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The Impact of Product Recovery on Logistics Network Design

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Abstract

Reverse logistics is a quickly growing trend. Driven by environmentally conscious customers, regulation, and economical benefits companies are taking back used products to recover added value and materials. Efficient implementation requires setting up an appropriate logistics structure for the arising flows of used and recovered products. In this paper we consider logistics network design in a reverse logistics context. We present a generic facility location model and discuss differences with traditional logistics settings. Moreover, we use our model to analyse the impact of product return flows on logistics networks. We show that the influence of product recovery is very much context dependent. While product recovery may efficiently be integrated in existing logistics structures in many cases, other examples require a more comprehensive approach redesigning a company's logistics network in an integral way.

1 Introduction

Recovery of used products and materials has become a field of rapidly growing importance. While reuse as such is not a new phenomenon and examples such as metal scrap brokers and glass recycling have been around for a long time both scope and scale of product recovery have expanded tremendously in the past decade. Recent examples include electronics remanufacturing, recycling of carpet material, and reuse of disposable cameras. Commonly recognized drivers for product recovery are threefold and include legislative, commercial, and economic aspects.

In view of depleting landfill capacity waste reduction has become a major concern in industrial countries. Consequently, environmental regulation is widely being extended. In addition to landfill bans and increasing disposal fees much emphasis is on enhanced producer responsibility. In several countries take–back obligations have been enacted or are underway for products such as cars (The Netherlands, Taiwan), packaging material (Germany), and electronic equipment (EU, Japan). While primarily focused on Europe, this kind of environmental legislation surely has a worldwide impact in view of today's global markets. A second driver for product recovery is due to growing environmental concern among customers. Customers increasingly expect companies to reduce the environmental burden of their activities and products. Therefore, a 'green' image has become an important marketing element. Last but not least, product recovery

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may be attractive from an economical perspective. Used products provide cheap resources from which added value and material may be recovered.

Implementation of product recovery requires setting up an appropriate logistics infrastructure for the arising flows of used and recovered products. Physical locations, facilities, and transportation links need to be chosen to convey used products from their former users to a producer and to future markets again. For many traditional 'forward' logistics environments quantitative models are readily available for supporting network design tasks. In particular, a number of standard mixed integer linear programming (MILP) approaches have been developed that are commonly recognized (see, e.g., Mirchandani and Francis [21]). For a reverse logistics context however, a standard set of models has not yet been established. The question arises whether traditional 'forward' approaches can easily be extended to cover product recovery and whether such an extension significantly changes the resulting network structure. In other words: How robust are traditional logistics networks when it comes to addressing product recovery activities? This is the question we are addressing in this paper. We consider the robustness issue on two levels, namely (i) a methodological level, concerning the appropriateness of standard network design tools in a product recovery context, and (ii) a topological level, analyzing the impact of product recovery on the physical network structure. We discuss both aspects in more detail below. As a basis for our analysis, we refer to a recent survey [11] comparing nine case studies on recovery networks in different industries, including carpet recycling [3, 20], electronics remanufacturing [7, 15, 18, 24], reusable packages [19], sand recycling from demolition waste [6], and recycling of by–products from steel production [22]. We briefly summarize each case.

- The design of a large–scale European recycling network for carpet waste is considered in a joint initiative by some chemical companies and the European carpet industry [20]. Recovery opportunities for valuable resources, in particular nylon fibres, and the threat of restrictive environmental regulation are the major drivers for this project. Through the network used carpeting is to be collected, sorted, and pre–processed in regional recovery centres to allow for material recovery. In the USA a similar network is set up by a chemical company [3]. A logistics network is investigated that concerns collection of used carpet from carpet dealerships, processing of collected carpet by separating nylon fluff, other re-usable materials and a remainder to be landfilled, and end-markets for recycled materials. In both studies high volumes are identified as a major critical factor for economical viability.

- The electronics industry is one of the most prominent sectors in product recovery. Many original equipment manufacturers (OEM) start taking back and recovering their products. In this context, several copier manufacturers reconsider their logistics networks [24, 18]. Given an existing 'forward' distribution network, logistics structures for reverse channel functions such as collection, inspection and remanufacturing are investigated. Similar issues arise for computer manufacturers [7]. On the other hand, electronics product recovery may also be attractive for specialized third parties, such as in the example of a US cellular telephone remanufacturer [15]. In this case, a new logistics network is to be set up comprising core collection, remanufacturing, and re-distribution activities.

- Reusable packaging is another important area of product recovery. A logistics service provider in The Netherlands considered a logistics system for reusable plastic containers that are rented out as transportation packaging [19]. To this end, the number and locations of depots for storing empty containers need to be determined.

- In the Netherlands the design of a sand recycling network is considered by a consortium of construction waste processing companies [6]. Since sand from processing demolition waste may be polluted it needs to be inspected and possibly cleaned before being reusable, e.g., for road–construction. To this end, a logistics network comprising cleaning facilities and storage locations is designed.

- In the German steel industry a recycling network for production residues and by–products is discussed on a branch level [22]. The production of one ton of steel gives rise to 0.5 tons of by–products, which need to be recycled in view of extended environmental regulation and increasing disposal costs. Therefore, processing facilities need to be installed allowing by–products to be reintegrated in the steel production process or sold as secondary materials to other industries.

Based on the above cases the following generic characteristics of product recovery networks have been identified (see [11]): (i) coordination requirement of two markets, (ii) supply uncertainty, (iii) dispositioning task. We briefly address each of these elements and take them as a starting point for the *methodological* part of our research question.

First of all, recovery networks form a link between two markets, namely a 'disposer market' where used products are set free by their former users and a 'reuse market' with demand for recovered products. Both markets may coincide, resulting in closed loop goods flows, or be different, forming an 'open loop'. Typical steps during the transition from disposer to reuse market include collection, inspection and separation, re–processing, re–distribution, and disposal. In general, the network includes a convergent part on the collection side, a divergent part on the distribution side, and an intermediate part depending on the specific re-processing steps. This role of recovery networks as an intermediate between two markets gives rise to a co-ordination issue concerning supply and demand. Availability of used products for recovery is much more difficult to control than supply of input resources in a traditional supply chain. Therefore, there may be a considerable mismatch between supply and demand with respect to timing and quantity in a recovery network. Furthermore, availability and quality of used products are, in general, not known beforehand, which makes supply uncertainty a major characteristic of recovery networks. As a direct consequence, separation and inspection become important issues in this context. In general, not all (components of the) collected products can be reused in the same way. Rather, feasibility of recovery options may depend on the condition of the individual product. For example, a used copy machine may be refurbished to be sold on a secondary market if it is in good condition. If it is worn out certain components may still be reused as replacement parts, whereas material recycling may be the only resort for heavily damaged machines. Since the quality of a returned product is, in general, not known beforehand an appropriate disposition – and hence the destination of the product flow – can only be determined after inspection and testing. Moreover, even if technically feasible a recovery option may not be economically attractive. Since total recovery costs depend on transportation and hence on the logistics network structure, designing the recovery network sets important constraints for the economical viability of recovery options. The above characteristics need to be taken into account when formulating a general quantitative model for product recovery networks.

The *topological* aspect of our research question concerns the impact of product recovery on the physical network structure. In many cases, recovery networks are not set up independently 'from scratch' but are intertwined with existing logistics structures. In particular, this is true if products are recovered by the OEM. In this case the question arises whether to integrate collection and recovery with the original 'forward' distribution network or rather to separate both channels. To this end, it is important to know how much product recovery is restricted by the constraints that are implied by existing logistics infrastructure. This question is the more important since many companies have gone through a major redesign phase of their logistics networks recently, notably in Europe. Global logistics structures have replaced national approaches. However, in many cases product recovery has not been taken into account yet. This raises the question whether product recovery will require another fundamental change in logistics structures or whether it can efficiently be integrated in existing ones.

The goal of this paper is to give answers to the above questions and in this way to contribute to a better understanding of the impact of product recovery on logistics networks. We proceed as follows. In the next section we present a generic model for recovery network design and discuss its applicability in different contexts. In Section 3 we illustrate our model by means of two examples. We show that the impact of product recovery on the logistics network structure is very much context dependent. In Section 4 we provide a more rigorous sensitivity analysis and discuss which factors determine the robustness of logistics networks with respect to product recovery. Moreover, we link our results back to the initial set of case studies. Finally, we point out possible extensions of our model in Section 5 and summarize our findings in Section 6.

2 A Generic Recovery Network Model

In this section we propose a general quantitative model for product recovery network design. Our model is based on the recovery network properties discussed in the introduction and on models developed for the individual case studies we referred to. These models are quite similar to each other, most of them being MILP models akin to classical warehouse location models (WLM). We formulate a generic model, capturing the commonalities of the above approaches. To this end, we start from a traditional WLM and incorporate the specific recovery network characteristics discussed above.

First of all, we need to specify the number of facility levels considered. As discussed above, recovery networks form a link between two markets, which thus define the network boundaries. We consider three intermediate levels of facilities, namely disassembly centres where the inspection and separation function is carried out, factories for the re–processing and possibly new production, and distribution warehouses. Moreover, we consider two dispositions for the collected goods, namely recovery and disposal, where recovery is only feasible for a certain fraction of the collected goods. The general structure of this network is displayed in Figure 1.

Include Figure 1

It is easy to translate this structure into a MILP facility location model. We use the following notation.

Index sets

$I \quad = \quad \{1, ..., N_p\}$ potential plant locations
$I_0 \quad = \quad I \cup \{0\}$, where 0 denotes the disposal option
$J \quad = \quad \{1, ..., N_w\}$ potential warehouse locations
$K \quad = \quad \{1, ..., N_c\}$ fixed customer locations
$L \quad = \quad \{1, ..., N_r\}$ potential disassembly locations

Variables

$X^f_{ijk} \quad = \quad$ forward flow: fraction of demand of customer k to be served from plant i and

		warehouse j; $i \in I, j \in J, k \in K$
X^r_{kli}	=	reverse flow: fraction of returns from customer k to be returned via disassembly centre l to plant i; $k \in K, l \in L, i \in I_0$
U_k	=	fraction of unsatisfied demand of customer k; $k \in K$
W_k	=	fraction of uncollected returns of customer k; $k \in K$
Y^p_i	=	indicator opening plant i; $i \in I$
Y^w_j	=	indicator opening warehouse j; $j \in J$
Y^r_l	=	indicator opening disassembly centre l; $l \in L$

Costs

c^f_{ijk}	=	unit variable cost of serving demand of customer k from plant i and warehouse j, including transportation, production, and handling cost; $i \in I, j \in J, k \in K$
c^r_{kli}	=	unit variable cost of returns from customer k via disassembly centre l to plant i; including transportation and handling cost minus production cost savings at plant i; $k \in K, l \in L, i \in I$
c^r_{kl0}	=	unit variable cost of disposing returns from customer k via disassembly centre l, including collection, transportation, handling, and disposal cost; $k \in K, l \in L$
c^u_k	=	unit penalty cost for not serving demand of customer k; $k \in K$
c^w_k	=	unit penalty cost for not collecting returns of customer k; $k \in K$
f^p_i	=	fixed cost for opening plant i; $i \in I$
f^w_j	=	fixed cost for opening warehouse j; $j \in J$
f^r_l	=	fixed cost for opening disassembly centre l; $l \in L$

Parameters

d_k	=	demand of customer k; $k \in K$
r_k	=	returns from customer k; $k \in K$
γ	=	minimum disposal fraction

We then formulate the general recovery network design model (RNM) as follows.

$$\begin{aligned}\min \quad & \sum_{i \in I} f^p_i \, Y^p_i + \sum_{j \in J} f^w_j \, Y^w_j + \sum_{l \in L} f^r_l \, Y^r_l \\ + \quad & \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} c^f_{ijk} \, d_k \, X^f_{ijk} + \sum_{k \in K} \sum_{l \in L} \sum_{i \in I_0} c^r_{kli} \, r_k \, X^r_{kli} \\ + \quad & \sum_{k \in K} c^u_k \, d_k \, U_k + \sum_{k \in K} c^w_k \, r_k \, W_k\end{aligned}$$

subject to

$$\sum_{i \in I} \sum_{j \in J} X^f_{ijk} + U_k = 1 \qquad \forall k \in K \qquad (1)$$

$$\sum_{l \in L} \Big(\sum_{i \in I} X^r_{kli} + \boldsymbol{X^r_{kl0}} \Big) + W_k = 1 \qquad \forall k \in K \qquad (2)$$

$$\boldsymbol{\sum_{k \in K} \sum_{l \in L} r_k X^r_{kli} \leq \sum_{j \in J} \sum_{k \in K} d_k X^f_{ijk}} \qquad \boldsymbol{\forall i \in I} \qquad (3)$$

$$\gamma \boldsymbol{\sum_{i \in I_0} X^r_{kli} \leq X^r_{kl0}} \qquad \boldsymbol{\forall k \in K, l \in L} \qquad (4)$$

$$\sum_{j \in J} X^f_{ijk} \leq Y^p_i \qquad \forall i \in I, k \in K \qquad (5)$$

$$\sum_{i \in I} X^f_{ijk} \leq Y^w_j \qquad \forall j \in J, k \in K \qquad (6)$$

$$\sum_{i \in I_0} X^r_{kli} \leq Y^r_l \qquad \forall k \in K, l \in L \qquad (7)$$

$$Y^p_i, Y^w_j, Y^r_l \in \{0,1\} \qquad \forall i \in I, j \in J, l \in L \qquad (8)$$

$$0 \leq X^f_{ijk}, X^r_{kli}, U_k, W_k \leq 1 \qquad \forall i \in I, j \in J, k \in K \qquad (9)$$

In this formulation, equations (1) and (2) are logical constraints ensuring that all customer demand and returns are taken into account. Inequality (3) requires total outgoing flows to be at least as big as total incoming flows for each plant (the gap representing the quantity of new items produced). Inequality (4) enforces a minimum disposal fraction for each return flow to comply with technical (in-)feasibility of reuse. Finally, inequalities (5) through (7) are the usual facility opening conditions.

We have marked in boldface the elements that distinguish the above model from a traditional 'forward' facility location model. First of all, constraints (3) reflect the coordination issue concerning supply and demand from the disposer market and reuse market, respectively. While expressing a standard flow conservation condition the particularity of these constraints is the dependence on two sets of exogenous parameters that need to be balanced. Furthermore, variables X_{kl0} together with constraints (4) represent the additional degree of freedom concerning the dispositioning issue. Note that there is no demand corresponding to the flow $\sum_l \sum_k r_k X_{kl0}$.

The formulation is very general and can reflect many different recovery situations as encountered in the above cases. In particular, different market structures can be taken into account. First of all, both closed–loop structures (as, e.g., in [7, 24]) and open loop structures (as in [20, 22]) can be modelled by selecting the parameters d_k and r_k accordingly. If $d_k * r_k > 0$ then customer k belongs to both the disposer and the reuse market. In contrast, $d_k * r_k = 0$ indicates a distinction between both markets. Furthermore, both push and pull driven collection can be expressed. Large penalty costs c^w_k result in small values of W_k and hence by (2) in a collection obligation as, e.g., in [6, 22]. In contrast, a purely economically driven collection decision (as, e.g., in [3, 15]) is captured by setting $c^w_k = 0$ for all k. Similarly, through the value of c^u_k both a push approach to the end market for recovered products (as in [3, 22]) and a demand pull (as in [19, 24]) can be modelled. Finally, a regular production source in addition to product recovery can be included (see [7, 24]) or suppressed (see [3, 6]), which results in small or large values, respectively, of c^f_{ijk} relative to c^r_{kli} and c^u_k. Furthermore, it should be noted that the 'disassembly centres' may refer to any form of inspection and separation installations rather than being restricted to mechanical disassembly in a strict sense. What is essential is that feasibility of recovery options for the individual products is determined at this stage. Similarly, 'disposal' may include any form of recovery that is outsourced to a third party, e.g., material recycling. We only require this flow to leave the network at the disassembly centres.

In spite of this flexibility, it is worth noting that there are a number of additional aspects that are not taken into account in the above model. In particular, uncertainty which we named as a major characteristic of product recovery is not modelled explicitly. We address this issue in detail in Section 4 where we analyze the impact of (supply) uncertainty on the network design. Another aspect that is not included in the above formulation is the dynamic aspect of gradually developing and extending a recovery network. We return to this point in Section 4. Finally, additional details could be included, such as capacity restrictions or alternative recovery options.

We discuss these and other possible extensions in Section 5. At this point, we keep the model as simple as possible to focus on essential characteristics and to avoid a parameter overload.

3 Examples

In this section we illustrate our model by means of two examples concerning copier remanufacturing and paper recycling, respectively. In particular, we pay attention to the different impact of the goods return flow in both cases. The examples are inspired by real–life industrial cases and parameters are chosen in a realistic order of magnitude. However, we do not pretend to model any specific company's business situation.

3.1 Example 1: Copier Remanufacturing

Our first example follows in broad terms the direction of several case studies on copier remanufacturing (see, e.g., [23, 5]). Major manufacturers such as Xerox, Canon, and Océ are remanufacturing and reselling used copy machines collected from their customers. To be considered for remanufacturing a used machine must meet certain quality standards, which are checked during an initial inspection at a collection site. Remanufacturing is often carried out in the original manufacturing plants using the same equipment. Machines that cannot be reused as a whole may still provide a source for reusable spare parts. The remainder is typically sent to an external party for material recycling. In this example, we focus on the remanufacturing and recycling/disposal options. As mentioned before, our model may be extended to include additional recovery options such as spare parts dismantling. However, this extension does not change the essence of our analysis.

We consider the design of a logistics network for copier remanufacturing in a European context. To this end, we assume that a copier manufacturer serves retailers in 50 major European cities (capitals plus cities with more than 500,000 inhabitants). Customer demand at each retailer is assumed to be proportional to the number of inhabitants of the corresponding service region. In a first step, we consider a 'traditional' situation without product recovery. In this case, we need to determine a standard 'forward' production–distribution network, i.e. determine locations for plants and distribution warehouses and allocate the resulting goods flows. We restrict the possible plant locations to the 20 capitals, whereas warehouses may be located in any of the 50 cities considered. Moreover, for the sake of simplicity we assume that all relevant costs are location independent. Table 1 summarizes the parameter settings for this example (ignoring the return flow parameters for the time being.)

Include Table 1

For this example the RNM formulation reduces to a standard 2–level warehouse location problem involving 70 binary variables, 50050 continuous variables, and 3550 constraints. We solve this problem with a standard MILP–solver of CPLEX 6.0 based on LP–relaxation. Solution time on an IBM RS6000 is in the order of one minute. The bold lines in Figure 2 show the resulting optimal forward network, consisting of one central manufacturing plant in Frankfurt and five regional warehouses in Frankfurt, London, Barcelona, Milano, and Belgrade. (For the sake of clarity we have omitted the flows to and from the customers. Each customer is assigned to the closest warehouse.) Total costs for this solution amount to k€ 44,314.

Include Figure 2

Let us now assume that product recovery is introduced as an additional activity, which has to be integrated into the existing forward network. Suppose that the return volume of used products amounts to 60% of the sales for each retailer. Moreover, due to environmental regulation and service considerations all returned products have to be collected. After inspection 50% of the returned products turn out to be remanufacturable while the remainder has to be sent to an external material recycler. To design the return network, locations for the inspection/disassembly centres and allocations of the return goods flows need to be determined. (Note that this includes a dispositioning decision for the remanufacturable machines, which may but do not have to be reused.) We assume that inspection centres can be located in any of the 50 cities. Other parameters are again summarized in Table 1. The design of the return network for fixed forward locations results in a MILP problem with 50 binary and 5350 continuous variables and 5401 constraints, which we solve again with standard CPLEX routines. The dotted lines in Figure 2 show the optimal return network, comprising six regional inspection centres located in Frankfurt, London, Paris, Valencia, Milano, and Budapest. Moreover, it turns out that all machines that are technically acceptable should actually be remanufactured. Total costs (including the forward network) are k€ 45,366. We see that forward and return network are very similar in this example. This may not be surprising since the degree of freedom for the return network design is fairly limited due to the fixed forward structure.

Include Figure 3

To assess the impact of this restriction let us now consider an integral design optimizing both forward and return network simultaneously. We again use the parameters in Table 1. The resulting MILP program now has 120 binary and 102,600 continuous variables and 8,620 constraints. Solving this problem in CPLEX requires about 10 minutes. Figure 3 shows the optimal integrated network for this example. It turns out that the optimal network now decomposes into two parts with manufacturing plants in Paris and Berlin, respectively. Clearly, the structure of this solution differs significantly from the network in Figure 2. Hence, we see that the product return flow can have an impact even on the forward network design. Due to the additional goods flows product recovery is a driver for decentralization in this example. However, considering the cost effects puts this picture in a different perspective: total costs for the integrated solution amount to k€ 45,246, which comes down to savings of less than 1% with respect to the sequential approach. Hence, we conclude for this example that the sequential and the integrated recovery network design approach lead to different solutions but that cost differences are negligible. In other words, the fixed forward network structure does not impose significant restrictions on the design of an efficient return network. Clearly, this is good news for the manufacturer starting to engage into product recovery. We found essentially the same results in many other scenarios for varying input parameters. Before addressing this sensitivity analysis in more detail in Section 4 let us consider a second example.

3.2 Example 2: Paper Recycling

This case is motivated by European paper recycling business. Waste paper comprises about 35% of total household waste volume in Europe. At the same time, increasing demand for pulpwood in paper production puts a heavy burden on forest ecosystems. Therefore, paper recycling has been a major issue for at least twenty years now. As early as in 1975, Glassey and Gupta [14] investigated maximum feasible recycling rates given the state of pulp and paper technology. They propose a simple LP model to determine production, use and recovery of paper. Gabel et al. [12] point out that the level of recycling also has important consequences for national economies by influencing geographical allocation of industrial activities. In this context, Bloemhof et al. [9] studied the impact of mandated recycling quotas on the European paper industry. They show that forcing high levels of recycled content, taken as a measure to reduce Western Europe's solid waste problem, would severely hit Scandinavian industry. In view of the low population in the Nordic countries, these major pulp producers would have to import waste paper in order to produce recycled paper. Based on a LP network flow model the authors conclude that it is preferable both from an ecological and economical perspective to produce high quality paper, mainly containing virgin pulp, in Scandinavia while locating paper production with a high content of recycled pulp close to the population centres in Western Europe. Current observations from industry appear to confirm these findings [1].

In this context, we consider the design of a logistics network for a European paper producer. Customers and potential facility locations are the same as in Example 1. However, we now have to take into account an additional cost element, namely raw material transportation. We assume that pulpwood is exclusively supplied from forests in Scandinavia and add its transportation as a location dependent element to the production costs. Moreover, we assume that transporting pulpwood is significantly more expensive than transporting paper. The last column of Table 1 summarizes the parameter settings for this example.

Again, we first consider a pure 'forward' network without collection and recycling. Problem size and solution times are similar to Example 1. The bold lines in Figure 4 show the resulting optimal solution consisting of a central production plant in Stockholm and five regional warehouses in Stockholm, Hamburg, Zaragoza, Milano and Krakow. Total costs for this solution amount to k€ 19,570.

Include Figure 4

We now include recycling of waste paper. For this purpose, pre–processing centres need to be installed where collected paper is sorted and compacted and then transported to a production plant [25]. In our model, processing centres play the same role as disassembly centres in Example 1. We assume that a maximum of 70% of the sales volume is available for collection at each customer. (For comparison note, e.g., that EU directives set minimum targets of recycled paper content for packaging material of 60%.) In line with current policy we assume that there are no take–back obligations for used paper. Hence, collection follows a pull approach. Finally, we assume that 10% of the collection volume is extracted at the pre–processing centres as being non–recyclable. The dotted lines in Figure 4 indicate the optimal collection network in this case. Six regional pre–processing centres are located in Stockholm, London, Paris, Milano, Hannover and Wroclaw. Moreover, collection in southern Europe turns out not to be economically attractive, including the Iberian peninsula, southern Italy, and the Balkan. Total costs of this network (including the fixed forward locations) amount to k€ 17,990.

Include Figure 5

Finally, for this example also we consider an integral design optimizing forward and return network simultaneously. Parameters are again as in Table 1. Figure 5 shows the resulting optimal solution. As in Example 1 the optimal network now decomposes into two parts. A plant in Stockholm now only serves the northern and north-eastern part of Europe, while all other countries are served from a new plant in Brussels. Note that this result is in accordance with what we observe in industry, as discussed at the beginning of this subsection. The collection strategy has also changed when compared to the sequential approach. With exception of Athens and Palermo collection is now beneficial at all locations. As a consequence, the number of pre–processing centres increased to eight. However, what is even more significant is that the total network cost decreased to k€ 14,540, which is about 20% lower than the sequential design. Hence in contrast with Example 1, optimizing the forward and return network simultaneously not only leads to a different solution than a sequential approach in this case, but also results in a significant cost benefit.

4 Parametric Analysis and Network Robustness

In order to understand the differences between the two examples presented in the previous section we analyze the impact of the return flows in our model more systematically. For this purpose, we first place this issue in a formal, mathematical context and reconsider our model from this perspective. Then we derive an explanation for our observation by analysing structural differences between the two exemplary cases and verify our hypotheses in additional numerical experiments. Finally, we apply our findings to the initial set of case studies from literature.

From a mathematical perspective investigating the impact of the return flows on the network design comes down to a parametric analysis of the RNM with respect to the parameters r_k. Therefore, we can make use of the well developed theory of parametric mixed integer linear programming [13]. Considering the MILP formulation introduced in Section 2 we saw that each r_k occurs both in the objective function and in constraint set (3). This is a significant difference with traditional 'forward' uncapacitated facility location models which can be formulated such that (demand) volume parameters occur only in the objective function [21]. In the latter case the objective function is known to be piecewise linear and concave in the volume parameters and is therefore easy to compute on an arbitrary interval [16]. For the recovery network it is the coordination of exogenous supply and demand represented by constraint set (3) that makes things more difficult. It is worth noting that these constraints, which couple the forward and the return network, somewhat resemble a capacity restriction for the recovery activities. In this sense, product return flows introduce a capacity issue into an otherwise uncapacitated network model. It is easy to see that the RNM can be reformulated such that the parameters d_k and r_k occur only in the right-hand side, by considering arc variables $X^f_{ij} := \sum_k d_k X^f_{ijk}$ (and analogously for all other transportation links.) Therefore, the minimum cost function of the RNM is still piecewise linear in r_k for each k. However, it is not necessarily concave. For computation we can use Jenkins' heuristic [16] in this situation.

Figure 6 shows the minimum costs for Examples 1 and 2 as a function of the return rate $\lambda \in [0;1]$ where $r_k = \lambda d_k$ for all k. The solid lines refer to the cost function of the integral design optimizing both forward and return network simultaneously, whereas the dotted lines indicate the costs of the sequential approach. Not surprisingly, both approaches coincide for small return rates. For larger values of λ costs for both approaches differ, indicating that for these cases the return flows change the optimal design of the forward network. However, in the copier example the cost difference is negligible on the entire interval whereas costs for both approaches deviate significantly in the paper recycling example.

Include Figure 6

To explain the different impact of the return flows we consider the cost structures in both examples. First of all, it should be noted that the forward flows will, in general, dominate the optimal network structure since they are more important than return flows in terms of volumes, values, and time-criticality. Therefore, return flows can only be expected to influence the overall network structure significantly in case of a major difference between the cost structures of the forward and return channel. In the electronics example geographical cost drivers are very similar for both channels. Demand and return volumes are distributed along the same geographical patterns and forward and return flows correspond with each other. Therefore, it is not surprising that optimal solutions for the forward and return network are also fairly similar and the impact of the returns on the overall structure is small. In contrast, there is an important difference between the cost elements of the forward and the reverse channel in the paper example. The structure of the forward network is dominated by costly raw material transportation from a fixed source on the boundary of the geographical area considered (i.e. forrest in Scandinavia). In contrast, costs of the return network are independent of this source and are determined by the locations of the major customers (i.e. the population centres in Western and Central Europe). It is due to this difference in 'centres of gravity' that product recovery has a significant impact on the overall network structure in the paper recycling example. By substituting virgin input resources recycling literally 'pulls' the network away from the original source towards the vicinity of the customers.

We have carried out a series of numerical experiments to test our argumentation and conclude that the similarity between supply and demand side both in terms of geographical distribution and cost structure is indeed a major determinant of the impact of product recovery on the overall network structure. We have varied parameters in the copier example over a large range without finding any case with a significant cost difference between the integral and the sequential design approach. This includes relaxing proportionality of returns and demand per customer, i.e., a non–uniform return rate. We have considered different return rates in different parts of Europe motivated, e.g., by regulation or customer attitudes (e.g. high return rates in Northern and Western Europe, intermediate return rates in Southern Europe and low return rates in Eastern Europe.) Still the cost deviation we observed between both design approaches was marginal.

We only found a relevant impact of product recovery on the overall network structure when including a major structural difference between forward and reverse channel as in the paper recycling example. However, even in this case, product returns do not always change the optimal forward network design. The economic incentive for product recovery is another important factor in this context. Lower production cost savings, lower penalty costs for not collecting returned products, and lower disposal costs all result in a smaller impact of the return flow since 'mismatching' returns can then be avoided altogether at low cost (to the producer). Finally, the number and uniformity of potential facility locations also appears to influence the cost deviation between the optimal integrated and sequential network design. Fewer potential locations tend to increase sensitivity.

We conclude that existing forward distribution networks do not form a barrier for setting up an efficient logistics structure for product recovery in many cases. Hence, product recovery can often be implemented efficiently without requiring major changes in existing production–distribution networks. Moreover, from a modelling perspective this means that forward and return networks may be addressed separately, which significantly reduces the problem sizes. Care must be taken if forward and reverse channel differ largely with respect to geographical distribution and cost structure and return volumes are substantial.

Even if return flows do not have a significant impact on the forward network, the return part of the network may still be sensitive to changes in return volumes. In terms of the Figure 6 this refers to the changes in the slope of the minimum cost function. Sensitivity of the return network is an important aspect, e.g., when extending product recovery from a low volume activity to a larger scale. It should be noted that the situation is similar to traditional warehouse location models, for which a fairly robust behaviour with respect to moderate parameter changes and a flat cost function are well known (see, e.g., [10]). In our numerical experiments we have observed a similar behaviour for the RNM. Moderate changes in the system parameters result in small changes of the recovery network design, if any. For larger parameter variations the significance of network changes depends, in particular, on the investment costs for the disassembly centres. Sensitivity tends to increase along with investment costs until only one centre is opened. Other factors that tend to increase return network sensitivity include a decreasing minimum disposal fraction γ and, as for the forward network, a decreasing number of potential locations.

Table 2 summarizes our empirical results and lists the major factors determining the impact of product recovery on the logistics network design. One of the consequences of our observations is that supply uncertainty, which is often mentioned as a major characteristic of product recovery environments appears to have rather limited effect on the network design. Therefore, a traditional deterministic MILP approach seems appropriate for recovery network design in many cases. The dependence of the network structure on the return volumes may be more important for long–term non–stationary considerations, such as the gradual extension of collection and recovery activities, rather than for taking into account stochastic variations. To this end, multi–period versions of the network design models may be worth considering.

Include Table 2

We conclude this section by using our observations to estimate network robustness for the set of case studies we started from (see Section 1). To this end, Table 3 recalls the major characteristics for each case. Figure 7 then places each of these cases in the space of the two sensitivity aspects discussed above. The horizontal and vertical axis refer to sensitivity with respect to return flows of the forward and return network, respectively.

Include Table 3 & Figure 7

We can divide the cases in two major clusters depending on the relation between disposer and reuse market. A first clusters contains cases with a closed loop structure and a close link between forward and reverse channel. The second group refers to cases where disposer market and reuse market are commercially and geographically separated. From our analysis we conclude that product recovery can be expected to be easy to integrate efficiently in existing logistics structures for the examples of the first cluster. This is in line with the real-life solutions we find in the cases. In 4 out of the 5 cases of this cluster the recovery network is built upon a previously existing logistics structure. Further differentiation within the groups is based on the factors discussed above. In contrast, the cases in the second cluster may require an integral network design approach according to our findings. However, since product recovery forms an entirely new business channel in all of these cases rather than supplementing existing 'virgin' production a sequential network design does not seem natural anyway. Hence, the need to consider the entire network simultaneously does not really seem to be a restriction here.

5 Extensions

As pointed out before the RNM is meant as a basic model capturing the major aspects of logistics network design in a product recovery context. The model can be extended in many ways to address more specific situations. In this section we discuss some extensions of the RNM which seem particularly relevant in a product recovery context. From a facility location point of view our model can be characterised as a discrete, static, deterministic, one-product, uncapacitated, fixed-plus-linear multi-echelon cost minimization problem. Analogous to the traditional uncapacitated (or simple) plant location problem, the RNM can be modified into a dynamic, stochastic, multi-product, capacitated, nonlinear cost minimization problem. Moreover, it can include both revenues and costs as objective function and can be used in a multicriteria optimisation context. We do not consider these extensions in detail here since they are well known from other contexts. Instead, we focus on additional elements that appear to be specific of product recovery, namely economics of integration and technology impact. We shortly discuss each issue below and show how to integrate it in the RNM formulation.

Integrating forward and reverse locations
Installing a warehouse and a disassembly centre at the same location may allow for a sharing of fixed assets, such as building infrastructure, power supply, etc. Integration thus may result in lower fixed costs than opening two separate facilities. For the model formulation define:

f_l^s = savings in fixed costs for opening an integrated warehouse-disassembly facility at location $l, l \in J \cap L$ as compared to $f_l^w + f_l^r$.
Y_l^s = indicator opening an integrated warehouse-disassembly facility at location l.

In the RNM add $-f_l^s Y_l^s$ to the objective function and add the following three constraints: $Y_l^s \leq Y_l^w$; $Y_l^s \leq Y_l^r$; $0 \leq Y_l^s \leq 1$. Note that in any optimal solution we have $Y_l^s = \min(Y_l^w; Y_l^r)$ and hence the new decision variable Y_l^s will automatically be integer valued.

Combining forward and reverse transportation
In a similar way, we can model joint distribution and collection. The benefit of combined transportation is clear when a warehouse and a disassembly centre are located together and the same fleet is used for delivery and collection. In the extreme case one may assume that collections have no due dates and can be carried out along with the next delivery visit using the forwarding vehicles at no extra costs. Typically however, even if combined, collection activities do imply additional costs due to the use of additional resources [8]. On the strategic decision level we suggest to model the savings of combined transportation on a given path to be proportional to the minimum of the forward and reverse flow on that path. Therefore we define:

c_{kli}^s = unit variable cost savings for combining transportation on reverse path kli with transportation on forward path ilk.
X_{kli}^s = fraction of total returns of customer k on path kli combined with deliveries on path ilk.

For each path ilk for which potential savings are defined we now add the term $-c_{kli}^s r_k X_{kli}^s$ to the objective function. Moreover, we add the constraints $r_k X_{kli}^s \leq d_k X_{ilk}^f$; $X_{kli}^s \leq X_{kli}^r$; $X_{kli}^s \geq 0$. Analogous to the previous example we have $r_k X_{kli}^s = \min(d_k X_{ilk}^f; r_k X_{kli}^r)$ in any optimal solution. This approach may be further generalized by including savings from combined transportation of any two forward and reverse streams even if facilities and/or customers do not coincide.

Selecting recovery processing technologies
Different technologies may result in different processing costs and different recovery yields. More-

over, applicable technology may be volume dependent. In [4] for example, an automated sorting line for plastics from disassembled electronic goods is compared with manual sorting. Automated sorting turns out to preferable only at high throughput rates. Since our network design involves decisions on the number of disassembly centres and the assigned processing volumes the selection of the best recovery technology and the outcomes of the model may be interdependent. In that case, we should integrate technology selection into the RNM.

To this end, we can follow the approach presented in the Multi-Activity Un-capacitated Facility Location Problem [2]. In addition to fixed costs for opening recovery centres we include technology specific fixed and variable costs associated with implementing and operating a specific technology at a specific recovery centre. For selecting the mix of processing technologies at each site that minimizes total costs define:

c^r_{klim}	=	unit variable cost of returns from customer k via l to i using technology m.
X^r_{klim}	=	fraction of returns from k via l to i using technology m.
f^r_{lm}	=	fixed cost to install processing technology m at disassembly centre l.
Y^r_{lm}	=	indicator installing processing technology m at disassembly centre l.
γ_m	=	minimum disposal fraction of technology m

In the objective function and in constraints (2), (3) and (4) we then substitute c^r_{kli} by c^r_{klim}, X^r_{kli} by $\sum_m X^r_{klim}$, X^r_{kl0} by $\sum_m X^r_{kl0m}$ and γ by γ_m. In (7) we replace X^r_{kli} by X^r_{klim} and Y^r_l by Y^r_{lm}. Moreover, we add the term $\sum_l \sum_m f^r_{lm} Y^r_{lm}$ to the objective function and introduce the following additional sets of constraints: $Y^r_{lm} \leq Y^r_l \;\; \forall\, m, l;$ $\;\; Y^r_{lm} \in \{0;1\} \;\; \forall\, m, l;$ $\;\; 0 \leq X^r_{klim} \leq 1 \;\; \forall\, k, l, i, m$. Finally, we can relax the integrality constraints concerning the variable Y^r_l.

In addition to the above model extensions, it seems worthwhile to take a look at how certain policies may be used to influence parameter values. We discuss three examples.

Value of information concerning quality of returns
Knowing product quality as soon as or even before products are returned by customers can result in a number of advantages. First of all, this allows for better maintenance during use and a better return policy depending on the product's life-cycle, which again may lead to a higher recovery potential (a lower value for γ) and lower recovery costs (lower c^r_{kli}). Second, inferior return products may be disposed of directly (or treated locally) without shipping to a disassembly centre. Again, this results in a lower value of γ in the model. Knowledge on product quality can, for example, be supported by modern information technology including sensor-based data recording devices, electronic data logs and information systems for product recovery [17].

Regional legislative requirements
We define $R = \{1, ..., N_e\}$ regions with different local regulation and let K_e indicate the set of customers in region e. One of the measures in legislative proposals concerns the amount of goods diverted from landfill. A minimum recovery level ρ_e as a percentage of total returns in region e can be incorporated in the RNM by adding the constraint $\sum_l \sum_{k \in K_e} X^r_{kl0} \leq 1 - \rho_e$.

End-of-life management
Enhancing the product recovery strategy may be a measure to change model parameters. Consider the following examples: (1) *product eco–design* could lead to different forward flow costs c^f_{ijk}, lower reverse flow costs c^r_{kli} and a higher or lower recovery potential (lower or higher value of γ, respectively); (2) a *buy-back scenario* where a cash payment is offered to customers for returning end-of-life products may result in higher average costs c^r_{kli} but also in a higher return

rate r_k and, if refunding depends on the product quality, a higher recovery potential (lower value of γ) (compare [17]); (3) *contract redesign* from sales towards lease contracts may lead to both a higher return rate r_k and a higher recovery potential, at the expense of increased forward flow costs c^f_{ijk}.

6 Conclusions

We conclude by summarizing our investigations. First of all, we pointed out that engaging in product recovery requires the set up of an appropriate logistics infrastructure for the arising flows of used and recovered products. This leads to the questions whether traditional MILP approaches from 'forward' logistics environments can easily be extended to include product recovery (methodological issue) and whether there is a significant impact of recovery on the physical network design (topological issue).

We proposed a MILP recovery network design model (RNM) based on generic characteristics of a set of case studies from literature. Essential elements include an inspection and separation stage to determine the feasibility of recovery options for each individual returned product. Other characteristics concern a need for coordination between supply and demand and an additional degree of freedom with respect to returns dispositioning. We have shown our model to be fairly general in that it can reflect different scenarios including closed–loop versus open-loop structures, push versus pull driven collection, and the omission or admission of a regular production source in addition to product recovery.

We have carried out a detailed numerical analysis based on two cases concerning copier remanufacturing and paper recycling. These cases served to illustrate the model and to investigate the impact of different return rates on the network design by means of a parametric analysis. In particular, we addressed the question whether adding a recovery network to an existing forward network (sequential design) entails substantially higher costs than the simultaneous design of forward and reverse network (integral design). We found different results in both cases: while the integral design, in general, resulted in a more decentralised network, cost differences were significant only in the paper recycling example.

Based on an extended numerical analysis we conclude that, in general, forward flows dominate the network design. The impact of return flows increases with the economic incentive for product recovery (namely higher production cost savings, higher penalty costs for refusing collection, and higher disposal costs) and with a decreasing number and uniformity of potential facility locations. Moreover, we only found a significant impact of return flows on the forward network (and hence a cost difference between the integral and sequential design) in case of a major structural difference between forward and reverse channel cost structures together with high return volumes (as in the paper recycling case). This is good news in the sense that product recovery can in many cases be implemented without requiring major changes in existing 'forward' production-distribution networks. Moreover, separate networks can be expected to be much easier to deal with organisationally. A company can create a new, dedicated organisational unit to deal with return flows. Therefore the cost of coordination and restructuring tends to be lower. From a methodological point of view the observed robustness means that forward and return networks can be modelled separately in many cases, which significantly reduces the problem sizes. Finally, our results suggest that supply uncertainty can be expected to have limited effect on the network design and that a deterministic modelling approach appears to be appropriate for recovery network design in most cases. Long-term non-stationary effects as implied by starting up and extending product recovery activities may be an argument for multi-period models, which certainly deserve further attention.

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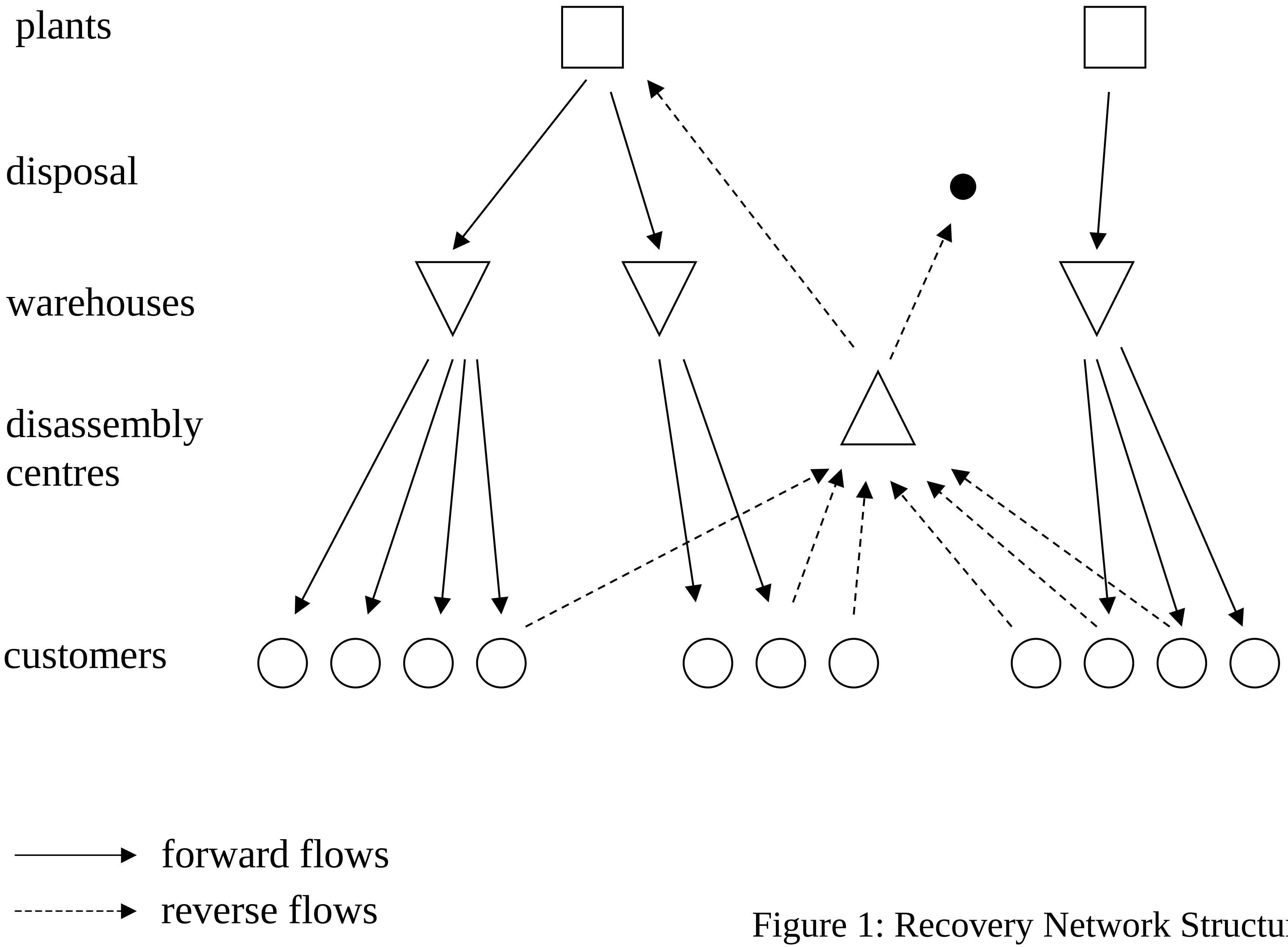

Figure 1: Recovery Network Structure

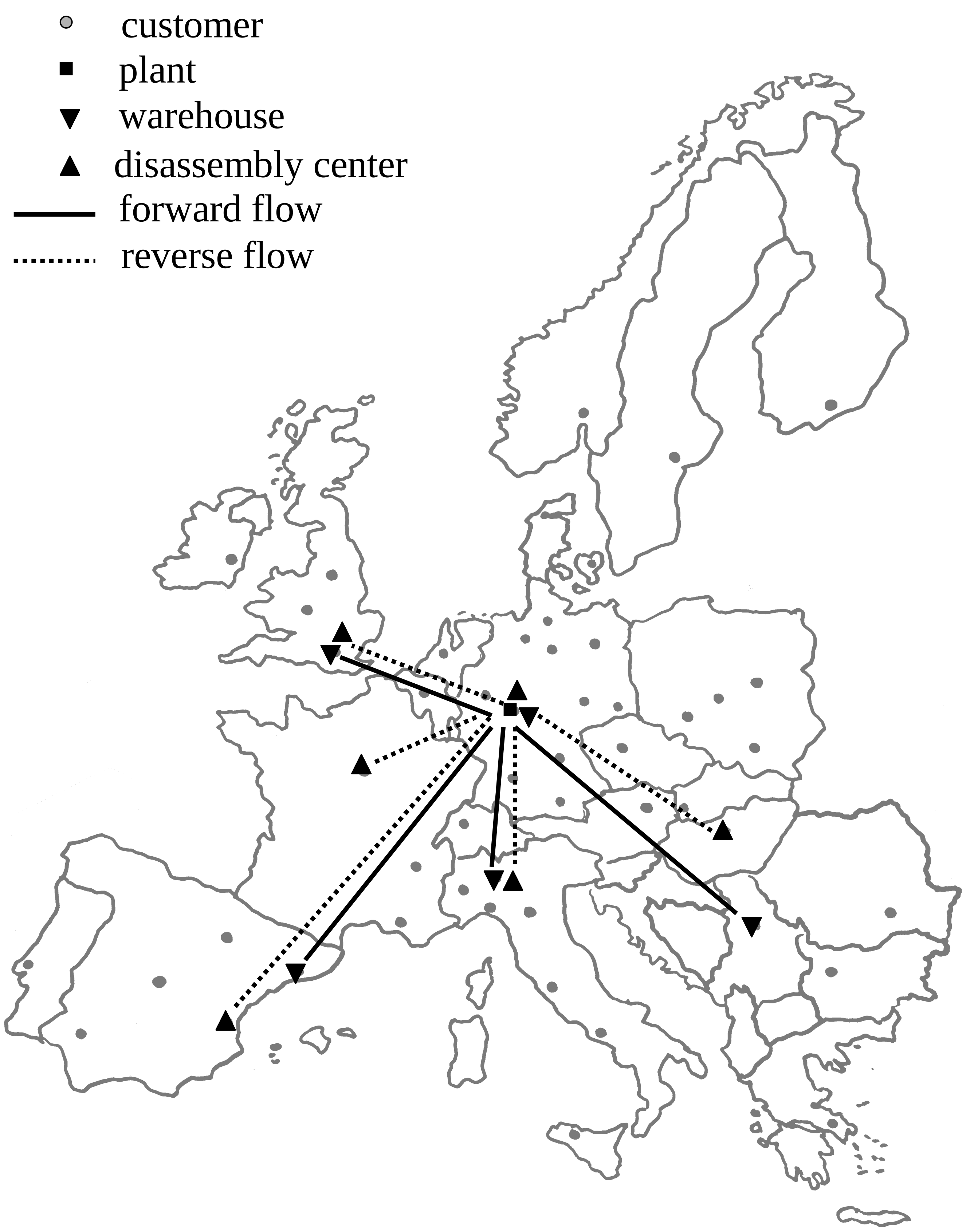

Figure 2: Optimal Sequential Network - Copier Remanufacturing

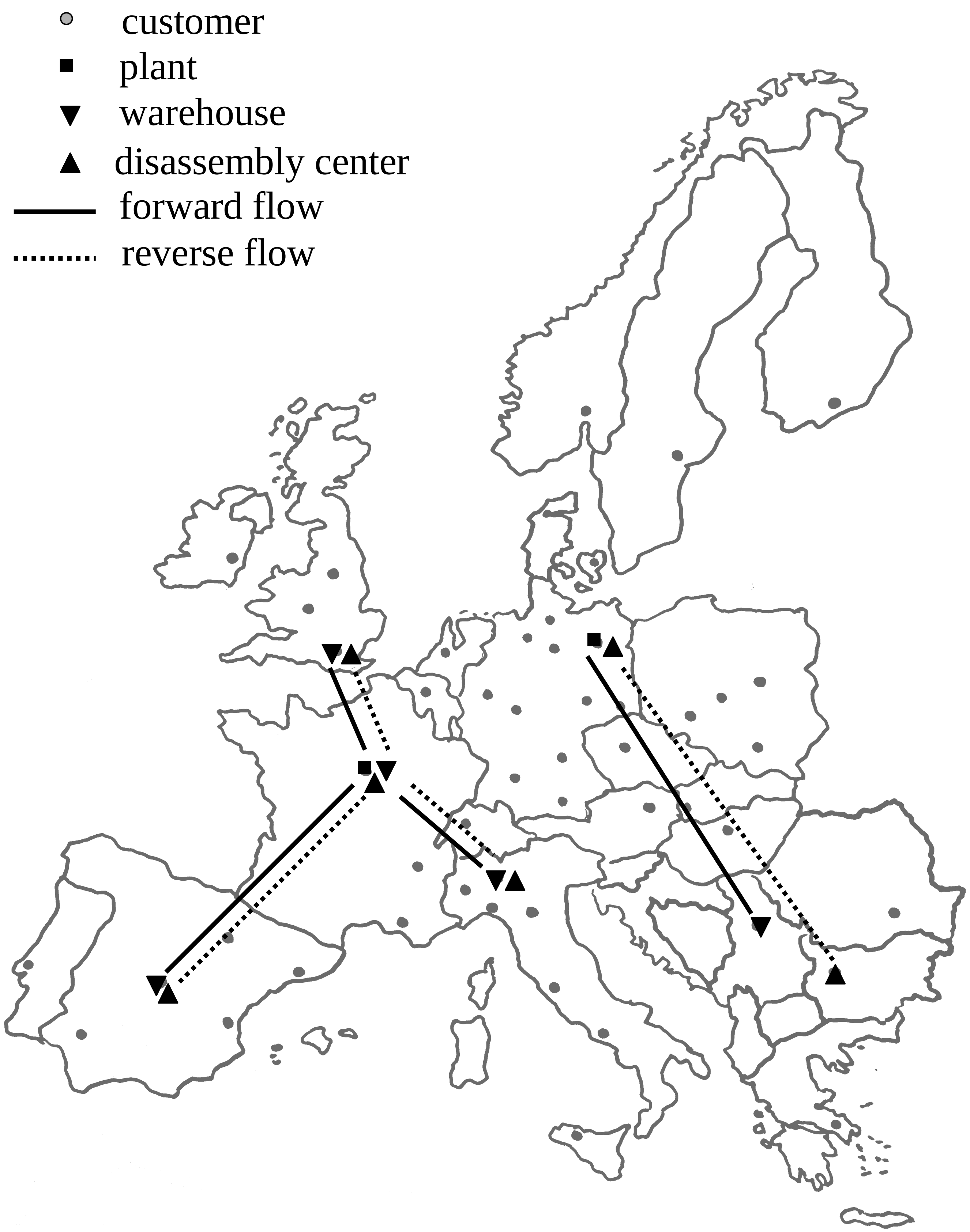

Figure 3: Optimal Integrated Network - Copier Remanufacturing

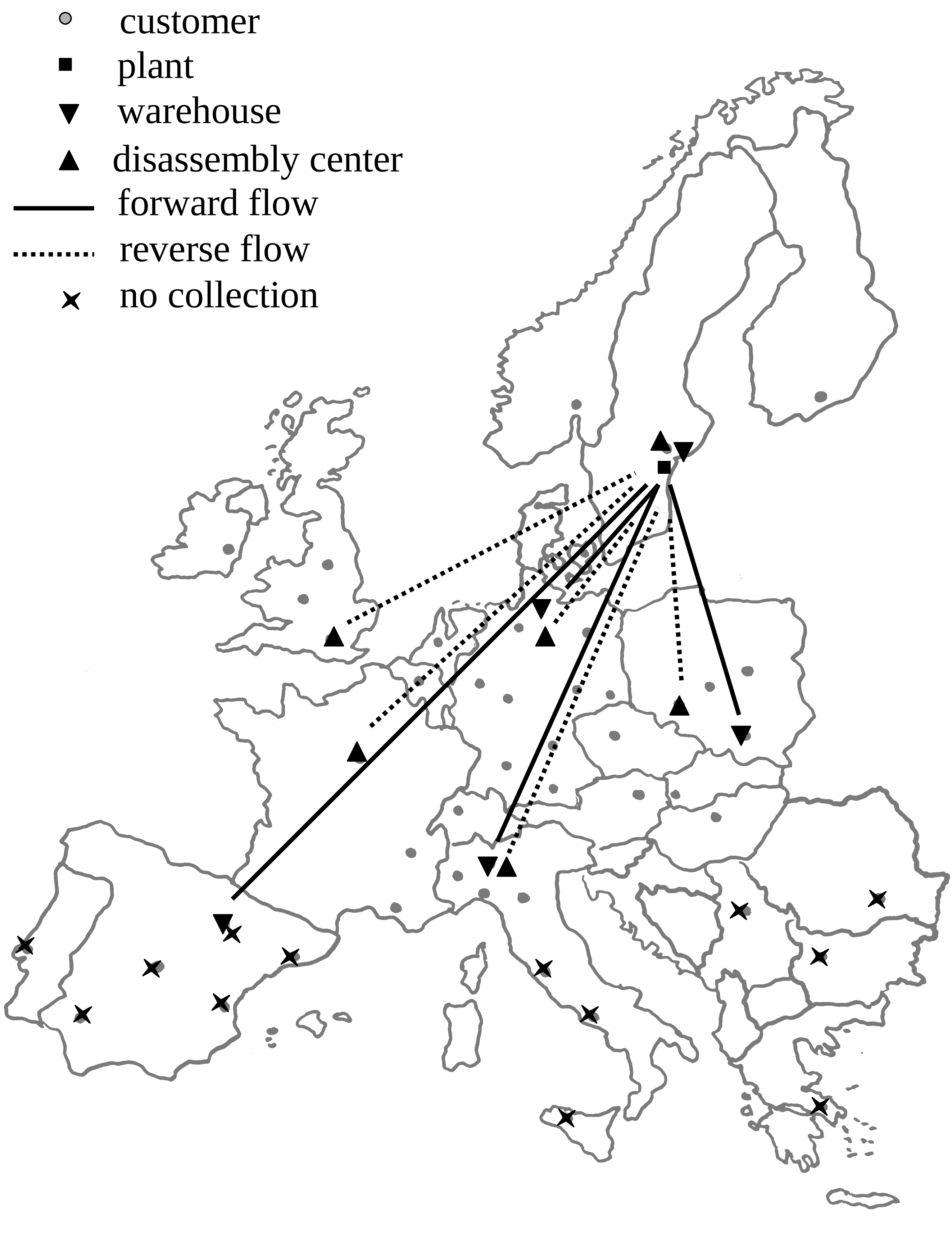

Figure 4: Optimal Sequential Network - Paper Recycling

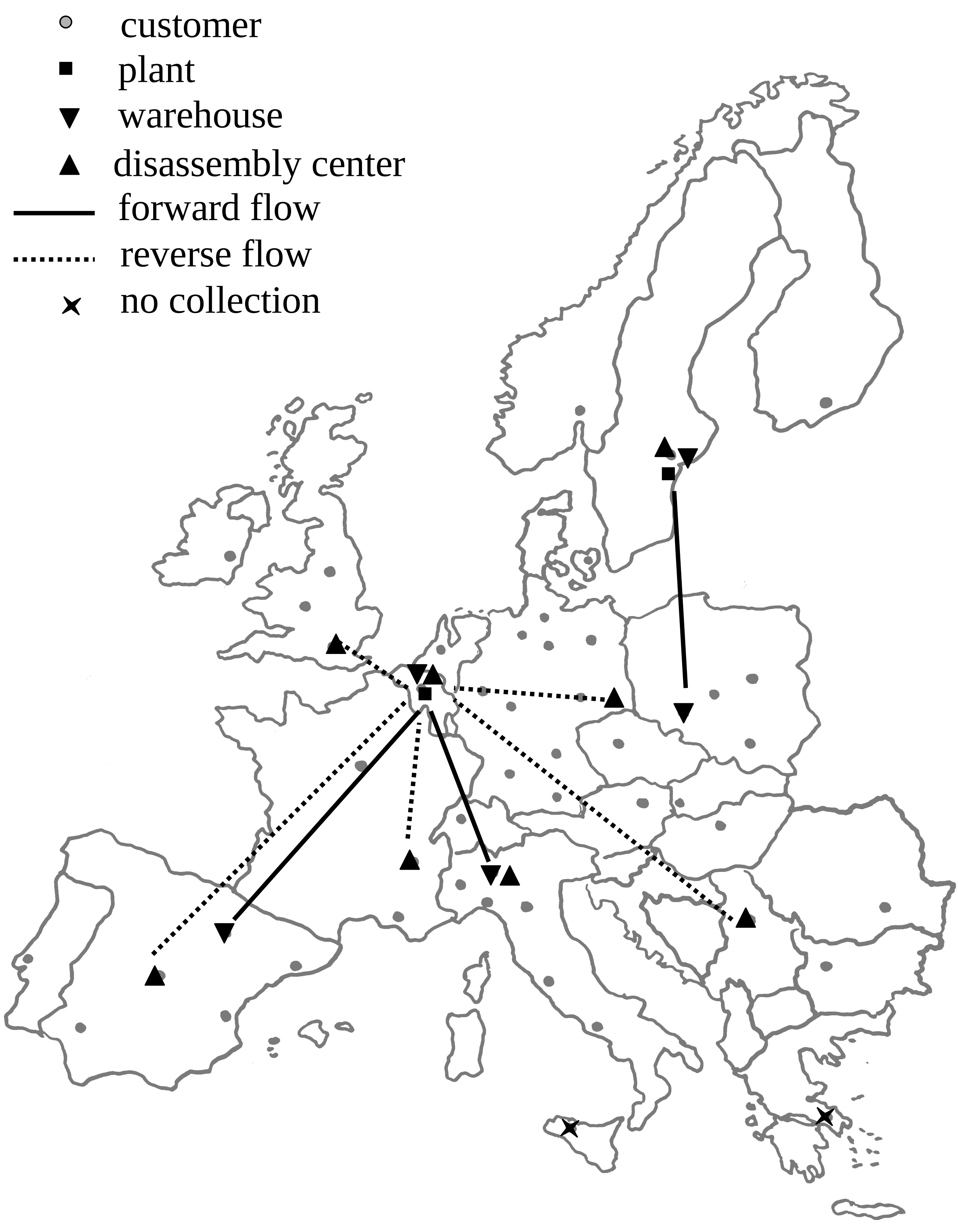

Figure 5: Optimal Integrated Network - Paper Recycling

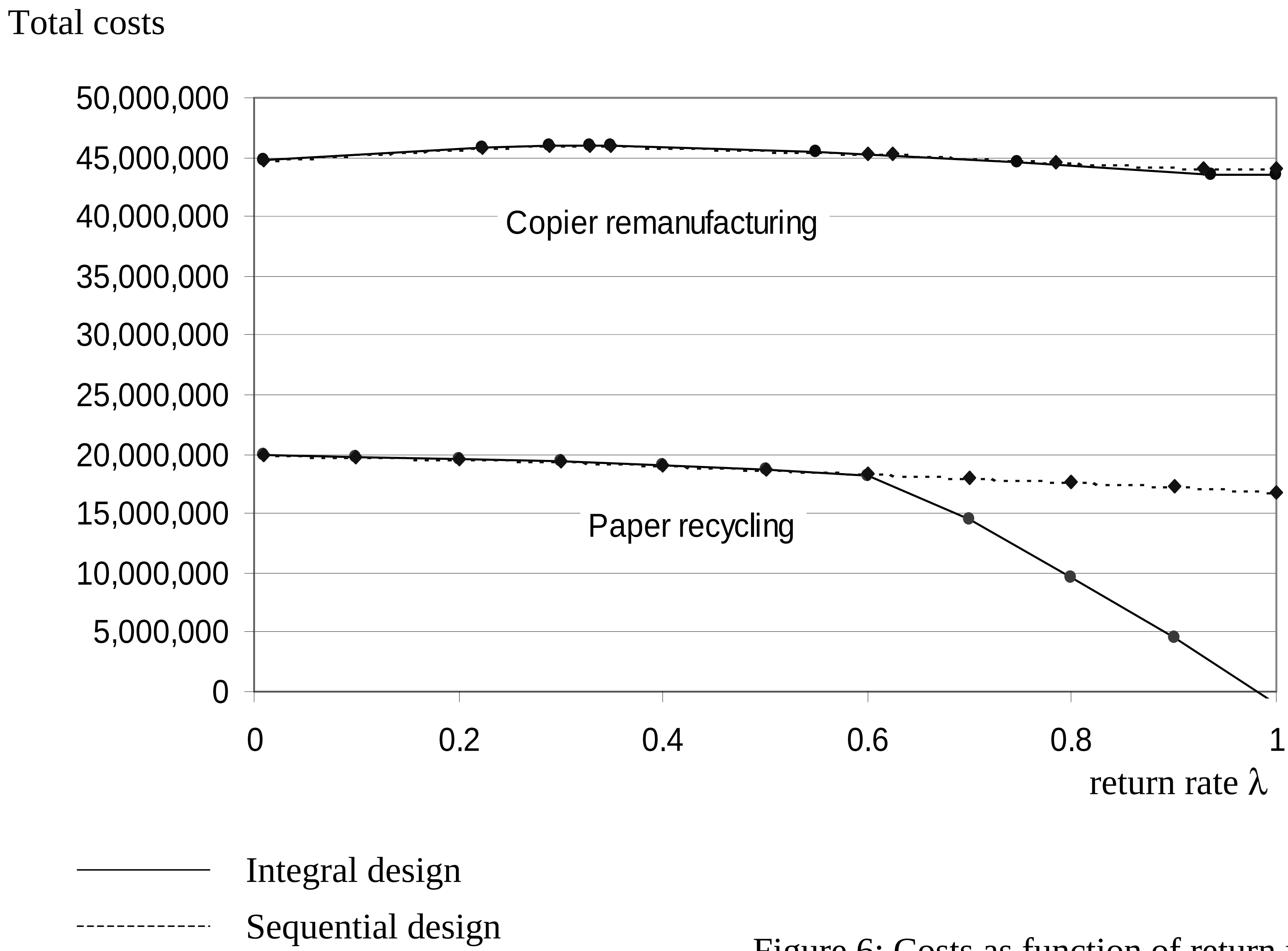

Figure 6: Costs as function of return rate

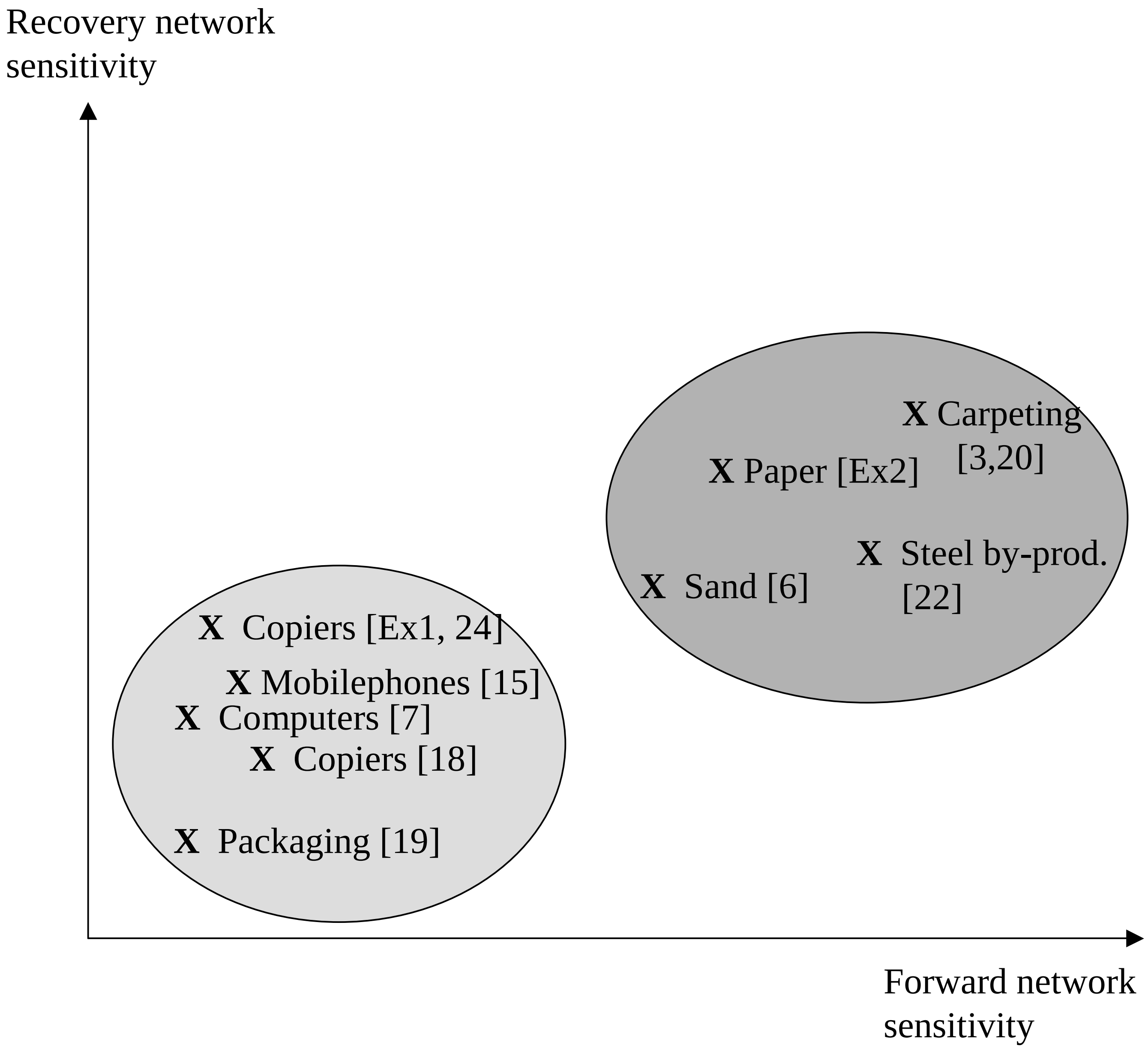

Figure 7: Network Sensitivity to Return Variations in Case Examples

Description	Parameter	Value	
		Example 1 **Copier Remanufacturing**	**Example 2** **Paper Recycling**
Fixed cost per factory	f^{p}	5,000,000	1,500,000
Fixed cost per warehouse	f^{w}	1,500,000	500,000
Fixed cost per disassembly center	f^{r}	500,000	125,000
Transportation costs per km per product :*		*(product volume in pieces)*	*(product volume in t)*
plant - warehouse	c^{pw}	0.0045	0.0040
warehouse - customer	c^{wm}	0.0100	0.0080
customer - disass.center	c^{mr}	0.0050	0.0060
disass.center - plant	c^{rp}	0.0030	0.0030
raw material source - plant	c^{sp}	-	0.0160
demand per 1000 inhabitants	d_k / # inhab.	100	0.3
return rate	λ	0.6	0.7
minimum disposal fraction	γ	0.5	0.1
disposal cost per product	c^{d}	2.5	0.05
cost savings (recovery - new production) per product	c^{r}	10.0	10.0

*aggregated cost coefficients in model formulation:

$c^{f}_{ijk} = d_k * (c^{sp} * t_i + c^{pw} * t_{ij} + c^{wm} * t_{jk})$

$c^{r}_{kli} = d_k * \lambda * (c^{mr} * t_{kl} + c^{rp} * t_{li} - c^{r})$

$c^{r}_{kl0} = d_k * \lambda * (c^{mr} * t_{kl} + c^{d})$

where t_{xy} denotes the distance between locations x and y

and t_x denotes the distance between location x and the raw material source

Table 1: Parameter settings in Examples 1 + 2

Table 2: Determinants of network sensitivity to return flow variations

Factor	forward network	return network
Geographical difference between disposer market and reuse market	+	
Different cost structures of forward and reverse channel	+ +	
Incentives for product recovery	+	(+)
Few potential locations	(+)	+
High investment costs		+
Low minimum disposal fraction	(+)	+

+ + = large impact on sensitivity
+ = impact on sensitivity
(+) = limited impact on sensitivity

Table 3: Summary Case Studies (adapted from Fleischmann et al. [12])

Case	product type	material re-use	parts / product re-use	OEM responsible	recovery mandatory	open loop	closed loop	new network	extend existing network	high investment costs	high operational costs
Louwers et al. [20]	carpeting	x		x	x	x		x		x	
Ammons et al. [3]	carpeting	x				x			x	x	
Thierry [24]	copiers		x	x	x		x		x		x
Krikke et al. [18]	copiers		x	x	x		x		x		x
Berger and Debaillie [7]	computers		x	x	x		x		x		x
Jayaraman et al. [15]	cellular telephones		x			x		x			
Kroon and Vrijens [19]	reusable packaging		x	(x)	(x)		x		x		x
Barros et al. [6]	sand	x			x	x		x		x	
Spengler et al. [22]	steel by-products	x		x	(x)	x		x		x	

X = applies
(X) = partly applies