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Reverse Cross-Docking

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Abstract

Companies continuously look for new ways to optimize their processes according to their competitive priorities. Returns process management, as a part of reverse logistics, has become an important field of performance improvement, especially in businesses with seasonal demand patterns, like fashion, books, or electronics. Consequently, unsold articles are often commercialized through secondary channels, such as outlet stores. To approach the management of reverse logistics systems, models used to optimize the forward flow of articles have been analyzed and adjusted to cope with the characteristics of reverse flows. Despite the recognized impact of cross-docking in forward logistics, approaches to apply this strategy in the returns context are lacking. This paper demonstrates how cross-docking can be implemented in a reverse logistics context and it proposes a corresponding linear programming model. Results show that the application of "reverse cross-docking" can increase the efficiency of reverse logistics in terms of cost reductions, time savings, and improvement of information management in returns processes. Sensitivity analyses show that a reverse cross-docking system can help companies to improve competitiveness in situations where a) the outlet flexibility related to products and quantities received is high, b) the probability of returns from secondary markets is low, or c) the combination of return and cross-docking costs in comparison with warehousing costs are low. The reverse cross-docking model in its basic form covers the main system characteristics and is flexible for further extensions. An extension presented herein refers to the consideration of heterogeneous article prices, indicating the usefulness of reverse cross-docking, particularly in industries with low price levels.

Keywords

cross-docking, reverse logistics, linear programming

1. Introduction

Reverse logistics (RL) is a concept that has increasingly gained importance in both business and research over the last 20 years. The introduction of environmental laws, increasing environmental consciousness of customers, and growing competitive pressure has led to the development of multiple models and solutions for RL activities [1,2,3,4].

Reverse logistics is defined as the process of "planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal" [5]. In this sense, all activities related to processes involving the movement of products or materials from the customer back to the manufacturer are included within the RL framework [5]. Reverse logistics is widely accepted as a source of profitability and competitiveness for companies [2,6,7]. This is particularly significant in sectors with seasonal demand patterns, wherein companies understand returns as a part of their business and systematically look for ways to capture value from the RL systems [8,9].

The number of publications in the field of RL has been documented by Govindan et al. [10], from its origin in the late '60s to an increasing number of publications over the last eight years. Literature on RL focuses on the analysis of practices to develop efficient processes and techniques to deal with RL problems that companies are facing in fields like network design, inventory management, production planning, distribution planning, performance measurement, or quality control [10,11,12,13]. The heterogeneity of returned products or materials (e.g., defective, unsold, or end-of-life products), increases the complexity of the RL systems [14,15,16].

Many existing models and theories of forward logistics have been analyzed and modified to match the characteristics of RL [7,11,17,18]. However, while the positive impact of cross-docking in forward distribution is widely recognized [19,20], approaches to apply this strategy in the returns context are far lacking.

Cross-docking consists of transferring incoming shipments directly to outgoing vehicles without storing them in between [21,22,23,24]. The transfer is ideally done within less than 24 hours [20, 25]. The main benefits derived from the introduction of cross-docking are cost reductions related to inventory holding, order picking, and transportation, as well as reductions of delivery times in supply chains [26,27,28,29]. One of the first reported cases of successfully applying cross-docking dates from the early ‘90s was when it was introduced by Wal-Mart. This strategy strongly contributed to the competitive advantage and growth of Wal-Mart in the US [21], which was an important stimulus for other organizations to implement cross-docking as a way to improve their supply chain management [30]. Table 1 shows a description of the main activities and actors participating in forward cross-docking systems [29].

Table 1. Main activities and actors in forward cross-docking systems.

Activity	Actor	Description
Placement of product order	Primary market stores	Based on sales forecast, primary market stores place orders through a purchasing department.
Order consolidation	Purchasing department	Purchasing department sends orders to the suppliers, specifying the destination store.
Order preparation and transportation	Supplier	Suppliers pick and pack the articles and label the boxes according to the orders received. Boxes are sent to the cross-docking platform.
Cross-docking	Cross-docking platform	Cross-docking platform consolidates the orders from different suppliers and distributes them to the destination stores.
Order verification	Primary market stores	Stores receive the boxes and verify order fulfillment.

With seven papers about cross-docking documented in the ‘90s and 87 papers between 2000 and 2012 [21], cross-docking entered research slowly. Until now, it is still a concept that lacks a significant body of academic literature [20,25].

Considering the success of cross-docking and the tendency to optimize RL systems by modifying strategies, concepts, or models applied in forward logistics, this paper aims to integrate these two concepts into a conceptually supported reverse cross-docking system and optimization model. The characteristics of return processes, such as a lack of information about the product quantity and quality, the final destination of returned boxes, and clients’ orders (i.e. outlets), seem contradictory to the application of cross-docking, which requires efficient information flows. Nevertheless, the proposed reverse cross-docking system introduces managerial practices to cope with these characteristics.

This paper contributes to the literature in three different aspects. First, the proposed reverse cross-docking system demonstrates how cross-docking can be implemented in the RL context. Second, a linear programming model, denoted as the “reverse cross-docking model” (RCDM), is presented to optimize the cost of return process management for unsold products. Third, numerical examples help to deduce recommendations for the management of reverse cross-docking systems.

The paper is organized into five sections. Section 2 introduces the characteristics of reverse cross-docking systems. The RCDM and its mathematical formulation are presented in Section 3, leading to numerical examples that are applied to assess model consistency and to develop managerial recommendations in Section 4. The paper concludes and provides an outlook for future research in Section 5.

2. Reverse cross-docking systems: characteristics and processes

A reverse cross-docking system manages the direct transfer of returned products coming from primary markets to outgoing vehicles routed to secondary channels without storing the products. The reverse cross-docking system itself is embedded into an RL network, which determines its general structure. Focusing on unsold products, RL networks traditionally manage return processes as follows (see Fig. 1):

1. Given a typical amount of unsold products from companies with seasonal demand patterns [31], these companies withdraw unsold products from the primary market stores for further distribution in RL networks [32].
2. A reverse distribution center (ReDC) receives returns from the primary market stores, opens the boxes, assesses article quality and characteristics, refurbishes or repairs (if necessary and economically feasible), classifies, sorts, and keeps products in stock until they are assigned and sent to a secondary channel. The product assignment can follow push or pull principles. Because returned articles are treated individually and not per lot, as in forward distribution, the processing costs in a ReDC can be assumed to be higher than in forward distribution [33].
3. The majority of returned products result in practices, such as reselling "as is" (outlets), remanufacturing/refurbishment, recycling, landfilling, or repacking and "selling as new" [34,32]. With the "sell as new" option, Internet sales are often employed. Outlets are the preferred option because the economic return is higher than in other channels [33]. If the quality of the article is poor and cannot be recovered, the decision to dispose of the article is an alternative at the ReDC.
4. Merchandise that has not been sold by the outlets within a determined period is returned to the ReDC and processed through different secondary channels.

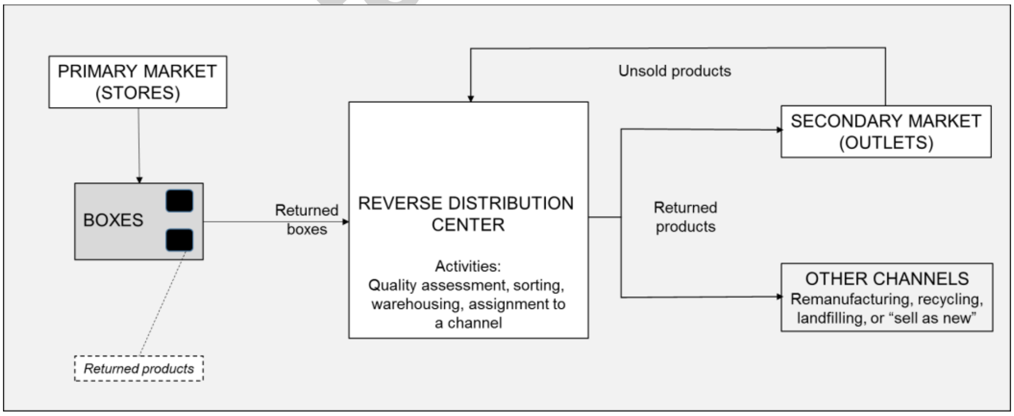

Fig. 1. Generic structure of reverse logistics networks for unsold products.

The generic structure of RL networks (see Fig. 1) provides a framework for the application of strategies to improve network performance. As stated above, cross-docking is a strategy that is proven successful in forward distribution. The general system structure of cross-docking is comprised of a source, a distribution platform, and a destination, and this applies to both forward distribution and RL systems. Cross-docking approaches in RL have been introduced in the context of processes to recover waste [35]. However, to the best of the authors' knowledge, they have not been applied for returned unsold products so far. Potential reasons may be related to the information requirements of the system to operate cross-docking properly; in forward flows, the supplier (article manufacturer) needs the order information in terms of products and quantities per client (primary market store). This information allows the supplier to prepare the boxes adequately for the clients. To avoid opening the boxes at the distribution center, they must be labeled at the source with the destination address. While this information is generally available in forward flows, it is difficult to fulfill these information requirements in RL for the following reasons:

1. There are no orders from a client (here, the secondary market outlets).
2. Boxes are packed based on the surplus of goods at the supplier (here, the primary market stores).
3. Boxes are not labeled at the source since the destinations are unknown.

To adapt cross-docking to the RL context, the system needs to introduce three practices into the management of the returns process:

1. Demand information: To substitute the traditional client order, the creation of an ideal product assortment for each secondary market store (outlet) is necessary. The corresponding list should contain product identification codes and quantities, while taking into account the historical data and preferences of outlet customers.
2. Supply information: Although the boxes are packed with the surplus of goods at the primary market stores, information about the box contents needs to be sent to the ReDC. The information should at least refer to product identification codes and quantities.
3. Assignment based on the matching of supply and demand: To fulfill the main function of cross-docking—transferring boxes without storage from the source to the destination—the ReDC needs to assign the boxes to the outlets while considering ideal product assortment (1) and box contents (2). To match supply and demand, the system requires the flexibility of the outlet stores concerning the product types and quantities they will receive. At this point, the RCDM (see Section 3), an optimization tool, is applied to assign boxes to outlets or to traditional warehousing.

These practices can be observed in the European apparel industry. In particular, when companies own the direct store chain and the outlet store chain, the application of these practices helps to coordinate product and information flows between both chains.

Table 2. Characteristics of forward and reverse flows of products and reverse cross-docking.

Criteria	**Characteristics of the forward flow**	**Characteristics of the reverse flow**	**Reverse cross-docking**
Order system	Pull system (demand known)	Push or pull system (demand unknown)	Pull and push system (demand known but flexible)
Type of products	New products	Unsold products	Unsold products
Supplier: source of products	Product manufacturer	Primary market stores	Primary market stores
Client: destination of products	Primary market (stores)	Secondary market (outlets)	Secondary market (outlets)
Distribution center: operations	Cross-docking and traditional warehousing	Traditional warehousing	Cross-docking and traditional warehousing
Client flexibility: product types and quantities	Inflexible	Flexible	Flexible
Box content: quantity and quality	Known	Unknown	Known
Labeling: box destination	Defined by the order and placed at the supplier	Non-existent	Defined by and placed at the ReDC

These three practices allow the introduction of cross-docking as a viable strategy for returned products, particularly unsold products. As shown in Table 2, the reverse cross-docking system becomes a pull/push system wherein a stronger orientation toward the outlets' demand is implemented. The creation and communication of the ideal product assortment by the outlets integrate this client orientation into the system. As long as the optimization model finds boxes with a high level of matching, the system works as a pull system that follows the ideal product assortment of the outlet. Nevertheless, a determined level of outlet flexibility established by the ReDC, allows the optimization model to shift from a pull to a push assignment of boxes to keep the cost of the ReDC low. Table 2 summarizes the main characteristics of the forward and reverse flows of products, as well as of the reverse cross-docking system.

With the introduction of these managerial practices to the reverse cross-docking system, the traditional RL network maintains its generic structure (see Fig. 1), but it is modified with respect to the information flows and potential product flows (see Fig. 2). In addition to the initial network description, the following components transform an RL network into a reverse cross-docking system:

1. At the end of the sales season, the primary market stores pack unsold products and send the boxes and the information about the boxes' contents to the ReDC (supply information).
2. Outlet stores create the ideal product assortment and send it to the ReDC (demand information).
3. The ReDC assigns boxes to outlets or to traditional warehousing using the RCDM (see Section 3). A label is attached at the ReDC, and boxes are sent to the outlets through cross-docking without being opened. If a box is not assigned to an outlet, it is processed through the traditional warehouse operation. With the option to assign boxes directly to outlets, the standard steps and times of traditional warehousing will be reduced.
4. Unsold products at outlet stores are returned to the ReDC and sent for further treatment in other channels. The amount of products returned from the outlets is determined by a return probability.

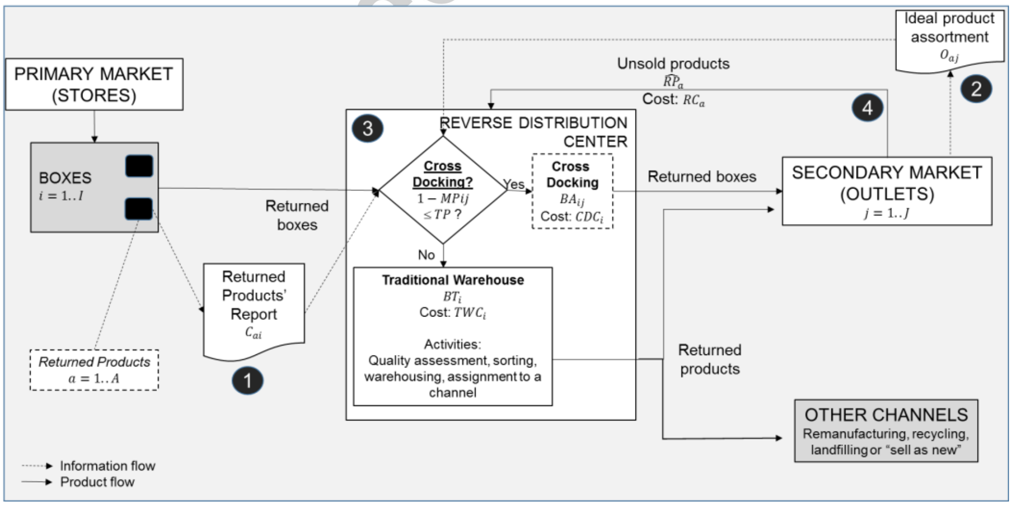

Fig. 2. Structure of a reverse cross-docking system for unsold products.

3. The reverse cross-docking model

The RCDM is used at the ReDC to assign returned products coming from primary market stores to secondary market outlets or to traditional warehousing (see Fig. 2). To make this decision, the model receives the information about the returned products from primary market stores (supply information) and the information about the ideal product assortment from the outlets (demand information). The model minimizes the total costs of the system, which consist of traditional warehousing costs, cross-docking costs, and return costs.

3.1. Operationalization of outlet flexibility

The required flexibility of outlet stores regarding product types and quantities is integrated into the RCDM as a parameter denoted as Tolerance Percentage (TP). This constant parameter represents the threshold of mismatch related to the box contents to be accepted by the outlets. The TP can take values from 0% to 100% and is determined for all outlets at the ReDC.

If the TP is too high, many unwanted products will arrive at the outlet stores, increasing the probability of articles returned from outlets. This reduces traditional warehousing costs, but increases the cross-docking and return costs. Furthermore, a high TP does not fulfill the commercial expectations of the outlet expressed with the ideal product assortment. In the extreme case of a TP value of 100%, all boxes are authorized to be sent through cross-docking to any outlet.

If the TP is too low, few unwanted products will arrive at the outlet stores, reducing the probability of articles returned from outlet stores. This reduces the cross-docking and return costs, but increases the warehousing costs, as more boxes will go to traditional warehousing. In the extreme case where the TP value is 0%, only boxes with a perfect match with the ideal product assortment will go to an outlet.

In addition to the TP, the RCDM computes for each pair of box *i* and outlet *j* a matching percentage *(MP_{ij})* using the following formula:

$$MP_{ij} = 1 - \frac{\#\ of\ articles\ within\ box\ i\ not\ belonging\ to\ the\ ideal\ product\ assortment\ of\ outlet\ j}{Total\ number\ of\ goods\ within\ box\ i}$$

The MP indicates how much box *i* matches the ideal product assortment of outlet *j*.
Once the MP is calculated, the model will only allow boxes with an MP_{ij} greater than *1-TP* to be assigned to an outlet. This model constraint does not represent the final assignment decision, as one box can be assigned to several outlets. Therefore, the model will recommend the final assignment decision for a box in such a way that costs are minimized. In the case where a box is not assigned to any outlet, it will be processed through traditional warehousing.

3.2. Model assumptions and notation

1. The model optimizes traditional warehousing costs, cross-docking costs, and return costs, which are considered the total costs relevant for the assignment decision.
2. The supply information from the primary market stores and the demand information from the outlets are available at the ReDC.
3. Boxes that are not processed through cross-docking are opened, and their articles become a part of the warehouse inventory. All boxes received from primary market stores are processed.
4. The RL network consists of two or more outlets.
5. Traditional warehousing costs are the same for every box.
6. Cross-docking costs are the same for every box.

7. Traditional warehousing costs are higher than cross-docking costs.
8. Return costs are identical for every article.

Table 3 describes the model notation.

Table 3. Model notation.

Model Indexes	
a	index for articles a = {1..A}
j	index for outlets j = {1..J}
i	index for boxes i = {1..I}
Model Parameters	
p	Probability of those articles being returned from the outlets to the ReDC that were previously sent in excess to the outlets; *p* can be calculated from historical records.
TWC_i	Traditional warehousing costs for box *i*.
CDC_i	Cross-docking costs for box *i*. Costs of primary market stores to collect and send information about product returns to the ReDC are considered part of the cross-docking costs for box *i*.
RC_a	Return costs for article *a*.
C_{ai}	Number of units of article *a* that are stored in box *i*.
O_{aj}	Number of units of article *a* that are ordered by outlet *j*.
TP	Tolerance percentage that any box is allowed to have to be considered for cross-docking.
Model Variables	
BA_{ij}	Binary variable: 1 if box *i* is assigned to outlet *j;* 0 otherwise.
BT_i	Binary variable: 1 if box *i* is assigned to traditional warehousing; 0 otherwise.
SP_{aij}	Surplus articles: number of articles *a* that belong to box *i*, which were not ordered by outlet *j*.
LP_{aij}	Lacking articles: number of articles that box *i* lacks to fulfill the ideal product assortment of outlet *j*.
$E[\widehat{RP}_{aj}]$	Returned articles estimation: estimated number of units of article *a* returned to the ReDC from an outlet *j*.
GS_{aj}	Global surplus: number of articles *a* sent in excess to outlet *j*.
GL_{aj}	Global lacking: number of articles *a* lacking to fulfill the ideal product assortment of outlet *j*.
$MPij$	Matching percentage of box *i* with respect to the ideal product assortment of outlet *j*. Obtained from formula: $$MP_{ij} = 1 - \left(\frac{\sum_{a=1}^{A} SP_{aij}}{\sum_{a=1}^{A} C_{ai}}\right)\ \forall i, j$$
$\widehat{RP}aj \sim B(GS_{aj}, p)$	Random variable estimating the number of articles *a* that will be returned from outlet *j*. This variable is estimated from a binomial distribution that depends on a) the articles sent in excess to the outlet and b) a probability *p* established by the ReDC. Therefore, the expected number of articles returned corresponds to $E[\widehat{RP}_{aj}] = GS_{aj} \cdot p$.

3.3. Model formulation

The RCDM consists of the objective function (1) and eight constraints (2–9):

$$\boldsymbol{Min\ z} = \sum_{i=1}^{I} BT_i \cdot TWC_i + \sum_{i=1}^{I} \sum_{j=1}^{J} BA_{ij} \cdot CDC_i + \sum_{a=1}^{A} \sum_{j=1}^{J} E[\widehat{RP}_{aj}] \cdot RC_a \qquad (1)$$

$$\left(C_{ai} - O_{aj}\right) = SP_{aij} - LP_{aij} \ \forall a, i, j \qquad (2)$$

$$MP_{ij} = 1 - \left(\frac{\sum_{a=1}^{A} SP_{aij}}{\sum_{a=1}^{A} C_{ai}}\right) \forall i, j \qquad (3)$$

$$BA_{ij} \leq TP + MP_{ij} \ \forall i, j \qquad (4)$$

$$\sum_{j=1}^{J} BA_{ij} + BT_i = 1 \ \forall i \qquad (5)$$

$$\sum_{i=1}^{I} (C_{ai} \cdot BA_{ij}) - O_{aj} = GS_{aj} - GL_{aj} \ \forall \ a, j \qquad (6)$$

$$E[\widehat{RP}_{aj}] = GS_{aj} \cdot p \ \forall \ a, j \qquad (7)$$

$$BA_{ij}, BT_i \in \{0, 1\} \qquad (8)$$

$$SP_{aij}, LP_{aij}, MP_{ij} \ \geq 0 \qquad (9)$$

The objective function (1) minimizes the total costs relevant to the assignment decision. Constraint (2) calculates the amount of the surplus or lack of articles in box *i* in relation to the ideal product assortment of outlet *j*. If SP_{aij} adopts a positive value, there are articles *a* in box *i* that were not ordered by outlet *j*. If LP_{aij} adopts a positive value, then articles *a* ordered by outlet *j* were not available in box *i*. If SP_{aij} adopts a positive value, then LP_{aij} will be zero and vice versa. Equation (3) computes the matching percentage for box *i* and outlet *j*. This constraint considers the number of articles within box *i* not belonging to the ideal product assortment of outlet *j* in relation to the total number of products that box *i* contains. The MP is obtained by subtracting this value from 1. Constraint (4) assures that only boxes that fall below the TP can be assigned for cross-docking to an outlet *j*. If $TP + MP_{ij}$ (for some *i, j*) ≥ 1, then the constraint becomes redundant, as BA_{ij} is a binary variable and BA_{ij} can take any value (0 or 1). On the contrary, if $TP + MP_{ij}$ (for some *i, j*) < 1, then BA_{ij} must be equal to zero. In this case, the box cannot be assigned to the outlet through cross-docking. Equation (5) indicates that a box should be assigned to outlet *j* or be processed through traditional warehousing. Constraint (6) computes the global surplus GS_{aj} or global lack LP_{aj} per article *a* and outlet *j* in comparison with the ideal product assortment O_{aj} per article *a* and outlet *j*. This calculation includes the contents of all boxes assigned to outlet *j*. Equation (7) estimates the articles returned from the outlets to the ReDC. Constraints (8) define BA_{ij} and BT_i as binary variables. Finally, (9) are non-negativity constraints.

4. Numerical example: results and discussion

To evaluate the performance and consistency of the model, as well as to deduce recommendations for managing ReDCs, data for a reverse cross-docking system with 50 articles, 50 outlets, and 100 boxes returned from primary market stores were simulated.

To evaluate the effect of parameter variation on the binary decision variables and the objective function, sensitivity analyses were performed. The five parameters examined were: (1) tolerance percentage (*TP*), (2) traditional warehousing costs (TWC_i), (3) cross-docking costs (CDC_i), (4) return costs (RC_a), and (5) return probability (*p*). These five parameters are influenced by managerial decisions and, consequently, serve the purpose of deducing managerial recommendations for system performance improvements. CPLEX was used to solve the optimization problem. Tables 4 to 8 summarize the results of these sensitivity analyses.

Table 4. Sensitivity analysis for variations of the tolerance percentage.

Sensitivity analysis: ***Tolerance percentage (TP)***					
Articles	50	**Constraints**	770,100		
Outlets	50	**Variables**	517,600		
Boxes	100	**Binary**	5,100		
TP	*n/a*	**Others**	512,500		
p	0.5	**Non-zero coefficients**	1,391,800		
Parameter for sensitivity analysis: TP	**0**	**0.1**	**0.2**	**0.4**	**0.5**
Boxes assigned to traditional warehousing (BT_i)	96	55	25	24	24
Boxes assigned to cross-docking (BA_{ij})	4	45	75	76	76
Mixed-Integer Programming					
Objective ($Cost_{min}$)	96,800	78,800	70,800	70,800	70,800
Nodes	0	26	3,254	2,142	2,142
Iterations	0	733	172,447	170,100	170,100
Solutions Grouping					
Recount	1	7	11	9	9
Mean objective	96,800	81,771	76,009	76,167	76,167
Solution time	2:50 min.	1:38 min.	2:23 min.	2:29 min.	2:44 min.

Table 4 shows the sensitivity analysis when modifying TP. With an increasing TP, the number of boxes assigned to cross-docking increases, and the total system costs decrease. However, there is a point where the costs curve is flattened, as increasing the number of boxes assigned to cross-docking will lead to an increase in return costs. Therefore, the model maintains the assignment. As shown in Table 4, even the introduction of a reverse cross-docking system with a TP value of zero achieves savings, as long as boxes that fit 100% to the ideal product assortment of an outlet will be directly sent through the cross-docking process.

Modifications of the TP can be used by companies as a negotiation component when dealing with secondary market stores. Establishing a lower TP will force the ReDC to send more boxes to traditional warehousing, increasing the costs of processing. To compensate for this negative effect, prices for outlets should be set higher. However, if outlets accept a higher TP, then part of the savings obtained from the reduced processing costs can be transferred to the outlets through the article price (i.e., with a higher discount). This cost reduction can be transferred to the customers, resulting in unwanted articles being offered at lower prices. This is particularly important if outlets do not belong to the same company or have their own profit responsibility. Considering the expectations of the outlets expressed in the ideal product assortment may improve the motivation of the outlets within a centrally managed system.

Table 5. Sensitivity analysis for variations of the return probability.

Sensitivity analysis: ***Return probability (p)***			
Articles	50	**Constraints**	770,100
Outlets	50	**Variables**	517,600
Boxes	100	**Binary**	5,100
TP	0.2	**Others**	512,500

p	*n/a*	**Non-zero coefficients**		1,391,800	
Parameter for sensitivity analysis: p	**0.2**	**0.4**	**0.6**	**0.8**	**1**
Boxes assigned to traditional warehousing (BT_i)	0	11	35	56	72
Boxes assigned to cross-docking (BA_{ij})	100	89	65	44	28
Mixed-Integer Programming					
Objective ($Cost_{min}$)	42,720	63,360	76,560	84,160	88,800
Nodes	16,302	20,306	160	0	0
Iterations	1,061,003	1,043,873	8,099	899	404
Solutions Grouping					
Recount	24	10	14	7	5
Mean objective	46,838	68,536	79,637	87,543	91,400
Solution time	3:18 min.	3:31 min.	3:08 min.	2:55 min.	2:32 min.

Table 5 summarizes the results of the sensitivity analysis for the return probability *p*. The results show that if *p* increases, there will be fewer boxes assigned to cross-docking and the total cost increases because the total return costs increase. On the contrary, if *p* decreases, the RCDM will assign more boxes to cross-docking. In this case, more articles in excess, which are not actually wanted by the outlets, will be sent to them.

Particularly in business relationships between the ReDC and external outlets, *p* can be used as a negotiation parameter and can become a controlled parameter. If external outlets buy articles without the right to return them (i.e., $p = 0$), then the RCDM will assign boxes with a lower level of matching to these outlets. The corresponding savings in the ReDC can be shared with the external outlets by offering the products at lower prices. The value of *p* in such arrangements can vary between zero and one.

Table 6. Sensitivity analysis for variations of the traditional warehousing costs.

Sensitivity analysis: *Traditional warehousing costs (TWC)*					
Articles	50	**Constraints**		770,100	
Outlets	50	**Variables**		517,600	
Boxes	100	**Binary**		5,100	
TP	0.2	**Others**		512,500	
p	0.5	**Non-zero coefficients**		1,391,800	
Parameter for sensitivity analysis: TWC	**-50%**	**-25%**	**0%**	**+25%**	**+50%**
Boxes assigned to traditional warehousing (BT_i)	83	48	25	10	4
Boxes assigned to cross-docking (BA_{ij})	17	52	75	90	96
Mixed-Integer Programming					
Objective ($Cost_{min}$)	47,000	62,500	70,800	74,700	76,300
Nodes	0	0	3,254	27,370	254,046
Iterations	175	1,300	172,447	1,485,315	17,125,948
Solutions Grouping					
Recount	3	6	11	12	15

Mean objective	48,033	65,308	76,009	80,779	84,733
Solution time	5:23 min.	3:18 min.	3:32 min.	3:48 min.	10:47 min.

Table 6 shows the sensitivity analysis of TWC. With increasing TWC, more boxes tend to be assigned to cross-docking. On the contrary, if TWC decreases, then more boxes are assigned to the traditional warehousing process. The total costs of the system vary depending on the compensation effect between the increase of total TWC and the modified assignment of boxes in favor of cross-docking, which increases the total CDC+RC. In the underlying parameter constellation, the total costs increase. In sectors with high traditional warehousing costs, the implementation of reverse cross-docking can be a suitable alternative.

Table 7. Sensitivity analysis for variations of the cross-docking costs.

Sensitivity analysis: ***Cross-docking costs (CDC)***					
Articles	50	**Constraints**		770,100	
Outlets	50	**Variables**		517,600	
Boxes	100	**Binary**		5,100	
TP	0.2	**Others**		512,500	
p	0.5	**Non-zero coefficients**		1,391,800	
Parameter for sensitivity analysis: CDC	**-50%**	**-25%**	**0%**	**+25%**	**+50%**
Boxes assigned to traditional warehousing (BT_j)	17	20	25	25	32
Boxes assigned to cross-docking (BA_{ij})	83	80	75	75	68
Mixed-Integer Programming					
Objective ($Cost_{min}$)	62,900	66,900	70,800	74,550	78,300
Nodes	24,840	7,340	3,254	322	146
Iterations	1,352,955	379,229	172,447	22,878	6,974
Solutions Grouping					
Recount	12	11	11	9	6
Mean objective	67,250	71,418	76,009	78,833	83,367
Solution time	2:49 min	3:09 min	3:32 min	2:49 min	3:24 min

Table 7 evaluates the impact of CDC variations on the decision variables. If the CDC increases, the model will assign more boxes to traditional warehousing. It is the opposite effect in comparison with the variation of TWC because the costs resulting from the cross-docking assignment are represented by CDC+RC. Here, the compensation effect between the increase of total CDC+RC and the modified assignment of boxes in favor of traditional warehousing leads to a total costs increase.

Table 8. Sensitivity analysis for variations of the return costs.

Sensitivity analysis: ***Return costs (RC)***			
Articles	50	**Constraints**	770,100
Outlets	50	**Variables**	517,600
Boxes	100	**Binary**	5,100
TP	0.2	**Others**	512,500
p	0.5	**Non-zero coefficients**	1,391,800

Parameter for sensitivity analysis: RC	-50%	-25%	0%	+25%	+50%
Boxes assigned to traditional warehousing (BT_i)	1	10	25	35	48
Boxes assigned to cross-docking (BA_{ij})	99	90	75	65	52
Mixed-Integer Programming					
Objective ($Cost_{min}$)	48,300	61,150	70,800	77,750	82,550
Nodes	23,954	28,027	3,254	55	7
Iterations	1,459,715	1,348,861	172,447	4,086	1,371
Solutions Grouping					
Recount	13	19	11	8	7
Mean objective	54,554	64,399	76,009	82,806	86,014
Solution time	3:41 min.	5:27 min.	3:32 min.	2:34 min.	2:26 min.

Table 8 summarizes the sensitivity analysis for the variations of RC. With increasing RC, fewer boxes will be assigned to cross-docking. As in the case of variations in CDC, the new assignment of boxes in favor of traditional warehousing leads to an increase of total costs. The behavior of the decision variables regarding changes of RC is also similar to the variations of p, resulting in a managerial option to compensate for high values of p with low values of RC. Therefore, a systematic reduction of RC through business process improvements will lead to more flexibility when dealing with high values of p.

The sensitivity analyses a) show that the model helps to reduce costs in RL networks through flexibility in the assignment of boxes to cross-docking or to traditional warehousing and b) help to deduce managerial implications under diverse parameter conditions. The analyses furthermore show that a reverse cross-docking strategy is suitable to be used in return environments with a) high values of TP, b) low values of p, or c) a low sum of CDC+RC in comparison with TWC.

Reverse cross-docking systems improve information management in comparison with traditional RL systems due to the integration of TP and ideal product assortment, with both aspects integrated into the RCDM. The proposed reverse cross-docking system, in combination with the RCDM, leverages the performance of ReDCs to become potential contributors to the competitiveness of organizations.

5. Model extension: consideration of heterogeneous article prices

In comparison with products ordered by an outlet, a product in excess is considered as having a higher risk to be returned from an outlet to the ReDC. Such a return leads to higher RC_a, including lost sales.

The basic RCDM described in Section 3 only considers the quantity of SP_{aij} sent in excess to the outlet stores to determine the MP. This is justified when companies assign homogenous prices to unsold articles returned from the direct stores. The logic behind such a practice is that outlet sales represent an additional contribution to company profits, reducing sunk costs. Some retail companies in the apparel industry owning direct stores and outlet stores apply this practice.

With heterogeneous article prices, lost sales for the system vary not only due to the quantity of the articles in excess, as in the basic model, but also due to their prices and consequently, their values. The model should reduce this “value at risk” by assigning high-price articles to outlets that ordered them. Consequently, the option of sending a box with a high product value in excess to traditional warehousing becomes more likely, and the assignment of boxes to outlets may change in comparison with the basic model. The type of risk considered in the model shifts from "quantity at risk" to "value at risk" (see Table 9).

To incorporate this effect into the model, the former quantity-based MP is transformed into a value matching percentage (VMP_{ij}), as determined by the following formula:

$$\boldsymbol{VMP_{ij} = 1 -} \left(\frac{\sum_{a=1}^{A} \boldsymbol{SP_{aij}} * \pi_a}{\sum_{a=1}^{A} \boldsymbol{C_{ai}} * \pi_a} \right) \forall \boldsymbol{i, j}$$

where parameter Π_a represents the price for article *a*.

For every pair of box *i* and outlet *j*, the VMP_{ij} computes the value of the articles sent in excess to the outlet stores as a proportion of the total value of the articles within the box. In case the value of the articles in excess in relation to the total value of the box is high, the VMP_{ij} gets a smaller value and the model tends to send a box to traditional warehousing, as the risk of not selling those excess articles and returning them to the ReDC will increase. In the opposite case, the box tends to be assigned to cross-docking.

In addition to this main effect, the introduction of heterogeneous prices affects the model in Constraints (3) and (4). As in the basic RCDM, the *TP* indicates a company's accepted risk level to receive unsold products from the outlets. With VMP_{ij} replacing MP_{ij}, an assignment to cross-docking requires $VMP_{ij} \geq 1\text{-}TP$ (see Constraints (3) and (4) in Section 3.3).

In comparison with the basic model, the introduction of heterogeneous prices may lead to different assignment decisions resulting from different values of VMP_{ij} in comparison with MP_{ij} (see Fig. 3):

1. For a box *i* without articles *a* in excess, both the MP_{ij} and VMP_{ij} will be 100%. All articles will be assigned to cross-docking.
2. In the case of homogeneous prices for articles *a* (i.e. $\Pi_a = \Pi_{a+1} = \ldots = \Pi_n$), $VMP_{ij} \cong MP_{ij}$. This case corresponds to the basic model.
3. With articles in excess and heterogeneous article prices, prices weigh these quantities. Consequently, VMP_{ij} will differ from MP_{ij}, depending on the value of the articles in excess in relation to the total box value. In comparison with the case of homogeneous prices (2), the assignment of boxes will change.
   Comparing different cases of heterogeneous prices, the number of boxes assigned to traditional warehousing will increase with increasing prices of articles in excess. In this situation, VMP_{ij} will tend to be lower than MP_{ij} (3a). On the contrary, a low value of the articles in excess leads to a VMP_{ij} that is higher than MP_{ij}. Subsequently, more boxes will be assigned to cross-docking (3b).

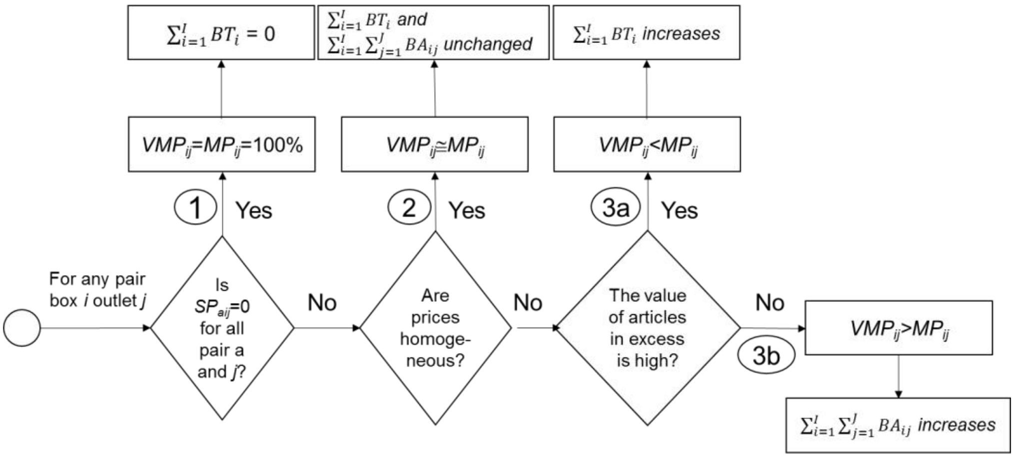

Fig. 3. Comparison of VMP and MP, and its impact on box assignment.

Providing a numerical example using the same database as in Section 4, Table 9 shows a sensitivity analysis when heterogeneous article prices are introduced.

Table 9. Sensitivity analysis for variations of article prices.

	Sensitivity analysis: ***Price (Π_a)***			
Articles	50		**Constraints**	770,100
Outlets	50		**Variables**	517,600
Boxes	100		**Binary**	5,100
TP	0.1		**Others**	512,500
p	0.5		**Non-zero coefficients**	1,391,800
	Homogeneous prices		**Heterogeneous prices**	
Case	**MP_{ij}**	**$VMP_{ij}\cong MP_{ij}$ (2)**	**$VMP_{ij}<MP_{ij}$ (3a)**	**$VMP_{ij}>MP_{ij}$ (3b)**
Average **article prices π_a**	**n/a**	**10**	**19.80**	**11.18**
Boxes assigned to traditional warehousing (BT_i)	55	55	46	29
Boxes assigned to cross-docking (BA_{ij})	45	45	54	71
Average **Value Matching Percentage (*VMP_{ij}*) of boxes assigned to cross-docking**	0.9265	0.9265	0.9325	0.9500
Mixed-Integer Programming				
Objective ($Cost_{min}$)	76,550	76,550	75,000	70,750
Nodes	32	32	12	214
Iterations	664	664	651	10,250
Solutions Grouping				
Recount	6	6	4	13

Mean objective	80,633	80,633	80,8	75,023
Solution time	2:32 min	2:35 min	2:25 min	2:18 min

The three relevant cases concerning articles in excess introduced in Fig. 3 are shown in the sensitivity analysis of Table 9. Case 2 demonstrates that the initial box assignment will not change as long as prices are homogeneous. Comparing Cases 3a and 3b of heterogeneous prices, the number of boxes assigned to traditional warehousing increases with an increasing average article price π_a. These results show that companies prefer to send high-price articles through traditional warehouse operations to outlets that have ordered them because having ordered an article indicates a higher probability of selling it. Furthermore, these results stress the usefulness of reverse cross-docking, particularly in industries with low price levels.

6. Conclusions

This paper integrated cross-docking and RL into a reverse cross-docking system and presented a linear programming model to optimize the total costs relevant for the assignment decision. To apply cross-docking in the context of RL, this paper proposed three managerial practices based on the improvement of information in returns processes. First, outlets send demand information, as represented by the ideal product assortment to the ReDC. Second, supply information about products and their quantities returned from primary market stores is sent to the ReDC. Third, at the ReDC, boxes are assigned, taking into account the matching percentage between demand and supply. To reduce total system costs, the model optimizes the assignment of boxes to outlets applying cross-docking or to traditional warehousing. The model is particularly suitable to manage the returns of unsold products in industries with seasonal demand patterns and existing outlets as part of a secondary channel.

Findings indicate that reverse cross-docking systems can increase the efficiency of RL in terms of cost reduction, time savings, and improvements of information flows. Focusing on cost minimization, the model-based sensitivity analyses confirm that a reverse cross-docking system leads to total cost reductions, mainly in situations where a) outlets have a high degree of tolerance related to products and quantities received, b) the probability of returns from the secondary market is low, or c) the sum of the return and cross-docking costs is low compared to the traditional warehousing costs.

A model extension, including heterogeneous article prices, transformed the quantity-based MP into a VMP. Therefore, managerial decisions consider the “value at risk” when deciding on traditional warehousing or cross-docking. Through the TP, managers determine the proportion of the value they are willing to risk when sending articles to an outlet that did not order them. If this value is high, the model tends to recommend the assignment of boxes to traditional warehousing. To minimize costs, cross-docking becomes a suitable alternative, particularly when article prices are low.

This paper contributes to the literature by integrating cross-docking with RL and developing the concept of reverse cross-docking. Adding a new option for product flow and several new information flows to the traditional structure of RL networks allows for the idea of reverse cross-docking to open a new field for research, addressing mainly efficiency aspects in returns processes by combining mathematical modeling with managerial practices. Furthermore, the paper provides managers insights into a modified method of managing returns in their companies (e.g., managing returns at the box level).

The results of this paper are promising because they show that reverse cross-docking can be a new way to improve RL network performances in terms of cost savings and time reductions, which might ultimately increase competitiveness. Nevertheless, some limitations are present, particularly the lack of real data to evaluate system performance. In addition, it is necessary to explore sample sizes that are closer to real-life problems. To do so, it would be necessary to create a heuristic procedure to obtain results in reasonable computing times.

Future research should focus on model extensions related to, for example, return probabilities, objective functions, and box sizes. Return probabilities of products sent from the outlets back to the ReDC can be further specified by considering additional determinants, such as critical mass of products necessary to initiate return processes or direct disposal. Other objectives to be included could be a) maximizing the matching of box assignments with ideal product assortments or b) profit maximization, taking into account different product prices for both primary and different secondary channels. A probable impact on optimization results may also be generated by varying box sizes. For example, a reduction of box sizes can increase the matching between boxes and the ideal product assortment, leading to more boxes assigned to cross-docking, or different box sizes might influence transportation costs and environmental impact. With regard to the latter, future research should include considerations about packaging, transportation emissions, and fuel consumption to demonstrate that the value of reverse cross-docking may extend beyond the efficiency aspects.

7. References

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The paper demonstrates an integration of cross-docking and reverse logistics.
New ways of managing product and information flows in reverse logistics are shown.
A linear programming model optimizes the relevant system costs.
Reverse cross-docking helps companies to improve competitiveness.