printer is set at $200 and 15 percent price discount is applied to the repaired/refurbished units sold in the secondary market. The cost of repair is defined as 7.5 percent of the price of a new printer and the product handling costs at each stage lie in the range of 1 percent to 3 percent of the product price.

The decay parameter d for both the value of a new and a repaired/refurbished printer are assumed to be 1 percent per week. Lastly, the percentages of non-defective and disposal rate are set to 33 percent and 10 percent, respectively. In Fig. 4a, the x-axis represents the product's life cycle normalized to 365 days. The y-axis represents the percentage of the time each return channel is selected for collecting HP products daily. Figure 4a shows the percentage of the time each return channel is selected in the optimal solution for HP printer case on daily basis. For example, approximately 70 percent of HP printers are collected via I-R-M and I-M channels during the product life cycle. Since the product decay rate of an HP printer is relatively high, i.e., time is an important factor in the collection, consistent with the (Guide et al., 2006) analysis, the responsive reverse channels (I-R-M and I-M) are mainly used to collect the returns for HP printers. The Fig. 4a shows the significance of the reverse channels I-M and I-R-M in the collection of an HP printer. (i.e., More than 70 percent of the time the responsive channels are optimally preferred over the product's life cycle).

Bosch power tool case

Next, we use data from Bosch Power tool case of Guide et al. (2006) to test our model for a product with low value decay rate. Similar to the HP printer case, we calculate the return quantities of Bosch power tools by multiplying the total daily return number of 750 with the respective population percentages of each city in our data set. The price of a Bosch power tool is assumed to be $50 and a 15 percent price discount is applied to the repaired/refurbished unit sold in the secondary market. The cost of repair is defined as 7.5 percent of the price of a new power tool and the product handling costs at each stage lie in the range of 1 percent to 3 percent of the product price.

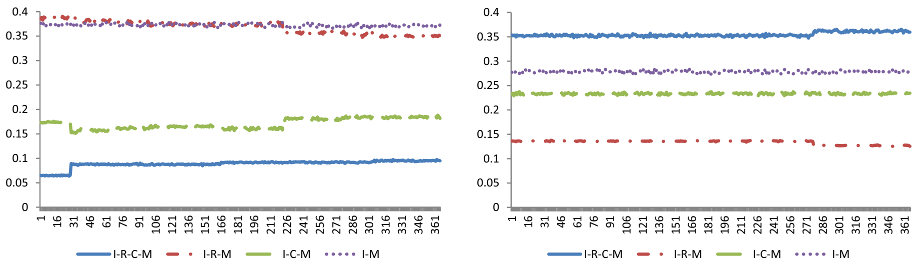
The decay parameter d for the value of a new or a repaired/refurbished power tool is assumed to be 1 percent per month. Lastly, the percentages of non-defective and disposal rates are assumed to be 0 percent and 10 percent, respectively.

Figure 4b depicts the percentage of return channels optimally chosen to collect returns of Bosch power tools. Unlike the HP case, all return channels are similarly preferred in the optimal solution to collect returned units, i.e. there is no dominant return channel as in the HP printer case. In Bosch power tool case, since all returned products are assumed to be defective, one can conjecture that sending directly to a recovery facility is a favorable option to collect products initially. According to Fig. 4b, all four return channels are actively used in Bosch power tool case. Especially, the return channels I-R-C-M and I-C-M, which stand as the cost-efficient reverse channel take approximately 50% of returns throughout the entire life cycle. Since the decay rate of the Bosch power tool is relatively low, time spent and the product value loss in the reverse channel has less impact on the optimal channel selection. For this reason, *the cost-efficient reverse channel* (I-R-C-M and I-C-M) is more likely to be observed in the optimal solution for the Bosch power tool. Although the cost efficient channels are heavily used in the Bosch case, the return channel I-M is the most preferred channel among the four return channels. As mentioned in HP Printer analysis, the return channel I-M is considered as the responsive reverse channel and the responsive channel doesn't fit a product with low decay value. In order to understand a high percentage of the return channel I-M in the solution, we analyze the channel selection based on characteristics of the reverse network. As explained in HP Printer analysis, the product's return volume is generated based on population and there are five customer locations resided relatively close to one of four RFs in the network. The return channel I-M now becomes the cost-efficient reverse channel for these customer locations since the distance between customer and RF is short. Also, five customer locations are a relatively big city and the sum of return volume from these locations is approximately 30% of total return volume. As a result, the channel I-M takes all returns from these locations and becomes the most preferred channel. In short, a reverse channel type is determined based on not only product characteristics, but also network characteristics. We further analyze the return channel strategy with network characteristics in detail in .

Remark 1 While our analysis confirms the findings of Guide et al. (2006) that a product of high (low) value decay rate should be collected via a responsive (cost efficient) reverse channel, we also find that a firm's reverse channel choice for each product type is in fact a *portfolio* of channel formats (i.e. involves all four structures with varying usage rates) to manage the cost efficiency versus responsiveness trade-off in the most profitable way. Furthermore, especially for a high value decay product (such as an HP printer), we find that the optimal portfolio of reverse channels evolves over the product life cycle, and gravitates towards more cost efficient channels at the end of the life cycle. Hence, it is not an either-or type of decision for a firm when it comes to determining the optimal reverse channel format, but it is about identifying the optimal portfolio of channel formats to use at different stages of a product's life cycle

Consideration of multiple products

In this sub-section, we extend this analysis to a multi-product setting with different product characteristics. To this end, we solve our decision model by considering the joint collection of both HP printers and Bosch power tools. Figure 5 presents the optimal channel selection for HP and Bosch individually when the model is solved jointly for both products. Since



(a) HP printer

(b) Bosch power tool

Fig. 5 Channel selections in multiple products

capacities at the retailers, distribution centers, and recovery facilities are shared by both products, from the findings of the previous section, we conjecture that a responsive return channel with shorter travel time would be more likely to be chosen optimally for HP printers with high product value decay rate, while a cost efficient return channel would be optimal for the Bosch power tools with low product value decay rate.

For HP printers, comparing the multi-product results from Fig. 5a with Fig. 4a, the average percentage of responsive channels I-M and I-R-M increases from 36 to 37 percent and 34 to 37 percent, respectively, whereas the percentages of channels I-R-C-M and I-C-M decrease from 10.5 to 8.8 percent and from 19 to 17 percent, respectively. On the other hand, for the Bosch power tools, comparing Fig. 5b with Fig. 4b, we observe completely the opposite result. The use of cost efficient channels I-R-C-M significantly increases, whereas the use of channel more responsive I-R-M channel decreases.

Remark 2 Interestingly, we find that when there are multiple products that are collected jointly and that have divergent product value decay rates, firm prefers a more focused reverse channel strategy aligned with each product's decay rate characteristic in the optimal portfolio. This happens despite the possibility of achieving better scale economies in transportation and handling by pooling of the resources on different collection channels. This result can be attributed to the presence of capacity limitations on resources. For example, if HP printer is allocated more capacity in the cost efficient channel (as in Fig. 4a) in joint channel selection, this would mean allocating Bosch to a responsive channel which can be prohibitively expensive. In a sense, we observe that multiple products with opposite decay characteristics act as strategic complements in the reverse channel and thus help firm use its reverse channel capabilities more effectively.

4.2 The effect of product characteristics on optimal reverse channel strategy

To gain insights about the sensitivity of the optimal reverse channel strategy to input parameters, we solve our model for a range of values for the *disposal rates, non-defective rates,* and *return processing times*.

4.2.1 Disposal rate

In our model, we assume that the disposal decisions are made after a major inspection is performed either at a distribution center or at a recovery facility. Hence, identifying recovery or disposal requirements early in the return process can help a firm save unnecessary

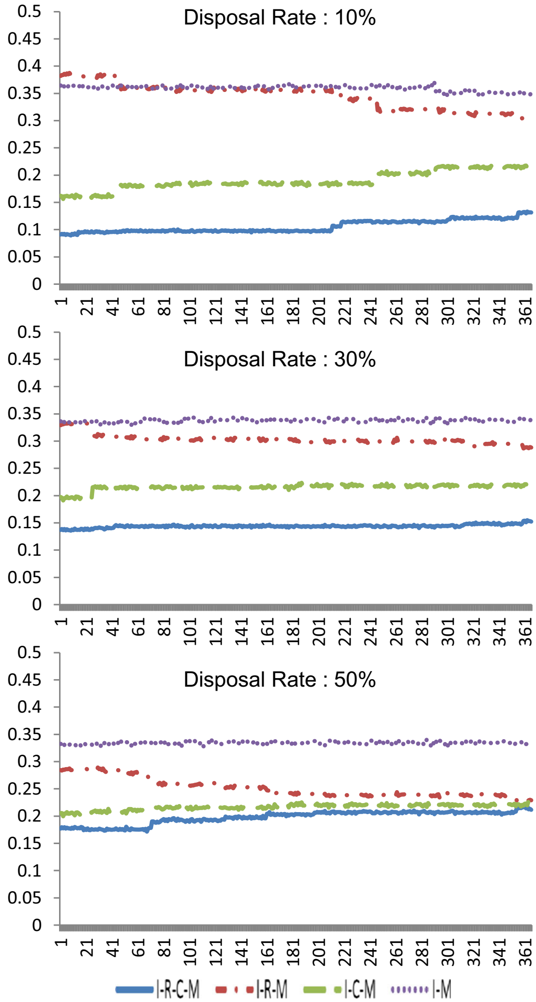


Fig. 6 Channel selections for HP printer under fixed 33% non-defective rate

transportation and product handling costs. Therefore, as the disposal rate increases, distribution centers or recovery facilities become particularly attractive primary touch points in the reverse flow. For HP printer case, we fix the non-defective rate (pr_p^G) to 33 percent and examine the disposal rates (pr_p^D) of 10 percent, 30 percent, and 50 percent. Figure 6 shows the channel selections of HP printer case under different disposal rates. The use of return channel I-R-C-M increases and the use of return channel I-R-M decreases as disposal rate increases. The return channel I-R-C-M balances the objective of maximizing value recovered from non-defective products while minimizing transportation costs. Although selection of I-M is still the highest percentages, return channel I-R-C-M and I-C-M become popular option as disposal rate increases.

In Bosch case, we fix the non-defective rate as 0 percent and change the disposal rates to 10 percent, 30 percent, and 50 percent. By the same reason in HP case, the percentage of return channel I-R-C-M and I-C-M increases as disposal rate increases. Both I-R-C-M and I-C-M channels save transportation and handling costs by shipping products from customers

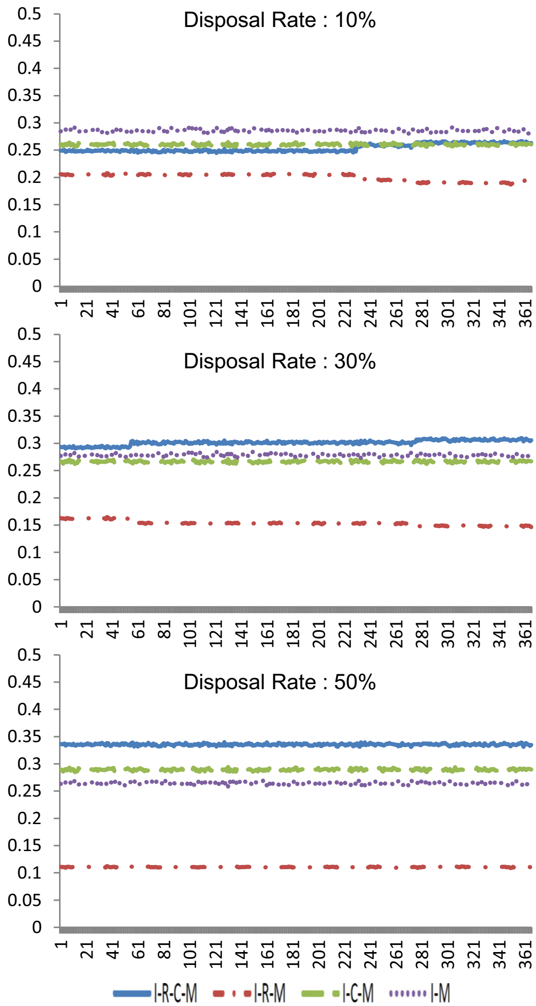


Fig. 7 Channel selections for BOSCH power tool under fixed 0% non-defective rate

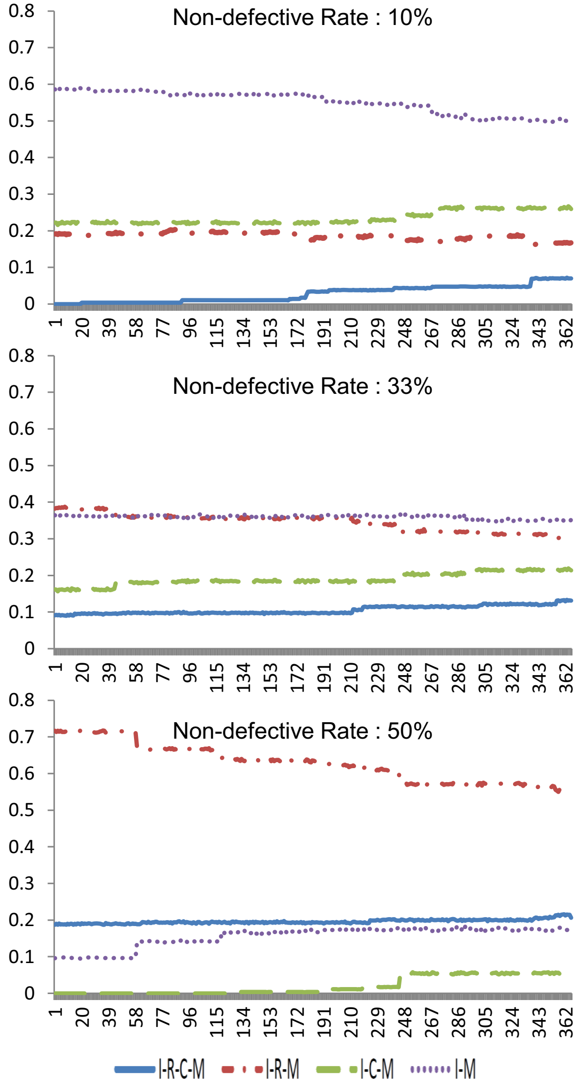
to recovery centers via intermediate locations. According to Fig. 7, in the optimal solution, more than fifty percent of the time both channels are selected for product returns and their selection percentages increase with disposal rate.

Remark 3 We observe that an increase in the disposal rate has a stronger effect on the optimal channel choice of the product with a higher value decay rate. Interestingly, we find that as disposal rate increases, even for a high value decay product like HP printers, the optimal reverse channel can revert to a more cost efficient channel format such as I-R-C-M which facilitates early disposal decision in the reverse channel and minimizes transportation costs.

4.2.2 Analysis on non-defective rate

If a returned product identified as non-defective after minor processing, it is resold at the retailer. Therefore, if non-defective rate is high, it is expected that retailers will initially

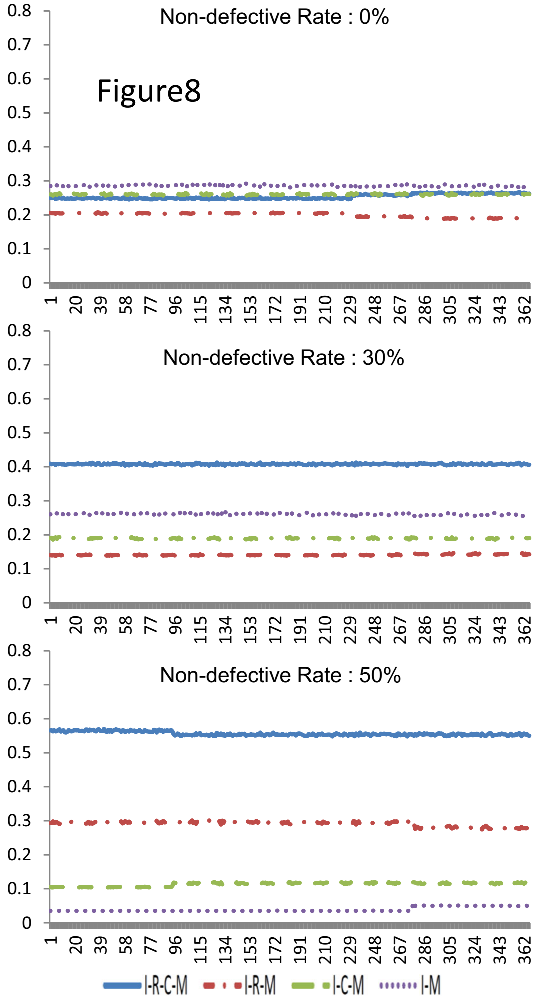
Fig. 8 Channel selections for HP printer under fixed 10% disposal rate



collect returns to avoid unnecessary costs. To analyze impact of non-defective rate in channel selections, we fix the disposal rate (R_p^D) as 10 percent and consider non-defective rates (R_p^G) of 10 percent, 33 percent, and 50 percent in HP printer case.

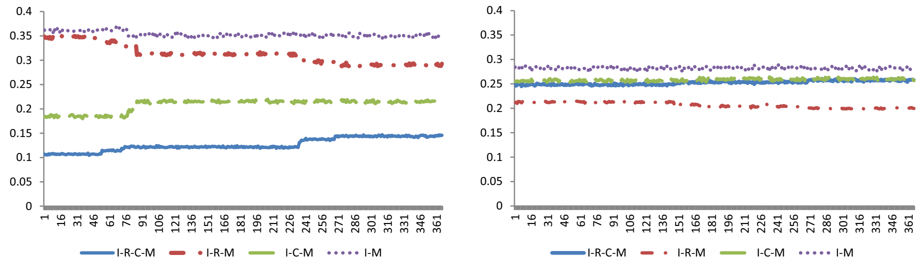
Figure 8 shows the optimal channel selection for the HP printer case under different non-defective rates. Low non-defective rate means that most products are defective and the major inspection is required. Thus, when the non-defective rate is only 10 percent, the return channel I-M becomes a major channel in collection. On the other hand, high non-defective rate means that most returned products are non-defective products and these products can be resold at the retailers after a minor inspection. Thus the return channel I-R-M dominates other channels, especially if non-defective rate is relatively high. For Bosch power tool case, we fix the disposal rate as 10 percent and consider the non-defective rates as zero percent,

Fig. 9 Channel selections for BOSCH power tool under fixed 10% disposal rate



30 percent, and 50 percent. According to Fig. 9, all four different return channels are used similarly throughout product life-cycle when the non-defective rate is zero percent. Unlike HP printer case, if non-defective rate is high, i.e. more than 30 percent, then the return channel I-R-C-M is the major return channel.

Remark 4 We find that the non-defective rate has a more profound impact on the optimal channel portfolio for products with high value decay rate than for products with low value decay rate. As the non-defective rate increases, channels such as I-R-M and I-R-C-M that involve retailer, become more prominent in the optimal channel portfolio for the high decay rate product, i.e. HP printer. This strategy allows the firm to turn around the non-defective units to market in a responsive fashion. However, for the low decay rate product, increasing non-defective rate only increases the utilization of the already dominant channel format, the I-R-C-M channel, in the optimal channel portfolio.



(a) HP printer (b) Bosch power tool

Fig. 10 Channel selection of HP and Bosch with less travel time

4.2.3 Analysis on return processing times

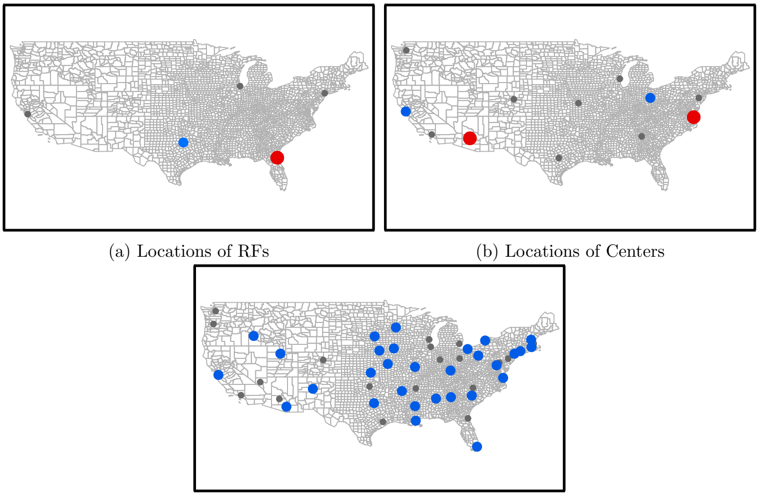
In our modelling, we assume that the product loses value over time. Therefore, if the product's decay rate is relatively high, then the return channel with less processing time is more often the optimal reverse channel to minimize product's value loss. In this section, we analyze the impact of time in channel selection for both HP printer and Bosch power tools by changing the processing time at the retailers, the distribution centers, and the recovery facilities. Initially, processing times at the retailer (P^1_{pr}), the distribution center (P^2_{pc}), and the recovery facility (P^3_{pm}) are defined as 7, 10, and 21 days respectively. We decrease the times by 30 percent and set them to 5, 7 and 15 days.

Figure 10 shows the optimal channel selections for HP printer and Bosch power tools with less processing time, which is obtained via decreasing the sojourn time of returned products in return process. For the HP case, in this new setting, the return channel I-C-M can handle both non-defective and defective products more quickly. Besides, the unnecessary transportation costs can be saved by disposing returned products earlier. Following the same reasoning, the return channel I-R-C-M handles products more quickly. Thus, the average percentage of return channels I-R-C-M and I-C-M increases from 10 percent to 12 percent, and from 19 to 21 percent, respectively, whereas the percentage of return channel I-R-M and I-M decreases. On the other hand, interestingly we find that the optimal channel selection is not changed for Bosch power tool case when compared to Fig. 4b.

Remark 5 We find that time is particularly an important factor in the reverse channel choice of high value decay products such as the HP printer. As the product processing time decreases on different legs of the return process, the differentiation between the channel formats decreases and all channel formats become equally attractive to collect high value products and this ensures a more effective use of reverse channel capability.

4.3 Channel selection strategies based on logistics network characteristics

In the previous section, we examined the return channel selection strategy of a firm as a function of product characteristics. However, reverse channel selection decisions are also affected by the configuration of the product recovery logistics network. For example, customers in New York, generally return products to a recovery facility directly, since the recovery facility is located in close vicinity, i.e., the return channel I-M is selected. On the contrary, customers in Phoenix, return products to their closest retailers, since neither a recovery facility nor a



(a) Locations of RFs (b) Locations of Centers

(c) Locations of Retailers

Fig. 11 Location of RFs, centers, and retailers under different geographic scheme

distribution center does exist in close proximity. Thus, they send products to recovery facility via intermediate locations, either using retailers (I-R-M) or using retailers and distribution centers (I-R-C-M).

In this section, we examine how a product recovery network configuration affects return channel selections. For problem data, we use the same value from HP printer case, except for recovery facilities, distribution center, and retailer locations. For comparing channel selection strategies with different product recovery networks, we define three different network configurations by changing number of recovery facilities, distribution centers, and retailers.

In the original model, we use geographical data with 4 recovery facilities, 10 distribution centers, 50 retailers, and 120 customers. We regard this network configuration as medium network-M (N-M). Next, we decrease the number of recovery facilities, distribution centers, and retailers to 3, 8, and 20, respectively, and obtain a smaller test network (N-S). Lastly, we increase the number of recovery facilities, and distribution centers to 5 and 12, respectively, to generate a larger test network (N-L). The sets of locations in these three networks are depicted in Fig. 11. The smallest, grey dots represent the location of recovery facilities, distribution centers, and retailers in N-S. The medium-size, blue dots are added to N-S to obtain the set of recovery facilities, distribution centers, and retailer locations in N-M. Lastly, the largest, red dots are included in N-M to obtain the locations in N-L.

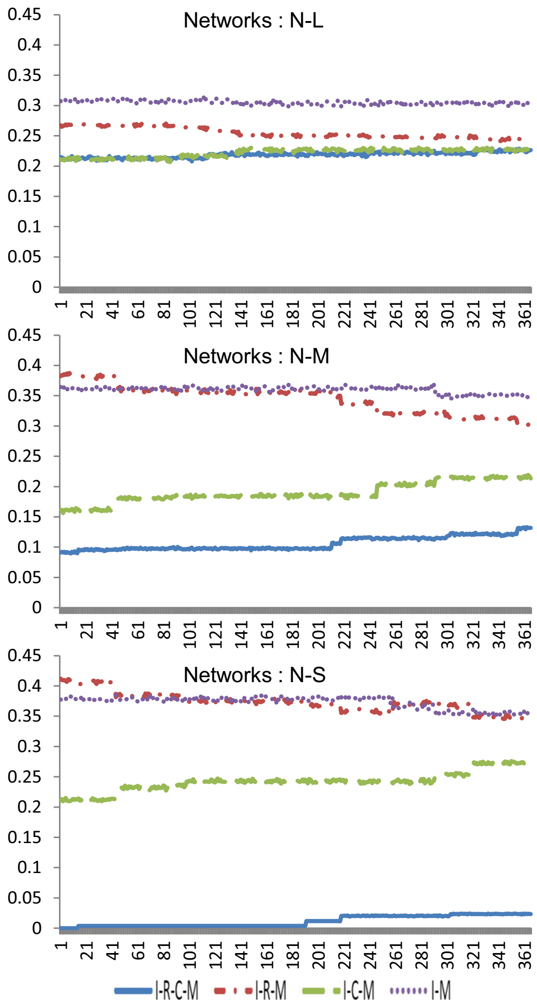
In Table 3, we provide data (number of links and average distance) on network characteristics that distinguish the varying sizes of networks in our test bed. While the number of links in each tier increases as the network becomes larger, the average distances decrease since the overall region of study is still same.

First, we analyze the HP printer case with 30 percent non-defective and 10 percent disposal rates under three different networks, N-S, N-M and N-L. Our results are summarized in Fig. 12. Based on our numerical study, we observe that the optimal reverse channel selection is sensitive to network configuration. As the network becomes larger, the percentage of channel I-R-C-M in the optimal solution decreases, while the percentages of I-R-M and I-M increase. For example, more than 20 percent of customers return products via the return channel I-R-

Table 3 Varying network sizes (number of links/average distance)

Network	$(\lvert\mathcal{M}\rvert, \lvert\mathcal{C}\rvert, \lvert\mathcal{R}\rvert)$	$\mathcal{I}-\mathcal{R}$	$\mathcal{I}-\mathcal{C}$	$\mathcal{I}-\mathcal{M}$	$\mathcal{R}-\mathcal{C}$	$\mathcal{R}-\mathcal{M}$	$\mathcal{C}-\mathcal{M}$
Small (S)	(3,8,20)	2400/1100	960/1180	360/1190	160/1128	60/1132	24/1208
Medium (M)	(4,10,50)	6000/1068	1200/1146	480/1150	500/1120	200/1097	40/1146
Large (L)	(5,12,50)	6000/1068	1440/1100	600/1105	600/1097	250/1030	60/1110

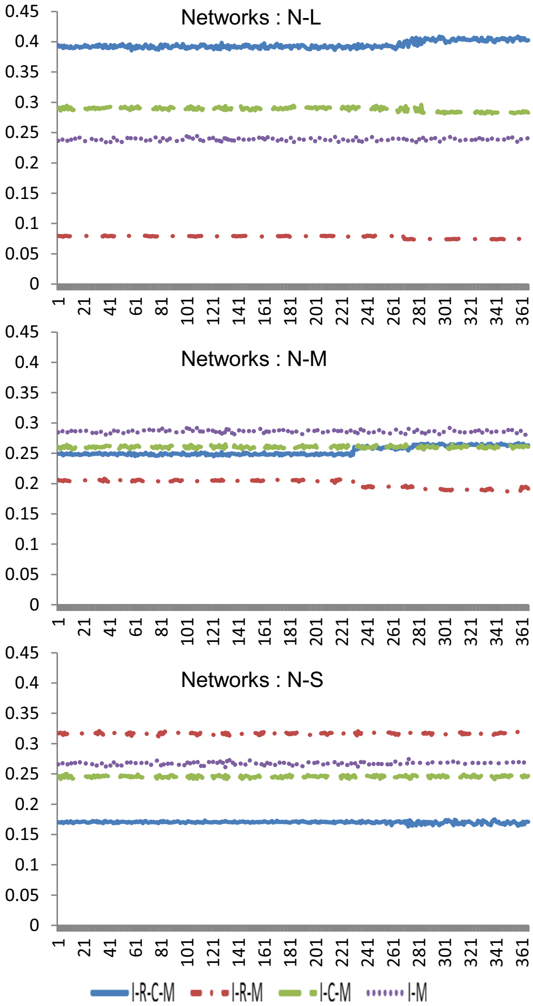
Fig. 12 Channel selection in HP printer, 30% non-defective and 10% disposal rates



C-M under N-S. Under N-S structure, customers in Dallas do not have a recovery facility or a retailer in close proximity, so they return their products to the closest retailer located in Oklahoma City. However, customers return products directly to recovery facilities under N-M and N-L since both retailers and a recovery facility are located in Dallas. Therefore, when identifying the optimal portfolio of reverse channel formats, a firm should not only consider the type of facility (R, C, M) where a product is going to be returned to, but also where these facilities are located relative to the customer locations, i.e. the network configuration. Generally, if customers are close to a recovery facility, then the return channel I-M is likely to be selected due to savings in transportation and handling costs. On the other hand, if retailers are close to customers but recovery facilities are few and far from the customer locations, then products are first returned to retailers.

Similar to the HP printer case, we analyze Bosch power tool case with 0 percent non-defective and 10 percent disposal rates under three different network formats. Our results are summarized in Fig. 13. As we observed earlier, all four channels are selected similarly in all

Fig. 13 Channel selection in Bosch power tool, 0% non-defective and 10% disposal rates



three networks. The percentage of channel I-R-C-M decreases as the percentages of I-R-M increase with increasing network size. Under network N-S, almost 40 percent of customers use return channel I-R-C-M but, in the network N-L, only 17 percent of customers select return channel I-R-C-M. As more recovery facilities and retailers are included in the network, more customers select return channel I-R-M instead of return channel I-R-C-M. For example, customers in Houston return power tools via channel I-R-C-M under network N-S, since they do not have a recovery facility or distribution center in their vicinity. However, once a recovery facility and retailers are located in Dallas, they change channel from I-R-C-M to I-R-M for return. That is, return channel I-R-M becomes more cost-efficient channel for customers in Houston under network N-L. Unlike return channel I-R-M, selection percentage of return channel I-M is quite similar in all three networks. The responsive return channel (I-M) is utilized less frequently for Bosch power tool case because a highly responsive channel is not needed due to low decay rate for the product value.

Remark 6 Our numerical study of network effects on reverse channel choice shows that the optimal portfolio of return channel formats can be strongly affected by the network structure which dictates the proximity of recovery facilities, centers, and retailers to customer locations. We conclude that when identifying the optimal reverse channel structure, a firm should not only consider the type of the facility where a product is going to be returned to, but also the structure of the RLN.

In the next subsection, we analyze channel selection by incorporating the interaction effects between product and network characteristics.

4.4 Channel selection under different networks and product characteristics

To analyze channel selection under general product characteristics (including decay, non-defective and disposal rates) in conjunction with the recovery network characteristics (including the locations of the retailers, the distribution centers, and the recovery facilities), we use the same three recovery network settings as shown in Fig. 11. Furthermore, we define two levels for decay, non-defective and disposal rates as being high and low. For the decay rate, we consider a product value loss of 1 percent in a day (high) or in a week (low). Similarly, we consider 10 percent (low) or 50 percent (high) for both non-defective and disposal rates.

Table 4 shows the average percentage of increase in objective value (total profits) for the selected reverse channel as the network becomes larger (Small-to-Medium and Medium-to-Large) under different product characteristics.

Observations under high non-defective rates

1. We first notice that, when the non-defective rate is high, the channels I-R-M and I-R-C-M are heavily utilized. That is, regardless of decay value and disposal rate, the returned products mostly reach to a retailer location first and the non-defective ones are put back on the shelf after minor processing. Further, if disposal rate of defective products is low, I-R-C-M is utilized significantly less than I-M since it unnecessarily introduces extra stop (at a retailer and a center) before processing at a recovery facility location. On the other hand, in addition to non-defective rate, if disposal rate is high as well, then channels I-R-C-M and I-R-M are both significantly utilized. Lastly, while a high decay value leads to dominant use of channel I-R-M, a low value favors more use of channel I-R-C-M.
2. In both of the high non-defective cases, regardless of the product value decay rate, as the network size increases, the channel I-R-M use increases while the I-R-C-M use decreases. This is because the increase in network size improves proximity of recovery facilities to retailers and renders I-R-M as a more cost-efficient channel when compared to I-R-C-M. A similar trend is observed when I-C-M and I-M are compared as well.
3. We further observe that, within low decay rate groups, regardless of the disposal rate level, the objective function values improve only slightly as the network becomes larger. For example, the total profit increases by 0.19 percent and 0.51 percent as the network size changes small-to-medium and medium-to-large, respectively. On the other hand, we observe larger improvements under high decay rate, that is, a larger spread of recovery facilities and distribution center locations increases reverse channel responsiveness and thus helps to improve profits significantly.

Table 4 Average percentage of selected channel and objective value under different product and network characteristics

Decay (H/L)	Low non-defective—low disposal					Low non-defective—high disposal				
Network (L/M/S)	I-R-C-M(%)	I-R-M(%)	I-C-M(%)	I-M(%)	ObjInc %	I-R-C-M(%)	I-R-M(%)	I-C-M(%)	I-M(%)	ObjInc %
L-L	0.0	14.6	28.3	57.1	0.67	0.0	10.0	39.0	50.9	1.15
L-M	2.8	18.7	23.5	55.1	1.24	6.6	14.7	31.0	47.7	1.48
L-S	7.7	11.6	35.7	45.0	–	10.2	10.0	39.8	40.1	–
H-L	0.0	10.6	22.7	66.7	14.88	0.4	9.3	35.8	54.5	105.93
H-M	2.5	16.7	18.1	62.6	5.44	6.3	13.2	29.7	50.8	31.15
H-S	5.9	14.5	28.5	51.1	–	9.3	9.7	39.3	41.8	–
Decay (H/L)	High non-defective—low disposal					High non-defective—high disposal				
Network (L/M/S)	I-R-C-M(%)	I-R-M(%)	I-C-M(%)	I-M(%)	ObjInc%	I-R-C-M(%)	I-R-M(%)	I-C-M(%)	I-M(%)	ObjInc%
L-L	13.3	66.5	1.1	19.1	0.19	38.8	51.5	2.4	7.3	0.21
L-M	19.8	54.8	3.1	22.3	0.51	40.0	42.8	5.5	11.7	0.36
L-S	30.0	39.8	9.8	20.5	–	41.8	32.7	11.1	14.4	–
H-L	14.5	68.6	4.2	12.7	1.16	32.7	53.7	3.4	10.3	1.19
H-M	18.5	61.2	5.3	15.0	4.84	35.7	46.5	5.6	12.2	5.11
H-S	26.5	48.1	9.1	16.3	–	39.7	36.5	9.2	14.7	–

Observations under low non-defective rates

1. In this case, when there is a high number of returned products requiring significant rework at recovery facilities (more so when disposal rate is low), the channel I-R-C-M is least utilized and the channels I-M and I-C-M are the most significantly employed ones. If the disposal rate is low, I-M is used significantly more than I-C-M and I-R-M, especially in larger networks, due to benefits of direct shipment to recovery facilities for repair. This is more pronounced in the high decay rate case where a responsive channel such as I-M is more beneficial. On the other hand, when the disposal rate is high, use of I-C-M increases significantly, especially when decay rate is low, due to the opportunities to dispose early without bearing additional transportation and handling costs. If the decay rate is high, the return channel I-M is more appropriate due to its responsiveness. We also observe that, for small and medium networks, use of I-R-C-M increases due to its cost efficiency when the recovery facilities are remote.
2. In both of the low non-defective cases, as the network size increases, the use of channel I-M increases while the use of I-R-C-M and I-C-M decreases. This is because the increased network size improves proximity to recovery facilities thus making I-M a cost-efficient channel when compared to I- C-M and I-R-C-M. This holds regardless of the product value decay rate. Perhaps an exception is the low decay rate with high disposal case in which the use of I-C-M increases with a larger network due to small amounts of time-insensitive returned products needing rework.
3. Furthermore, in terms of the objective value (profit) changes, we observe that, in the low decay rate case, slight improvements are obtained as the network size increases. This is because while most of the returned products are defective and need to be worked on, they do not lose much value in time and, thus, do not require extensive networks for realizing their value in logistically cost efficient manner. On the other hand, if the decay rate is high, profit improvements can be quite substantial when the network size is increased due to the fact that a large network (with many center and recovery facility locations) provides the ability to process returns both faster and cheaper.

4.5 Value of a channel portfolio

In this section, we explore the value of adopting a multiple reverse channels strategy for a firm and using a decision model, as proposed here, to optimally select where customers should be returning their products. Thus, in this section, we compare profits when a company optimally decides the return method for a product versus when the return process is constrained and handled by one channel format only. In other words, in this section, we capture the value of having a portfolio of reverse channel formats to collect returns. For this analysis, we employ the medium sized network N-M that is introduced above.

In our profit comparisons, first we calculate the optimal firm profits when reverse channel decisions are made using a multiple reverse channels decision model as studied above. Next, we modify our original model by restricting channel selection such that we force the model to collect products using only a single return channel, I-R-C-M, I-R-M, I-C-M, or I-M. For comparison, we define four decay rates including product value loss of 1 percent per day (1D), per week (1W), per two weeks (2W), and per three weeks (3W). We consider three different non-defective and disposal rates as 10 percent, 30 percent, and 50 percent, with other data (demand, cost, price, etc.) based on HP printer case. For each combination of these decay, non-defective, and disposal rates, we solve for the optimal solution and return

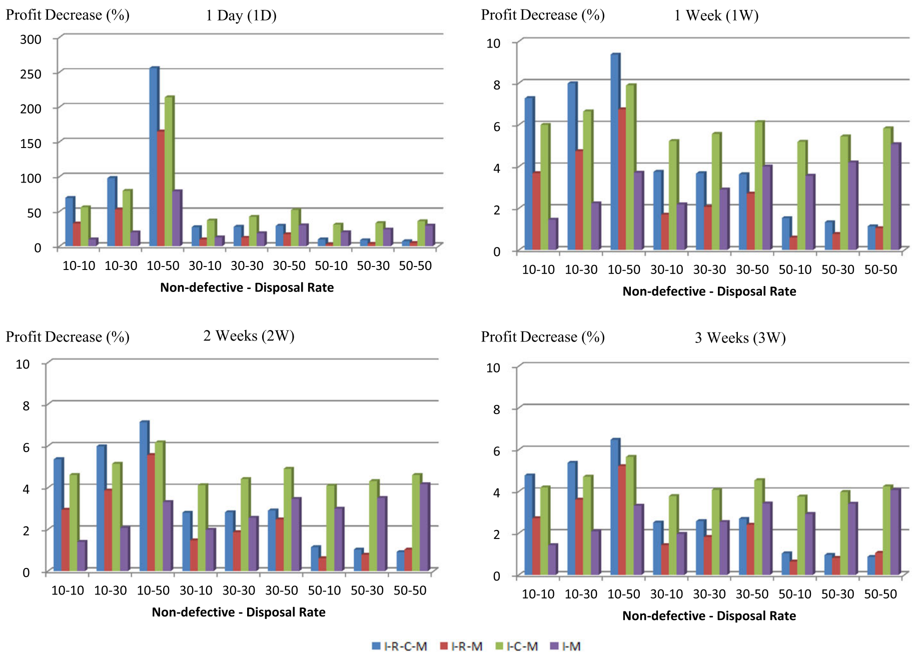


Fig. 14 Optimal solution gap percentage under different decay value

channel selections based on our original model setting. Secondly, we obtain the optimal firm profits by restricting the return channel to one of the four channel formats and calculate the loss in firm profitability from following the latter strategy. In Fig. 14, OptGap (%) shows the percentage decrease in the optimal firm profits when the corresponding specific channel is used as opposed to the optimal portfolio of channel formats. Our observation can be summarized as follows:

1. In Fig. 14, notice that the profit loss is significantly larger for the high decay rate (1D) case (note the differences in scale in y-axis). It is clear that the average profit decrease due to return channel fixing is the largest for high decay rate case, particularly when the non-defective rate is low.
2. As an overall trend, we observe that the reduction in profits for I-R-M and I-R-C-M channels decreases with non-defective and disposal rates. This happens because forcing of the returns to retailer locations for immediate re-shelving and quick access to disposal at a center or recovery facility (if not re-shelved) provide the least profit loss over the optimum solution. I-M and I-C-M appear to be behaving in a similar fashion, however, their profit decrease values are typically much higher than the ones with I-R-C-M and I-C-M and an improvement is observed only when the non-defective rate increases from 10 to 30 percent.
3. For each fixed non-defective rate group, we observe that the reduction in profits increases as the disposal rate increases. The reason for this is also related to the impact of disposal on the revenue, i.e., high disposal rate of returned products leads to lost revenues, and thus to lower profits. In summary, ad hoc choice of a channel for returns always introduces high profit loss which is very significant especially for the products with high value decay rate.

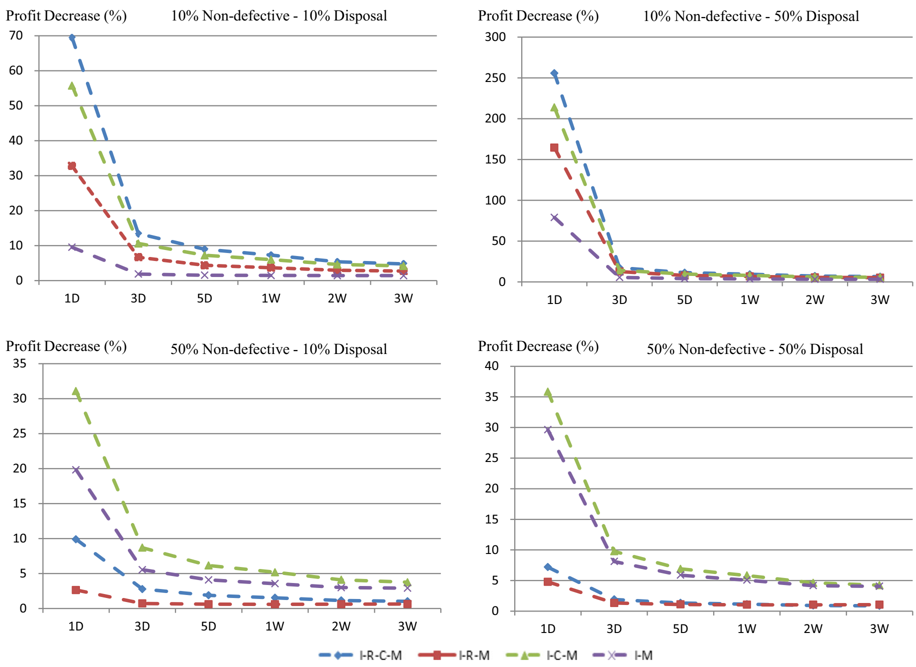


Fig. 15 Optimal solution gap under different non-defective and disposal rate

Next, in Fig. 15, we present profit decrease (over the optimum channel selection) due to channel presetting with respect to varying value decay rates including 1 percent decay rate per 3 days (3D) and per 5 days (5D). We observe that, for the high non-defective rate, the decrease in profits is generally low when return channel is preset to I-R-M or I-M. As mentioned above, these channels provide quick re-shelving of non-defective products and they are cost efficient channels for handling the defective products. On the other hand, when the non-defective rates are low, most of the products need to be re-worked, if not disposed, therefore channel presetting leads to large losses in profit, especially for high decay rate products. Overall, we clearly observe that optimal channel selection, rather than an ad hoc presetting, is critical for high value decay rate products, e.g., 1D case, but also not insignificant, in terms of profit losses, even for low decay rate products.

5 Concluding remarks

A well-developed reverse logistics strategy can improve customer satisfaction, reduce returns processing and transportation costs, maximize value recaptured from returned products on primary and/or secondary markets, and most importantly can eliminate waste from landfill and thus improve the environmental sustainability of a business. In this paper, we developed a multi-product and multiple-echelon reverse logistics channel selection decision model that incorporates a number of critical factors such as the time spent in the reverse logistics network, the scale effects in reverse logistics costs, the product value- decay rates, non-defective product rates and the network configuration. While previous research has recognized the importance of providing different reverse logistics capabilities for products of different demand characteristics, in this paper, in a multi-product setting, we offer a comprehensive modeling framework and analysis to unravel the interaction effects between product features and logistics network features in the design of optimal reverse logistics strategy. Furthermore, this paper is one of the first studies to present a profit-maximization decision model that captures the cost efficiency versus responsiveness trade-off in a rich network setting. In doing that, we show that a well-executed reverse logistics strategy not only reduces costs and maximizes firm profitability, but also can be a key capability for achieving sustainability in retail operations.

Our analysis provides a number of valuable insights for practitioners. First, we show that firms should develop a good understanding of the value decay process of their products before they can optimally design their reserve logistics network. For products exhibiting high value decay, product return and distribution network should be built to ensure high responsiveness in returns handling and resale, whereas for products exhibiting low value decay, firms should choose a network structure to ensure high cost efficiency. More interestingly, we show that a firm's RLN channel decision for each product type is in fact a *portfolio of channel formats* (i.e., involves four different structures with varying utilization rates) to optimize the cost efficiency versus responsiveness trade-off in the most profitable way. Furthermore, especially for a high value decay product (such as an HP printer), we find that the optimal portfolio of reverse channels evolves over the product life cycle, and gravitates towards more cost-efficient channels at the end of the product life cycle. *Consequently, we show that it is critical for practitioners to understand that it is not an either-or type of decision for a firm when it comes to determining the optimal reverse channel format, but it is about identifying the optimal portfolio of channel formats to use at different stages of a product's life cycle.*

Secondly, we demonstrate that firms should look beyond cost efficiency benefits and scale effects of pooled resources in the design of reverse logistics channel. Our analysis demonstrates that for certain products, it can be optimal to sacrifice scale effects to generate greater economic value through a more responsive reverse logistics design. Given the broad product assortments of today's retailers, each product exhibiting a unique life cycle demand patterns, we show that firms can be much better off by building a portfolio of reverse logistics channels optimizing profitability as a function of each product's value decay rate. In other words, a more focused reverse channel strategy aligned with each product's decay rate characteristic is optimal to maximize firm profitability, even if that means sacrificing scale economies in transportation and handling from pooling of resources.

Thirdly, our analysis sheds light on how product defect and disposal rates can be a critical factor in optimal reverse logistics decisions. Subject to strict environmental regulations, today we often find manufacturers invest in product design to improve reusability of returned products, reduce product defect rates and disposal rates. A great example is how engineering, manufacturing, and supply chain teams at Cisco systems Inc., a technology company, constantly explore new processes to use materials and new designs that are of higher quality and easier to recycle or reuse (CISCO, 2022). While these strategies reduce the direct costs of product returns, in our study, we also show that the disposal rate and non-defective rates can have a profound impact on the reverse channel strategy of a high decay rate product such as a HP printer. Interestingly, as the disposal rate increases, the optimal reverse channel portfolio gravitates towards more cost-efficient channel formats rather than the more responsive ones, as one would have anticipated for a product like a printer. As the non-defective rate increases, channels that involve retailer, become more prominent in the optimal reverse channel portfolio for the high decay rate products. This strategy allows the firm to turn around the non-defective units to market in a responsive fashion.

Lastly, we find that as companies stream line operations and reduce processing times in the reverse channel, the differentiation between reverse channel formats decreases and all channel formats become equally attractive, particularly in the collection of the high decay rate products. Implementing a multi-product multi-channel decision model as proposed in this paper, and identifying the optimal channel portfolio not only improves firm profitability, but also leads to positive environmental externalities for a company.

Even though our modeling framework offers novel insights into reverse logistics design decision of a firm, it exhibits certain limitations. For example, in a future study, one can relax the fixed facility location assumption and can jointly model the facility location and reverse channel design problems. In the current paper, we have abstracted away from the incentive issues. A possible avenue of future research is to study how incentives of different agents in the forward and reverse channel can impact the choice of RLN for a firm in a profit maximization setting. Lastly, one can extend the current modeling framework to incorporate carbon footprint of different channel formats, and thus can build a more comprehensive decision making model that incorporates profit as well as an elaborate environmental objective function.

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