A characterisation of logistics networks for product recovery

Mortiz Fleischmann\textsuperscript{a,}\textsuperscript{*}, Hans Ronald Krikke\textsuperscript{a}, Rompert Dekker\textsuperscript{b}, Simme Douwe P. Flapper\textsuperscript{c}

\textsuperscript{a}Faculty of Business Administration, Erasmus University Rotterdam, PO Box 1738, 3000 DR, Rotterdam, The Netherlands
\textsuperscript{b}Faculty of Economics, Erasmus University Rotterdam, PO Box 1738, 3000 DR, Rotterdam, The Netherlands
\textsuperscript{c}Faculty of Technology Management, Eindhoven University of Technology, PO Box 513, 5600 MB, Eindhoven, The Netherlands

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Abstract

Recovery of used products is receiving much attention recently due to growing environmental concern. Efficient implementation requires appropriate logistics structures to be set up for the arising goods flow from users to producers. We investigate the design of such logistics networks. As a basis for our analysis we review recent case studies on logistics network design for product recovery in different industries. We identify general characteristics of product recovery networks and compare them with traditional logistics structures. Moreover, we derive a classification scheme for different types of recovery networks. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Increasing interest in re-use of products and materials is one of the consequences of growing environmental concern throughout the past decades. Waste reduction has become a prime concern in industrialised countries. In view of depleted landfill and incineration capacities efforts are made to re-integrate used products into industrial production processes for further use. A concept of material cycles gradually replaces a ‘one way’ perception of economy. Several countries have enforced environmental legislation charging producers with responsibility for the whole life cycle of their products [6,11,12,43]. Take-back obligations for a number of product categories such as electronics, packaging material, and cars are some of the measures taken. Moreover, customer expectations urge companies to reduce the environmental burden of their products. A ‘green’ image has become an important marketing element [35,40]. Finally, re-use may be economically attractive due to material and added value recovery.

From a logistical perspective re-use activities give rise to an additional goods flow from the consumers back to producers. The management of this flow opposite to the conventional supply chain is the concern of the recently evolved field of ‘Reverse Logistics’ [40]. Issues arising encompass distribution, inventory and production management aspects. Important factors characterising specific re-use situ-
ations include economical and ecological drivers, actors involved and their respective roles, and the technical form of re-use. We refer to Fleischmann et al. [17] for a more detailed discussion.

In this paper we address the physical design of logistics networks for product recovery activities. More precisely, we define the object of our study as logistics structures constituted of physical locations, facilities, and transportation links, conveying used products from being set free by their former users to being re-used in some additional application. Re-use may take place on a product-, component-, or material-level. In contrast, we do not consider incineration (sometimes referred to as ‘energy re-use’) a form of re-use in the proper sense and hence do not include the corresponding waste collection networks in our definition. Our goal is to identify characteristics of ‘product recovery networks’ and to compare them with other logistics structures such as traditional production-distribution networks and waste disposal networks. Moreover, we aim at structuring the field by delineating distinct types of product recovery networks taking into account aspects such as topology, economics, parties involved, and decision and control issues.

We base our analysis on a set of recently published case studies on logistics network design in a product recovery context following the above definition. Each case study includes a quantitative model and provides detailed information on the network considered. Bringing together these cases involving different industries appears in itself worthwhile since literature in this area is not yet well developed. Moreover, commonalities among the cases indicate general characteristics of product recovery networks. To understand the observed differences we introduce a set of potential factors influencing logistics network design. Positioning the available case studies in this setting, we identify a number of clusters of similar network characteristics and explanatory factors and in this way derive distinct product recovery network classes. We underpin our findings by considering additional examples and experiences from industry.

The paper is structured as follows. In Section 1 we review literature on case studies concerned with logistics network design for product recovery. In Section 2 we bring the different examples together to identify common characteristics and compare them with other types of logistics networks. Moreover, we briefly discuss mathematical modelling aspects. In Section 3 we derive a classification of product recovery networks. Introducing a general map of recovery context dimensions we reconsider the set of case studies to identify distinct network classes. We summarise our findings in Section 4 and point out directions for further research.

2. Product recovery network design in current practice: a review

Recently, a considerable number of case studies have been reported which address the design of logistics networks in a product recovery context. Moreover, several decision support tools have been developed. In this section we provide a survey of these business cases. In each of the references a quantitative model for the network design problem is developed. While we do not focus on mathematical aspects here, it appears that cases involving quantitative analysis provide a particularly valuable source of information since they describe the situation considered on a fairly detailed level. Many other, qualitative papers exist, but do not offer such comprehensive information. We use the latter to substantiate our findings. For each case we state the activities carried out in the network and the parties involved together with their responsibilities. Moreover, we mention the main drivers for re-use in each example. Finally, we pay attention to the network boundaries and links with external parties and other networks. The material presented in this section forms the basis for our analysis developed in the remainder of the paper.

Barros et al. [2] report on a case study addressing the design of a logistics network for recycling sand coming free from processing construction waste in The Netherlands. While 1 million tons of sand used to be landfilled per year, re-use in large-scale infrastructure projects, e.g. road construction, is considered a potential alternative in line with environmental legislation. Therefore, a syndicate of construction waste processing companies investigates possibilities for establishing an efficient sand-recycling network. An important aspect to deal with is potential pollution of the sand, e.g. involving oil. Therefore sand needs to be analysed before being re-used. Three categories can be distinguished, namely clean sand that may be used without restrictions; half-clean sand, re-use of which is restricted to selected applications; polluted sand that needs to be cleaned after which it may be used freely. Cleaning of polluted sand requires installation of highly expensive treatment facilities. On the basis of these considerations a sand recycling network is to be set up encompassing four levels, namely crushing companies yielding sieved sand from construction waste, regional depots specifying the pollution level and storing clean and half-clean sand, treatment facilities cleaning and storing polluted sand, and infrastructure projects where sand can be re-used. The locations of the sand sources, i.e. crushing companies are known, the supply volume is estimated on the basis of historical data. Volume and location of demand not being known beforehand, scenario-analysis is resorted to. The optimal number, capacities, and locations of the
strengthened by valid inequalities. Approximately via iterative rounding of LP-relaxations an authors propose a multi-level capacitated facility location model for this problem formulated as a mixed integer linear program (MILP) which is solved approximately via iterative rounding of LP-relaxations strengthened by valid inequalities.

Louwers et al. [29] consider the design of a recycling network for carpet waste. High disposal volumes (1.6 million tons of carpet waste landfilled in Europe in 1996) and increasingly restrictive environmental regulation on the one hand, and a potential of valuable material resources (e.g. nylon fibres) on the other hand has lead the European carpet industry to setting up a joint recycling network together with some chemical companies. Through this network carpet waste is to be collected from former users and pre-processed to allow for material recovery. Since the content of carpet waste originating from various sources (e.g. households, office buildings, carpet retailers, aircraft and automotive industry) varies considerably identification and sorting is required. Moreover the sorted waste is to be shredded and pelletised for ease of transportation and handling. These pre-processing steps will be carried out in regional recovery centres from where the homogenised material mix is transported to chemical companies for further processing. Goal of the study is to determine appropriate locations and capacities for the regional recovery centres taking into account investment, processing and transportation costs. The authors propose a continuous location model. Using a linear approximation of the share of fixed costs per volume processed, all costs are considered volume dependent. The resulting nonlinear model is solved to optimality using standard software.

Carpet recycling is also addressed in a case study by Ammons et al. [1]. The volume of 5 billion pounds of used carpet material landfilled per year makes recycling an economically interesting option in the USA. While the entire carpet recycling chain involves several parties leadership is taken by a chemical company producing, e.g. nylon fibres. A logistics network is investigated including collection of used carpet from carpet dealerships, processing of collected carpet separating nylon fluff, other re-usable materials and a remainder to be landfilled, and end-markets for recycled materials. Currently, the system is operational with a single processing plant. For alternative configurations the optimal number and location of both collection sites and processing plants are to be determined while delivery sites for recovered materials are assumed to be known. Moreover, the amount of carpet collected from each site is to be determined. Facility capacity limits are the only restrictions in view of the vast volume currently landfilled. The authors propose a multi-level capacitated facility location MILP to address this problem. Reallff et al. [34] take this model as a starting point for a parametric analysis. They conclude that volume is a major critical factor for the network layout.

Spengler et al. [39] develop a MILP-model for the recycling of industrial by-products in the German steel industry. Steel is produced from raw materials in several production facilities. The production of 1 ton of steel gives rise to 0.5 tons of residuals. These residuals have to be recycled, in order to reduce negative environmental impact and to avoid disposal costs. Different processing technologies are available to reach this goal. Facilities can be installed at a set of potential locations and at different capacity levels, with corresponding fixed and variable processing cost. Thus, it has to be determined which recycling processes or process chains have to be installed at which locations at what capacity level. Maximum facility capacities are given. Furthermore, goods flows must be optimised assuming linear transportation costs. The proposed model, which is used for optimising several scenarios, is a modified multi-level warehouse location model with piecewise linear cost functions.

Loosely related with a case study on the recovery of copy machines [44] Thierry [43] proposes a conceptual model for evaluating combined production/distribution and collection/recovery networks. The model addresses the situation of a manufacturing company collecting used products for recovery in addition to producing and distributing new products. Recovered products are assumed to be sold under the same conditions as new ones to satisfy a given market demand. The production/distribution network encompasses three levels, namely plants, warehouses, and markets. Products may be transported from plants to markets either directly or via a warehouse, yielding different transportation costs. Moreover, from each market a certain amount of used products needs to be collected. Subsequently, collected products are to be disassembled and tested on reusability, after which accepted products need to be repaired while rejected products are disposed of. These activities are carried out in the facilities of the ‘forward’ production/distribution network. For each facility a set of feasible operations and capacity restrictions are specified. Additionally, disposal sites are given. Disposal is feasible for all used products and is obligatory for products rejected after testing. In this model all facility locations are fixed externally. The model objective is to determine cost-optimal goods flows in the network under the given capacity constraints. Since facilities are given, no fixed costs are considered. Decision relevant costs include variable production, handling, inspection, repair, disposal, and transportation costs. Since only variable costs are considered the problem is formulated as a linear program which can be solved to optimality.

A similar situation is addressed by Berger and Debaillie [3]. They propose a conceptual model for
extending an existing production/distribution network with disassembly centres to allow for recovery of used products. Responsibility for product recovery lies at the original product manufacturer (OEM) who incurs all costs. The model is illustrated in a fictitious case of a computer manufacturer. The existing distribution network encompasses plants, distribution centres and customers. In the extended network used products need to be collected from the customers. Collected products are to be inspected in a disassembly centre dividing them into three streams: high quality products can be repaired and shipped to a distribution centre for resale; products containing re-usable parts may be disassembled and shipped to a plant to be re-used in the production process; all other products are to be disposed of. Each plant and distribution centre can only use a limited amount of recovered products. While all facilities in the original network are fixed the number, locations, and capacities of disassembly centres are to be determined. In a variant of this model the recovery network is extended with another level by separating inspection and repair/disassembly. After inspection rejected products are disposed as before while recoverable products are shipped to a repair/disassembly centre before entering a distribution centre or a plant. The authors propose multi-level capacitated MILPs to address these problems.

Jayaraman et al. [26] analyse the logistics network of an electronic equipment remanufacturing company in the USA. The company’s activities encompass collection of used products (cores) from customers, remanufacturing of collected cores, and distribution of remanufactured products. Customers delivering cores and demanding remanufactured products do not necessarily coincide. Moreover, core supply is limited. In this network the optimal number and locations of remanufacturing facilities and the number of cores collected are to be determined considering investment, transportation, processing, and storage costs. The authors present a multi-product capacitated warehouse location MILP that is solved to optimality for different supply and demand scenarios.

Krikke and Vrijens [28] consider the design of a logistics system for reusable transportation packages. More specifically, a closed-loop deposit based system is considered for collapsible plastic containers that can be rented as secondary packaging material. The system involves five (groups of) actors: a central agency owning a pool of reusable containers; a logistics service provider being responsible for storing, delivering, and collecting the empty containers; senders and recipients of full containers; carriers transporting full containers from sender to recipient. The study focuses on the role of the logistics service provider. In addition to determining the number of containers required to run the system and an appropriate fee per shipment, a major question is where to locate depots for empty containers. At these depots containers are stored and maintained, shipped to a sender upon request, and eventually collected from the recipient. Note that transportation of empty containers is carried out independently of the full shipment from sender to recipient, which may be realised by a different carrier. The expected volume and geographical distribution of demand is estimated on the basis of historical data concerning the number of shipments between given parties. Uncertainty is covered via scenario analysis. An additional requirement is balancing the number of containers at the depots. Since the total number of containers shipped from a depot during a planning period should equal the number of containers received, containers may be relocated among the depots. The de-
cision problem is modelled as a MILP that is closely related with a classical uncapacitated warehouse location model.

Finally, while not related with a case study, we briefly mention the work of Marin and Pelegrin [30]. Taking a purely mathematical perspective, a MILP facility location model is analysed involving both distribution and product return flows. Lagrangian decomposition is discussed for constructing a solution heuristic.

3. General characteristics of product recovery networks

We now analyse the above cases in order to derive a general characterisation of logistics networks for product recovery. In a first step we identify common features of the presented examples. Subsequently, a comparison is made with more traditional logistics networks.

3.1. Commonalities

A first unifying factor of the above examples concerns the activities carried out within the logistics network. All networks considered span from a market setting free used products (in the sequel referred to as disposer market) to another market with demand for recovered products (denoted hereafter by re-use market). While the specific steps in this transition differ per case the following groups of activities appear to be recurrent in product recovery networks.

- Collection
- Inspection/Separation
- Re-processing
- Disposal
- Re-distribution

We briefly describe each of these steps below. We remark that our structuring slightly differs from earlier approaches [23,32] by taking a network perspective following the flows of goods. Therefore, we do not consider transportation and storage as distinct activities but rather as links between the above stages. In general, a transportation and a storage step may be required between each two of the above activities. Fig. 1 gives a graphical representation of the activities within a product recovery chain together with traditional supply chain activities.

Collection refers to all activities rendering used products available and physically moving them to some point where further treatment is taken care of. Collection of used carpet from carpet dealerships [1] and take-back of used copiers from customers [27] are typical examples from the above case studies. In general, collection may include purchasing, transportation, and storage activities. It should be noted that collection may, to some extent, be imposed by legislation (e.g. packaging material in Germany, white- and brown-goods in The Netherlands).

Inspection/Separation denotes all operations determining whether a given product is in fact re-usable and in which way. Thus, inspection and separation results in splitting the flow of used products according to distinct re-use (and disposal) options. This applies, e.g. for distinguishing repairable and recyclable subassemblies of copiers [27] and for inspection of sieved sand on pollution [2]. Inspection and separation may encompass disassembly, shredding, testing, sorting, and storage steps.

Re-processing means the actual transformation of a used product into a usable product again. This transformation may take different forms including recycling, repair, and remanufacturing [44]. In addition, activities such as cleaning, replacement, and re-assembly may be involved. Examples are numerous covering, e.g. nylon recycling from used carpet [1,29], parts remanufacturing from used copiers [43] and cleaning of polluted sand [2].

Disposal is required for products that cannot be re-used for technical or economical reasons. This applies, e.g. to products rejected at the separation level due to

![Fig. 1. The recovery chain.](image-url)
excessive repair requirements but also to products without satisfactory market potential, e.g. due to out-dating. Disposal may include transportation, landfiling, and incineration steps.

Re-distribution refers to directing re-usable products to a potential market and to physically moving them to future users. This may encompass sales (leasing, service contracts), transportation, and storage activities. Sales of recycled materials [1] and leasing of remanufactured copy machines [44] are among the typical examples.

The similarities in activities are also reflected by similar network topologies in the presented examples. Recovery networks can roughly be divided into three parts (see Fig. 2 for a graphical representation). In the first part, corresponding to the collection phase, flows are converging from the disposer market typically involving a large number of sources of used products, to recovery facilities. Conversely, in the last part, corresponding to re-distribution, flows are diverging from recovery facilities to demand points in the re-use market. The structure of the intermediate part of the network is closely linked with the specific form of product recovery. In case of a limited set of processing steps carried out at a single facility, as in the examples of re-usable packages [28] and carpet waste pre-processing [29], this network part may consist of a single level (comprising one or more parallel nodes). On the other hand, a complex sequence of processing steps involving several facilities may entail a multi-level structure of this network part including multiple interrelated flows. The latter case applies, e.g. to several remanufacturing examples [27,43]. We discuss these differences in more detail in Section 4. It is worth noting that only in the first part of a product recovery network flows are actually ‘reversed’ in the sense that they are directed from users to producers and undo steps of the original value chain. Subsequently, value is added and products move from a producer (recoverer) to a user just as in the traditional supply chain. To avoid misunderstanding, we therefore use the term ‘product recovery network’ rather than ‘reverse logistics network’.

In all of the above examples the party carrying out the recovery process is responsible for the logistic network. Determining the number and location of recovery facilities is a central task in the network design problems described above. In almost all cases geographical distribution and volume of both supply and demand are considered as exogenous variables. This gives product recovery networks a transhipment character. Sources and sinks are fixed while intermediary nodes are to be specified. We remark that sources and sinks, i.e. disposer market and re-use market, may coincide. Consider, e.g. re-use of containers [28] and of office equipment [43]. In this ‘closed loop’ case, interaction between collection and re-distribution may add complexity to the network design problem. We discuss differences between ‘closed loop’ and ‘open loop’ networks further in Section 4. Furthermore we note that take-back obligations due to environmental legislation and ‘green’ market pressure often result in a supply ‘push’ situation. That is, availability of used products that need to be taken care of trigger the sequence of events rather than end product demand [2,29,43]. At the same time, time restrictions tend to be weaker, in general, for collection than for distribution.

It has often been claimed that a high level of uncertainty is characteristic of product recovery management [17,27,43]. The above case studies support this vision with respect to network design issues. Demand for recovered products and materials appears to be difficult to forecast in many cases, the more so since re-use markets are often evolving only recently and are not yet well established. Even more important though, availability of used products on the disposer market involves major unknown factors. In general, timing and quantity of used products coming free are determined by the former user rather than by the reco-

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**Fig. 2.** Product recovery network topology.
3.2. Comparison with other logistics networks

Having characterised product recovery networks we now compare them with logistics networks in other contexts. In particular, we consider traditional production-distribution networks. We start by noting that product recovery networks encompass several supply chain stages. In this sense product recovery fits well in the mindset of supply chain management, advocating co-ordination of the entire supply chain rather than considering single stages independently [41]. Roughly speaking, product recovery networks correspond to distribution networks encompassing supply, production, and distribution stages (compare Fig. 1). The major differences between both contexts appear to arise on the supply side. In traditional production-distribution systems, supply is typically an endogenous variable in the sense that timing, quantity, and quality of delivered input can be controlled according to the system's needs. In contrast, as pointed out in the previous subsection, supply is largely exogenously determined in product recovery systems and may be difficult to forecast. Hence, supply uncertainty in a wide sense appears to be a major distinguishing factor between product recovery and traditional production-distribution networks.

As a direct consequence, traditional production-distribution networks typically do not include an 'inspection' stage similar to product recovery networks. Destinations of goods flows are, in general, known beforehand with more certainty as compared to the quality dependent processing routes in product recovery. While there may be exceptions, e.g. in case of by-products or re-work, this is not the major focus of traditional production-distribution networks. Therefore, network structures may be more complex for product recovery, including more interdependencies. Another element that may render recovery networks more complex than traditional production-distribution networks is potential interaction between collection and (re-)distribution, e.g. combined transportation in closed-loop networks. We recall, however, that network complexity depends on the specific recovery process and may vary considerably per example. Finally, the number of sources of used products tends to be fairly large as compared to the number of supply points in a traditional setting. Bringing together a high number of low volume flows therefore appears to be characteristic of product recovery networks in particular.

On the distribution side differences between traditional and product recovery networks appear to be rather small. Possibly, demand uncertainty may be somewhat more prominent in the latter case since reuse markets are not yet well established and professionalisation tends to be lower. However, it can be expected that this distinction gradually disappears with product recovery becoming a 'normal' business. To a less extent this last observation may also hold for the issue of supply uncertainty. Co-operation agreements on the one hand and modern information technology such as tracking and tracing, machine sensing, and electronic data interchange (EDI) on the other hand may contribute to a more stable environment for product recovery reducing, though surely not eliminating, supply uncertainty. As a general tendency, we expect logistics networks for product recovery and for production-distribution to become more similar in the future, with product recovery becoming a standard supply chain element.

Similarly, it is worth considering the relation between product recovery networks and waste disposal networks. Disposal networks provide the logistics structure for collection, processing, and disposal of discarded products in the form of landfilling or incineration. We refer to Jahre [25] for a detailed discussion. There are obvious analogies between disposal and recovery networks with respect to the 'supply' side. Used products need to be collected from many, possibly widespread sources and to be consolidated for further processing and transportation. Major differences between both network types arise on the 'demand' side. While a flow of recovered products is directed towards a re-use market, waste streams eventually end at landfill sites or incineration plants. The number of these disposal sinks is typically much smaller than the number of demand points in a re-use context. Hence, the divergent structure of the downstream network part is less prominent for disposal. Moreover, selection of disposal options is less sensitive to qualitative variations of the input. While waste streams may be sorted and split to some extent (e.g. material separation, removal of hazardous materials) according to different feasible disposal options (e.g. open or protected landfilling, incineration) these steps do not depend critically on the specific quality of discarded products. Hence, a considerably lower impact of input uncertainty is one of the major distinctions between disposal networks and networks for product recovery. However, it is worth noting that the line between both systems may not always be very sharp and that intermediate network types exist such as, e.g. for recycling of flue gas cleaning residues [24].
3.3. Modelling

We conclude this section by taking a brief look at quantitative modelling aspects of product recovery networks. In almost all of the case studies discussed above, MILP location-allocation models have been proposed to support network design. The only exception is found in [29] where a continuous location model is developed. In view of the transhipment character of product recovery networks (see Section 3.1), it is not surprising that many of the MILPs discussed closely resemble multi-level warehouse location models (see, e.g. [42] for a definition). The main differences with traditional models are due to splitting flows at the separation stage (see Section 3.1). Some cases can be interpreted as multi-commodity flows known from traditional distribution network models (see, e.g. [9,18,36]).

It is worth noting that the issue of uncertainty is not included explicitly in the above models. To the best of our knowledge, only deterministic facility location models have been presented for product recovery network design so far. Uncertainty is usually addressed via scenario and parametric analysis. Since we have seen that uncertainty is an important characteristic of product recovery, this issue seems to deserve additional research effort. More comprehensive quantitative results would be useful, concerning the impact of uncertainty on recovery network design and the appropriateness of traditional approaches for capturing this element. Recent work on robust network design is a first step in this direction [31]. Since stochastic approaches are not very well developed for logistics network design in general, research on product recovery may result in contributions in a larger context. Another aspect of recovery networks that deserves additional attention is potential interaction between forward and reverse channels. Quantitative results on, e.g. combination of collection and distribution in closed-loop networks or integration of facilities would be helpful for a better understanding of product recovery networks. Guidelines as to which activities to combine or to separate and an assessment of the transportation impact of product recovery would be valuable contributions.

4. Classification of product recovery networks

While we have identified a number of general characteristics of product recovery networks in the previous section, the networks encountered in the various case studies are surely not identical. Some discriminating factors such as network complexity and impact of uncertainty have already been mentioned in Section 3.1. In this section we consider the distinctions between different product recovery networks in more detail.

Main differences between the recovery networks in the case studies discussed earlier concern the following:

- degree of centralisation;
- number of levels;
- links with other networks;
- open vs closed loop structure;
- degree of branch co-operation.

Centralisation refers to the number of locations at which similar activities are carried out. In a centralised network each activity is installed at a few locations only, whereas in a decentralised network the same operation is carried out at several different locations in parallel. Centralisation may thus be seen as a measure for the horizontal integration or ‘width’ of a network. Analogously, the number of levels, referring to the number of facilities a goods flow visits sequentially, indicates the ‘depth’ or vertical integration of a network. In a single-level network all activities are integrated in one type of facility while in a multi-level network different activities are carried out at different locations. Links with other networks refer to the degree of integration of a new network with previously existing networks. A logistics network may be set up independently as an entirely new structure, or by extending an existing network. Open vs closed loop characterises the relation between incoming and outgoing flows of a network. In a closed loop network sources and sinks coincide so that flows ‘cycle’ in the network. An open loop network, on the other hand, has a ‘one-way’ structure in the sense that flows enter at one point and leave at another. Finally, the degree of branch co-operation relates to the parties responsible for setting up the network. Initiative may be taken by a single company, possibly involving subcontractors, or by a joint approach of an industry branch.

In Section 4.2, we characterise the networks considered in each of the case studies with respect to the above aspects. In order to explain the differences observed we analyse a set of context variables for each example. As a starting point, we introduce potential explanatory factors concerning product recovery situations in the next section. We structure these factors along three dimensions.

4.1. Characterisation of network structure context: the recovery situation

Here we work out our observation that logistic networks are context dependent, i.e. different ‘recovery situations’ should be distinguished. Careful analysis of the case studies reveals that variables concerning recovery situations can be split in three categories: (i) pro-
duct characteristics, (ii) supply chain characteristics, and (iii) resource characteristics.

4.1.1. Products

This concerns the physical and economical characteristics of discarded products as well as the chosen recovery options. Product characteristics can be numerous, e.g. weight, volume, fragility, toxic contents, perishability, economic value (valuable as a product or only few components) and obsolescence. Physical characteristics described in the above cases include the assembly structure and the recovery options. Products with complex assembled structures may involve extensive testing and disassembly as well as separate recovery of their components. It affects the centralisation/decentralisation decision and the number of levels in the system. This also depends on the recovery option chosen. Thierry et al. [44] describe five options at a conceptual level: repair, refurbishing, remanufacturing, cannibalisation and recycling. Depending on the option chosen, different disassembly, recovery and disposal facilities must be installed in the reverse logistic network. In general, a sub-set of the processes defined in Fig. 1 must be implemented in the reverse logistic network. Similarly, economic value may affect centralisation/decentralisation decisions (where to separate junk from valuable waste).

4.1.2. Supply chain

Here, we deal with the relationships between and the behaviour of actors in the supply chain: the suppliers, OEMs, service providers, policy makers and customers. Of course, supply chain management does cover many more aspects that may influence network structure, not to speak of aspects that are of no influence to reverse logistic network design. Here, we pay attention to the relevant aspects on which information is available in the case studies. These include responsibilities in the chain, driving force for product recovery and re-use (mandatory or commercial), disposer behaviour and type of re-user. They are discussed below.

Each actor has responsibilities, which may influence the network design. For example, on many occasions the OEM is responsible for the set-up of a reverse logistic system for its products and the packages used for their distribution. However, the responsibility may also be at a branch level, where syndicates take care of the actual set-up of the reverse logistic system. In the USA, OEMs are often not formally responsible and product recovery is driven by private, commercial initiatives. It is clear that different responsible actors can use different (existing) networks for the set-up of the reverse logistic system. Legislation may impose producer responsibility, thus making recycling mandatory. Disposer behaviour often causes strong uncertainty regarding quantity, quality, location and timing of returns. Supply uncertainty puts heavy burdens on the performance of reverse logistic systems, hence on the robustness of the network designs. On the re-use side it is of great relevance whether re-users are in the original or in some alternative supply chain, because this determines whether the system is open loop or closed loop.

4.1.3. Resources

In general, resources involve recovery facilities (dis-assembly lines, shredders etc.) and human resources. However, in the above cases only facilities are discussed. Concerning facilities, relevant aspects in the cases are flexibility (dedicated or universal) and costs (for investments and daily operations hence economies of scale effects). Universal systems may be more flexible than specialised systems in the sense that they can handle multiple product types, but may also be less efficient (i.e. more costly) for some individual product types. Facilities with high fixed costs generally require centralised operations, while other activities may be decentralised to reduce transportation costs.

4.2. Product recovery network types

We now bring together network properties and context variables in order to identify and characterise distinct product recovery network types. Table 1 below lists for each case study a number of characteristics concerning both the logistics network and the recovery situation. The network properties follow those discussed at the beginning of Section 4. The recovery situation is structured along the three dimensions Product, Supply chain characteristics, and Resources as introduced in the previous section. The selection of aspects included in Table 1 is based on the information available from the case descriptions.

The cases can roughly be clustered in two groups having similar characteristics, namely Cases 1–4 on the one hand and Cases 5–8 on the other. Case 9 (Kroon and Vrijens [28]) appears not to fit well in either group. Based on this observation and on general knowledge about other product recovery examples we propose to distinguish three types of product recovery networks, namely:

- bulk recycling network (Cases 1–4; [1,2,9,39]);
- assembly product remanufacturing network (Cases 5–8; [3,26,27,43]);
- re-usable item network (Cases 9; [28]).

We note that this classification is process-oriented in the sense that the form of product re-processing involved is the major discriminating factor. A similar structuring has been proposed by Bloemhof-Ruwaard and Salomon [5]. Other studies have considered classifications based on the network initiators, e.g. manufac-
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<th>Recovery network</th>
<th>Recovery situation</th>
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<th>OEM responsible</th>
<th>recovery mandatory</th>
<th>supply uncertainty</th>
<th>reuse in original market</th>
<th>high investment costs</th>
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<td>complex structure</td>
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<td>parts/reuse</td>
<td>OEM responsible</td>
<td>recovery mandatory</td>
<td>supply uncertainty</td>
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<td>Recycling networks</td>
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<td>1 Barros et al. [2]</td>
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<td>2 Louwesen et al. [29]</td>
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<td>3 Ammons et al. [1]</td>
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<td>4 Spengler et al. [39]</td>
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<td>5 Tierry [43]</td>
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<td>6 Jayaraman et al. [26]</td>
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<td>7 Berger and Debaillie [3]</td>
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<td>8 Krikke et al. [27]</td>
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<td>9 Kroon and Vrijens [28]</td>
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X = applies, (X) = applies partly.
4.2.1. Bulk recycling networks

A first group of networks showing similar characteristics encompasses examples of sand recycling [2], recycling of steel by-products [39], and carpet recycling [1,29]. All of these cases are concerned with material recovery from rather low value products. Disposer market and re-use market are different, in general, i.e. the recovered material is not necessarily re-used in the production process of the original product. Consequently, material suppliers play an important role in these networks in addition to OEMs. Moreover, investment costs turn out to be very substantial in all of the above examples, due to advanced technological equipment required. In addition, the above cases share a rather centralised, open loop network structure involving a small number of levels. Finally, it is worth noting that the network is often established relying on branch-wide co-operation.

Bringing the above aspects together we come to the following characterisation of bulk recycling networks. First of all, a low value per volume collected on the one hand and high investment costs on the other give the need for high processing volumes. This conclusion is also supported by examples of paper recycling [4] and plastic recycling [7]. Exploiting economies of scale is indispensable for making the recovery activities economically viable. Consequently, recycling networks tend to be highly vulnerable to uncertainty concerning the supply volume. The need for economies of scale is reflected by a centralised network structure. Moreover, co-operation within a branch may be an option to ensure high processing volumes. Car wreck recycling [22,33] and household electronics recycling [10] are additional examples of this approach. Co-operation is facilitated by an open loop character of material recycling, ensuring recovered material sales not to interfere with market shares in the original product market. Finally, a fairly simple network structure involving only a few levels results from the limited number of recovery options and the fact that technical feasibility of material recycling is not that critically dependent on the quality of the collected goods. Note, however, that input quality may be a major cost determinant, e.g. by influencing the purity of output materials.

4.2.2. Assembly product remanufacturing network

Examples of copier remanufacturing [27,43], cellular telephone remanufacturing [26], and printed circuit boards recovery [3] form another group of networks having similar characteristics. All cases are concerned with re-use on a product or parts level of relatively high value assembled products. Recovery is mainly carried out by the OEM, and re-use and original use often coincide. Furthermore, supply uncertainty is reported to be an important factor in all of the above studies and operational costs for recovery appear to be relatively high. As for the recovery network, most of the above examples involve a fairly complex multi-level structure. Moreover, networks most often form a closed loop and rely on extending existing logistics systems.

From the above observations we draw the following conclusions concerning assembled product remanufacturing networks. Added (manufacturing) value recovery is the main economic driver. Since the corresponding recovery activities (repair, remanufacturing) require (and reveal) intimate knowledge about the products concerned it is not surprising that they are carried out by the OEM in many cases (see [13,14,38,43] for additional examples concerning the computer and automotive industries). However, if market entry barriers are low product recovery opportunities may also attract specialised third parties as, e.g. for tyre retreading [15] or recovery of toner cartridges [37]. Product recovery has important marketing implications in these cases since markets for recovered products and original products may overlap. The latter also indicates a potential link between original logistics networks and recovery networks if the OEM is involved. Single-use cameras are an additional example [13]. For these types of assembled product remanufacturing networks opportunities may arise for combining transportation or handling of both flows. A closed loop structure integrating both networks may therefore be a natural choice. Consequently, extending existing logistics structures may be a good starting point for the design of a recovery network.

Another important characteristic of added value recovery is a complex set of interrelated processing steps and options, which may entail a rather complex structure of the corresponding logistics network. This applies, in particular, to the intermediate network part between collection and re-distribution (see Section 3). Additional examples from the automotive and computer industries support this finding (see above). Moreover, feasibility of recovery options and the sequence of processing steps required depend strongly on the specific condition of the collected product, giving uncertainty a prominent role in remanufacturing networks. Decentralisation of certain activities such as
4.2.3. Re-usable item networks

Yet another type of networks can be found in systems of directly re-usable items such as re-usable packages. Although in literature we only found one comprehensive case study on logistics network design falling into this area [28] there appears to be enough evidence to attempt a rough characterisation of this network class. As described in detail in Section 1 the above case considers a closed loop network for re-usable packages. Upon return to a central provider responsible for the entire life cycle, packages can be directly re-used. In this context timing of returns is reported to be an important element of uncertainty. Moreover, transportation and procurement of new packages are major cost factors. Finally, the logistics network has a decentralised, single-level structure extending a previously existing network.

We put these observations in a more general context as follows. Re-usable items requiring only minor ‘reprocessing’ steps such as cleaning and inspection can be expected to lead to a rather flat network structure comprising a small number of levels, e.g. corresponding to depots. Moreover, a closed loop chain structure seems natural in this context since there is no distinction between ‘original use’ and ‘re-use’. This applies, e.g. for many sorts of re-usable packages such as bottles, crates, pallets [5], plastic boxes [45] and containers [8]. Determining the number of items required to run the closed loop situation [21]. Moreover, a fairly large number of re-use cycles and absence of other processing steps makes transportation a major cost component [16]. This may be a reason for a decentralised network including depots close to customer locations. Availability and service aspects point to the same direction. On the other hand, decentralisation renders balancing of item flows an important task in re-usable item networks [8].

To conclude, we note that the line between ‘re-usable items’ and more traditional items that are used multiple times is rather thin. The networks described above show much similarity with other closed loop systems such as, e.g. transportation fleet systems or video rental systems.

5. Conclusions

In this paper we have analysed logistics network design in a product recovery environment. As a starting point we have presented a review of recent case studies. Bringing these examples together we have identified generic steps of activities carried out in product recovery networks. We have seen that a typical network structure includes a convergent part concerned with collection from a disposer market to recovery facilities, a divergent part for distribution to a re-use market, and an intermediate part related with the recovery processing steps required. Supply uncertainty both in quantity and quality appears to be a major distinction between product recovery networks and traditional production-distribution networks. This may be a reason for a more complex network structure. Considering recovery situations in more detail, including product, supply chain, and resource aspects, we have seen that product recovery networks can be subdivided into a number of classes. Re-usable item networks, remanufacturing networks, and recycling networks appear each to have their own typical characteristics.

This paper is a first step towards a comprehensive analysis of logistics networks in a product recovery environment. Further research effort is required to establish a good understanding of product recovery networks. In particular, additional case studies in this area are more than desirable. Moreover, a more detailed analysis of the aspects characterising different network types seems worthwhile. Furthermore, mathematical models as a tool for quantitative analysis of product recovery networks appear not be fully developed yet. Most models proposed to date stick rather closely to traditional facility location models. There exists a substantial opportunity to extend current network design approaches to new models that capture uncertainty and additional structural considerations for more complete analysis and better decision making.

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