Wageningen University - Department of Social Sciences

Operations Research and Logistics

MSc Thesis

A Reverse Logistics Network Design for Discarded Furniture in the Netherlands

The Dutch government aims for a circular economy in 2050, setting recyclability standards for furniture in the Transition Agenda of Consumption Goods. With an estimated 10 million tonnes of furniture disposed annually in the EU, the environmental impact of furniture production and transportation should be addressed through increased reuse. To encourage reuse, a reverse logistics network for discarded furniture in the Netherlands should be established.

In this study, a reverse network design for the reuse and repair of discarded furniture in the Netherlands is introduced. Through a multi-objective mixed-integer linear programming (MILP) model the study analyses storage (central, decentral, mixed) and reuse scenarios for costs and emissions. A mixed system is shown to be most cost effective, whilst a decentralised system is most effective for the minimisation of environmental impact. Despite initially highlighting transportation costs as a bottleneck, the research identifies repair costs as the primary costs in the reuse of discarded furniture. The study recommends policy interventions to reallocate costs and prioritise direct reuse to reduce environmental impact. Further research can address data gaps, supply uncertainty, evaluate the inclusion of the initial consumer and furniture collection systems for the implementation of an effective reverse logistics network.

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Chapter 1: Introduction

The Dutch government has the ambition to establish a circular economy in 2050, in which there is no waste and resources will be re-used (Rijksoverheid, n.d.-a). To facilitate this transition towards a circular economy, the government formulated five transition agendas in collaboration with the industry and civil-society organisations (Rijksoverheid, n.d.-b).

One of the five agendas is the *Transitieagenda Consumptiegoederen* (Transition Agenda of Consumption goods) which was published in 2018. The agenda describes the aims and required actions for the transition towards a circular economy for consumer goods (Transitieteam Consumptiegoederen, 2018). Certain measures and goals for 2050 are set for several sectors of consumer goods, including the furniture sector.

In 2050, furniture must meet the highest standard of circular product requirements possible in terms of recyclability and disassembly. Furniture will be reused, repaired, and refurbished so it is used its entire life span (Rijksoverheid, 2023). It is estimated that ten million tonnes of furniture are disposed of in EU Member states annually (Forrest et al., 2017). In contrast to e.g., electronics, no emissions are produced when the furniture is used. The environmental impact of furniture primarily stems from the production of furniture and its transportation (Parker et al., 2015). Therefore, reuse will be important for the reduction of the environmental impact of furniture. An increase in the reuse of furniture can reduce the production of new furniture and subsequently reduce environmental impact of the furniture sector. One measure to encourage the reuse of furniture is to implement a system for better collection of discarded furniture. Thus, an important aspect in a circular furniture sector is the existence of an efficient reverse logistics network for the return of used furniture.

1.1 Reverse Logistics of Furniture

Reverse logistics is an important process for the implementation of a circular economy (Mishra et al., 2022). Reverse logistics (RL) refers to the process of moving (final) products from their original destination back up in the supply chain to regain/add value or for appropriate disposal (Rachih et al., 2019; Agrawal et al., 2015). In the circular economy, its purpose is to recapture the value of a product for the product to be reused (Mishra et al., 2022).

Reverse logistics has three key processes (Rachih et al., 2019; Agrawal et al., 2015):

1. Collection.
2. Inspection and sortation.
3. Disposition.

The network design of a reverse logistic system has three specific characteristics. First, there is supply uncertainty, in contrast to forward logistics, where demand is often uncertain. Second, there is an extent of centralization for testing and sorting of returned products. Implementing testing early in the supply chain can minimise transportation distance (and thus costs), since products can be transported directly to the correct facility. However, high investment costs call for more centralized facilities. Finally, there is the relationship between forward and reverse flows (Fleischmann et al., 2004).

Limited literature exists on reverse logistics (RL) for furniture specifically. Mishra et al. (2022) conduct a literature review on reverse logistics and closed loop supply chains (CLSC). Of the 80 papers that are analysed, three (4%) concern the reverse logistics of furniture. Most of the papers regard a general industry (44%) the e-waste industry (18%), and the manufacturing industry (11%). No enablers or barriers for the implementation of reverse logistics for furniture are identified due to the limited research on furniture specifically. A similar result is found in a literature review on reverse logistics for a remanufacturing network by Zhang et al. (2021). The authors identify a lack of research on reverse logistics network for furniture, while research most commonly concerns the remanufacturing of electronic products.

There is research on the barriers for the implementation of reverse logistics for various other product groups than furniture. For electronics, Bouzon et al. (2016) find that the bottleneck for the implementation of a reverse logistics network is predominantly economic. Due to economies of scale issues and general economic uncertainty RL is considered unprofitable by companies. Yu and Solvang (2016) find there is a trade-off between the reduction of emissions and increased economic costs. In addition, findings show transportation costs to be the main influencing factor. Transportation is also costly for the reverse logistics of packaging (Togato de Oliveira et al., 2019). Barriers and enablers for the implementation of a reverse logistics network, however, will vary between products and sectors (Agrawal et al., 2015).

1.2 Current Situation in The Netherlands

Currently, there is no existing network dedicated to the reverse logistics of furniture for reuse. In addition, data on the flows of discarded furniture is limited. Intven et al. (2022) investigate the lifecycle of large seating furniture, such as sofas and sitting chairs, in the Netherlands. Findings show that currently, the supply chain of this furniture is predominantly linear. The lifespan of the furniture is on average between 7 and 17 years and is showing a declining trend. Lifespan is determined by the quality of material and consumer taste. In addition, Forrest et al. (2017) find there is limited infrastructure for the recollection of furniture in Europe.

Establishing a reverse logistics network for furniture presents several specific challenges. Furniture is (1) large and heavy, and varies in (2) form, (3) material and (4) quality of the product (Intven et al., 2022). In addition, furniture products are often poorly designed with low quality materials, which makes repair/refurbishment difficult. Even, when possible, high labour and transportation costs make this a costly process (Forrest et al., 2017). Actual data and costs on such a reverse network, however, do not exist.

1.3 Research Aim

The aim of this study is to introduce and assess a network design for the reverse logistic system for the reuse of discarded furniture in the Netherlands. Both costs and emissions are considered and optimised using a mathematical programming model. The implementation of a nation-wide reverse logistic network where disposed furniture is (if necessary) repaired and resold to a new consumer (C2B) is necessary to increase reuse of furniture. High costs are highlighted as a barrier for the implementation of reverse logistics for other product groups, such as electronics and packaging. Additionally, the high variety of (second-hand) furniture (size, weight, form, material, and quality) makes the implementation of a reverse network challenging.

This study proposes a mixed-integer linear programming (MILP) model for the network design of discarded furniture, with an emphasis on direct reuse and repair. In addition, the flow and volume of discarded furniture is estimated, which provides insight into the magnitude of furniture waste. The research contributes to the limited research on reverse network design specifically for furniture. Various scenarios are modelled for storage capacity and rate of reuse. Outcomes of the model are used to assess the network design and provide valuable insight into barriers and enablers in the implementation of such a system, especially regarding costs and emissions.

The research is performed in collaboration with '*het Groene Brein'*, an organisation that serves as a hub for the circular economy, fostering connections between business and research, developing comprehensive visions and promote sustainable projects.

1.4 Thesis Overview

The report consists of 7 chapters. In Chapter 2, a literature review is conducted concerning the reverse logistic network design for household appliances. This chapter provides information on how to design a reverse network design for furniture. In Chapter 3, interviews with stakeholders are conducted to gain an overview of the current system for furniture disposal and highlight barriers and enablers in the implementation of a reverse logistic system. In addition, data on flows of furniture are gathered. Then from existing data, estimations are made of the flow of discarded furniture and total volume. The methodology is discussed in Chapter 4. Based on the findings from Chapter 2 and 3, a network design for reverse logistics of furniture is described. The mathematical formulation of the model is provided, and the ε-constraint-method is discussed. Furthermore, the different scenarios for the logistic system of storage and rates of reuse are elaborated on. The model is run for the scenarios discussed in Chapter 4 and its results are discussed in Chapter 5. Costs and emissions are given and compared for the logistic systems of storage and reuse scenarios. The distribution of costs and emissions for a mixed storage system are elaborated on. Furthermore, the model is solved with the ε-constraint method and the pareto frontier is provided for the mixed storage system. In Chapter 6, the data analysis (Chapter 3) and results from the model (Chapter 5) are discussed. The implications of results for policy, limitations and recommendations are described. Finally, a conclusion can be found in Chapter 7.

Chapter 2: Systematic Literature Review

In this chapter, a systematic literature review is conducted on the reverse logistics of household products. The review aims to answer the question:

How are reverse logistics modelled for household products?

In a systematic literature review, a list of steps is followed to collect relevant studies which fit pre-defined criteria, in order to avoid bias (Denyer&Tranfield, 2009; Mengist et al., 2020). This research follows the method in Abidi et al. (2014), which is based on Denyer & Tranfield (2009) and Rousseau et al. (2008). The method includes six steps: (1) planning, (2) searching, (3) screening, (4) extraction, (5) synthesis, and (6) reporting. In this chapter, the steps are described for the literature review.

2.1 Planning

To design a network for the reverse logistics of furniture, a review of current literature is required. Since literature on reverse logistics for furniture is scarce (Mishra et al., 2022; Zhang et al., 2021), it is decided to broaden the scope of the review to household products. Household products include inedible products used in a household such as furniture and electronics. Household products are chosen since these have similar challenges to furniture especially bulky products or products with longer life span.

1. What modelling approach is used for reverse supply chain designs for household products?
2. What network structure is used for reverse supply chain designs for household products?
3. What problems are considered for reverse supply chain design for household products?
4. What indicators are used as objective in the design of a reverse supply chain for household products?
5. What processes are used in the design of a reverse supply chain for household products?

2.2 Search

Based on the research questions, key terms are developed with Boolean operators to identify and evaluate the literature. Two databases are used for the search: Scopus and ScienceDirect.

The search string uses the search words from keyword of ‘reverse logistics’ and ‘household products’. The final search string is: (“reverse logistics” OR “closed loop supply chain” OR “CLSC” OR “reverse supply chain”) AND (“household products” OR “household appliances” OR “domestic products” OR “domestic appliances” OR “furniture). The keyword had to be found in the title, abstract or keywords of the paper (TITLE-ABS-KEY). The search gave 130 results in total of which 113 in Scopus and 17 in ScienceDirect.

2.3 Screening

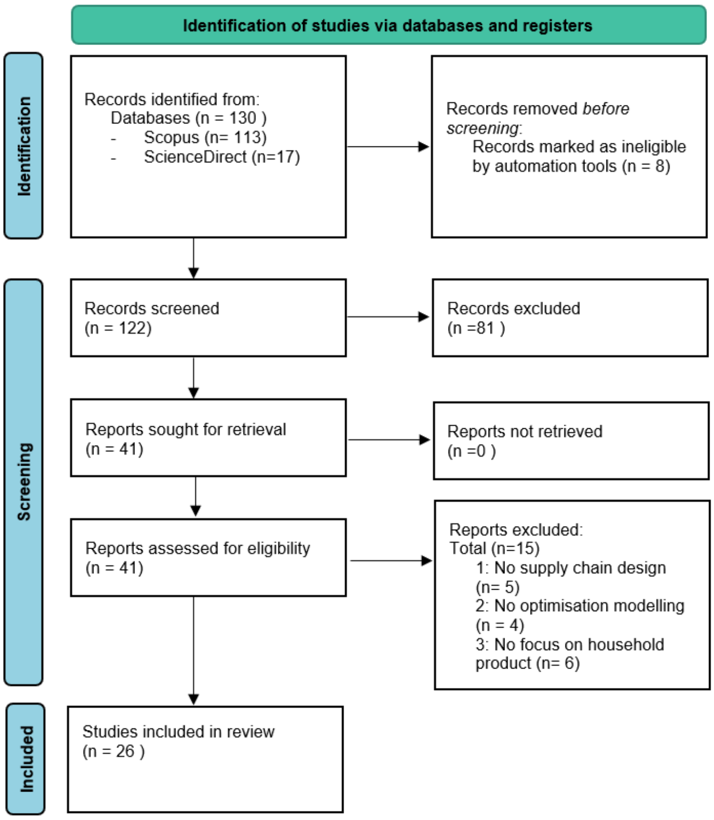
Papers are selected by applying the inclusion and exclusion criteria defined in Table 1.

Table 1
Inclusion and Exclusion Criteria for Paper Selection

Criteria	Decision
Pre-defined keywords are present in the title, abstract or keywords of the paper	Inclusion
Papers published in English	Inclusion
Papers published between 2000-2023	Inclusion
Papers published in peer-reviewed journals	Inclusion
Papers where at least one economic *or* environmental objective is addressed	Inclusion
Paper addresses a reverse supply chain where products are returned by households	Inclusion
Paper addresses a supply chain where products are not returned by a household (but e.g., a company), but the product is furniture	Inclusion
Papers concerning household waste (plastics, foods, paper, glass)	Exclusion
Papers concerning something other than supply chain design (no optimisation modelling)	Exclusion

Based on these criteria, 81 papers were excluded. The final 41 papers were studied. However, after quality assessment, another 15 papers are excluded. There were several reasons for the exclusion of the papers. In some papers a reverse logistics network was considered for another product than household, e.g., food packaging. These papers are excluded since the product does not contain similar characteristics to furniture (difficult to store, discard, transport). Other papers did not consider any supply chain design or optimisation modelling at all. Thus, a total of 26 papers are considered in this study. A summary of the selection process can be seen in Figure 1.

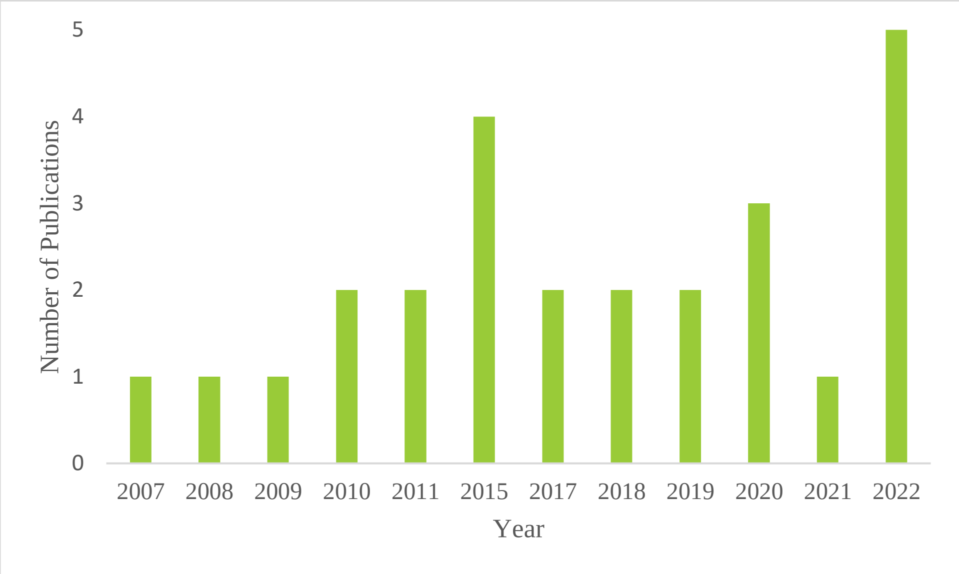
Figure 1
Selection Process
Sources from http://prisma-statement.org/prismastatement/flowdiagram.aspx



2.4 Extraction, synthesis, and reporting

In total, 26 papers are reviewed which are published in 19 different journals. For three journals, more than one paper was studied: *Journal of Cleaner Production* (5), *International Journal of Production Research* (3), and *European Journal of Operational Research* (2). Of the 26 papers, 7 are conference proceedings. The year of publication is shown in Figure 2.

Figure 2
Distribution of Papers per Year



Of all papers studied, 73% of papers are published between 2015-2022, with most papers published in 2015 (4) and 2022 (5). In addition, five of the seven papers published between 2007-2011 are conference proceedings (Zhao et al., 2007; Wan & Zhang, 2008; Meng & Zhang, 2009; Meng & Xu, 2010; Huo & Wang, 2011). The other two conference proceedings are published in 2018 and 2022 (Wei & Lv, 2018; Sing et al., 2022). Furthermore, no papers were published in the years 2012-2014.

A summary of the papers can be found in Table 2.

Table 2

Summary of Papers

Reference	Network Structure	Product	Multi-objective	Economic indicator	Environmental indicator	Level/problem	Modelling approach	Solution method
Accorsi, Manzini, Pini, & Penazzi, (2015)	CLSC	Furniture	✓	Cost minimisation	Carbon emission minimisation	Location-allocation	MILP	
Ali, Paksoy, Torgul, & Kaur, (2020)	Reverse flows	Air conditioners	*	Total expenses minimisation → profit maximisation	Environmental costs included in expenses minimisation*	Network design	Fuzzy hybrid multi-criteria optimisation, MILP	AHP, FAHP and BWM
Alshamsi, & Diabat, (2017)	Reverse flows	Household appliances (WEEE)		Profit maximisation		Facility- location	MILP	Genetic algorithm
Alumur, Nickel, Saldanha-da-Gama, & Verter, (2011)	Reverse flows	Washing machines and dryers		Profit maximisation		Network design	MILP	
Bal & Satoglu, (2018)	Reverse	Household appliances (WEEE)	✓	Cost minimisation	Carbon emission minimisation	Network design	Goal programming, MILP	AUGMECON2
Che, Lei & Jian, (2022)	Reverse	Household appliances		Profit maximisation		Facility-location	MILP	Decomposition-and-expansion heuristic
Chen, Kucukyazici, Verter, & Sáenz, (2015)	CLSC	Household appliances		Profit maximisation		Network design	Two-stage stochastic optimisation, MIQP	Sample average approximation with integer L-shaped method
Chu, Lin, Sculli, & Ni, (2010)	Reverse	Household appliances		Cost minimisation		Network design	MILP	Hybrid genetic algorithm
Huo & Wang, (2011)	Reverse	Household appliances		Cost minimisation		Network design	MILP	Genetic algorithm
Kazancoglu, Yuksel, Sezer. Mangla, & Hua, (2022)	CLSC	Household appliances	✓	Cost minimisation	Carbon emission minimisation	Network design	MILP	Weighted sum method
Lin, Chen, Tseng, Chiu, & Ali, (2020)	Reverse	Furniture		Profit maximisation		Flow allocation	Fuzzy optimisation, MILP	Particle Swarm
Meng & Mu, (2010)	Reverse	Household appliances		Cost minimisation		Network design	MINLP	AHP
Meng & Zhang, (2009)	Reverse	Household appliances		Cost minimisation		Location-allocation	MILP	

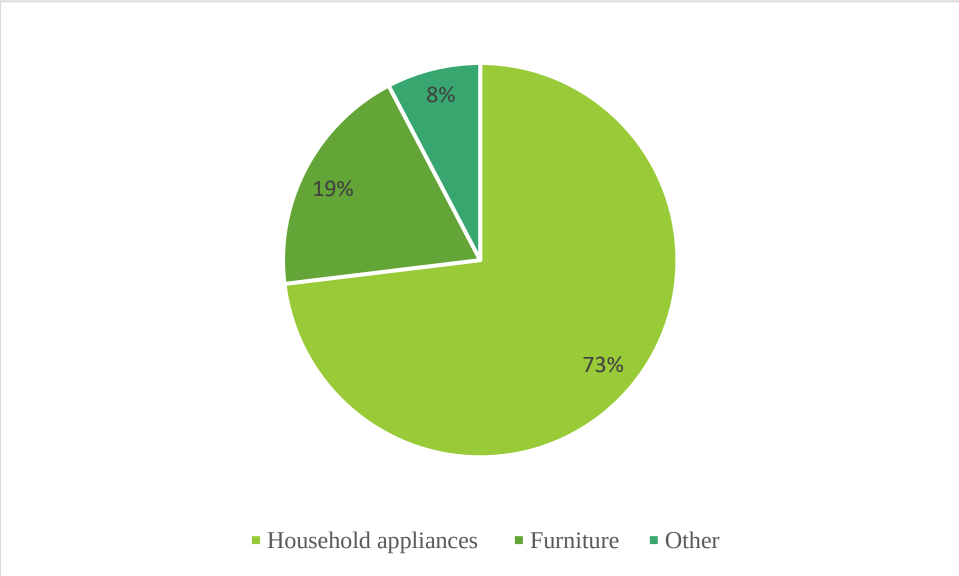
Mogale, Ghadge, & Aktas, (2022)	CLSC	Household appliances	✓	Cost minimisation	(Carbon) emission minimisation	Network design	MINLP	Genetic algorithm (non-dominated) & Co-Kriging approach
Özcelik, Yilmaz & Yeni, (2021)	Reverse	Household appliances		Recovered product maximisation		Network design	Robust optimisation, MILP	
Prakahs, Soni & Rathore, (2017)	CLSC	Furniture (hospital)		Cost minimisation		Network design	MILP	
Sadrnia. Langarudi, & Sani, (2020)	Reverse	Household appliances		Cost minimisation		Network design	MILP	Scenario-based approach
Shuang, Diabat & Liao, (2019)	Reverse	Household appliances	*	Profit maximisation	Emission costs included in economic objective*	Production-routing	Two stage stochastic optimisation, MILP	
Sing, Kumar, Bhandari & Soni, (2015)	CLSC	Furniture & home products		Cost minimisation		Network design	Robust optimisation, MILP	
Soleimani & Kannan, (2015)	CLSC	Furniture (hospital)		Profit maximisation		Network design & planning	MILP	Particle Swarm hybrid algorithm & Genetic algorithm
Wan & Zhang, (2008)	Reverse	Household appliances		Cost minimisation		Location-allocation	MINLP	Genetic algorithm
Wei & Lv, (2018)	Reverse	Household appliances		Cost minimisation		VRP	MILP	Ant colony algorithm
Yang, Guo, Zhang & Li, (2022)	Reverse	Household appliances		Cost minimisation		Location-routing	Fuzzy multi-objective optimisation, MILP	
Yanik, (2015)	Reverse	Household appliances (large)		Cost minimisation		Location-allocation	MILP	
Zarbakhshnia, Soleimani, Goh, & Razavi (2019)	Forward & Reverse	Household appliances	✓	Cost minimisation	Carbon emission minimisation	Network design & planning	MILP	Epsilon-constraint method
Zhao, Liu, Fan & Ci, (2007)	Reverse	Household appliances (electrics)		Cost minimisation		Network design	MILP	Benders analysing method

2.4.1 Products

As shown in Figure 3, household appliances are the most common product studied. From the 26 papers, 19 (73%) papers consider household appliances. Sadrnia et al. (2020) propose a MILP model for the network design for reverse logistics of household appliances to charities. The model considers three sizes of products and includes the option for repairment. The uncertainty of supply by consumers is considered and solved for cost minimisation using a scenario-based approach.

Figure 3

Distribution of Products



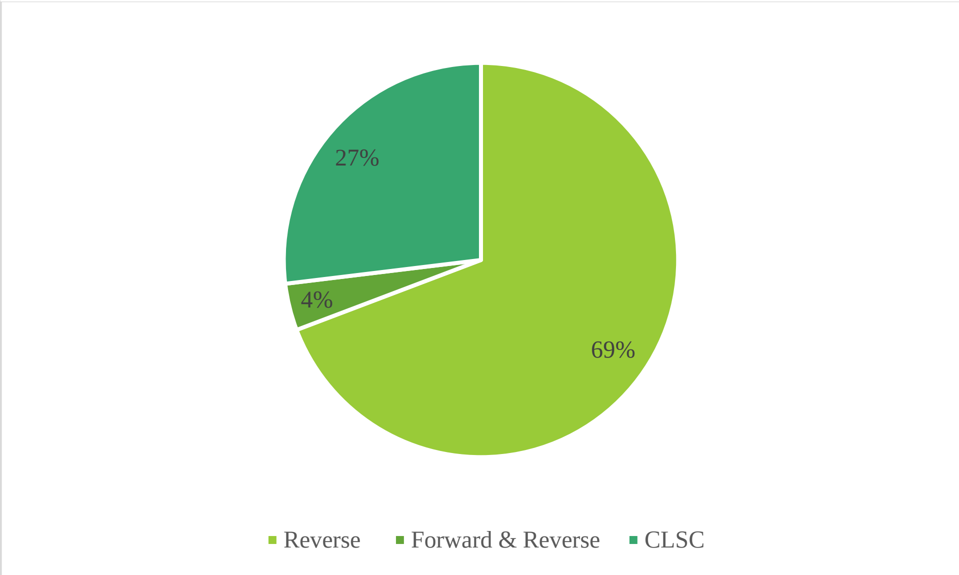
Furniture is considered in 5 (19%) of the papers. Soleimani & Kannan (2015) propose a closed loop supply chain (CLSC) network design problem for hospital furniture in Iran. A hybrid of particle swarm and genetic algorithm method is used to solve the problem considering cost minimisation. In addition, Prakash et al. (2017) also consider hospital furniture for a case study in India. A MILP model for a CLSC network design is proposed including supply chain risks such as quality disruptions and transport discrepancies and solved for cost minimisation. Furthermore, Sing et al. (2022) model a single-product, single-period CLSC network design of furniture in India using robust optimization considering demand uncertainty. Lin et al. (2020) considers waste of furniture for the allocation of flows for the reuse/recycle of furniture. Notably, it is the only paper that considers furniture with only the reverse flows and not a CLSC. The model considers uncertainty in demand, damage and repair feasibility and is solved using particle swarm optimization.

2.4.2 Modelling approach, network structure and problem type

Table 2 shows the modelling approaches adopted by the papers. Out of 26 papers, 22 (84%) consider a mixed-integer linear programming (MILP) model, whilst 3 (12%) consider a mixed-integer non-linear programming (MINLP) model and one paper (4%) considers a mixed-integer quadratic programming (MIQP) model. In addition, 7 papers (28%) consider uncertainty in their model, through fuzzy optimisation (Ali et al., 2020; Lin et al., 2020; Yang et al., 2022), robust optimisation (Ozcelik & Yeni, 2021; Sing et al., 2019) and two-stage stochastic optimisation (Chen et al., 2015; Shuang et al., 2019). Finally, Bal et al. introduce goal programming in addition to the formulation of a MILP model.

The distribution of network type is shown in Figure 4. From the 26 papers reviewed, 18 (69%) papers exclusively consider a reverse network. Huo and Wang (2011) develop a MILP network design model for used household appliances in China. The network consists of reverse flows that start at the collection centre for used products.

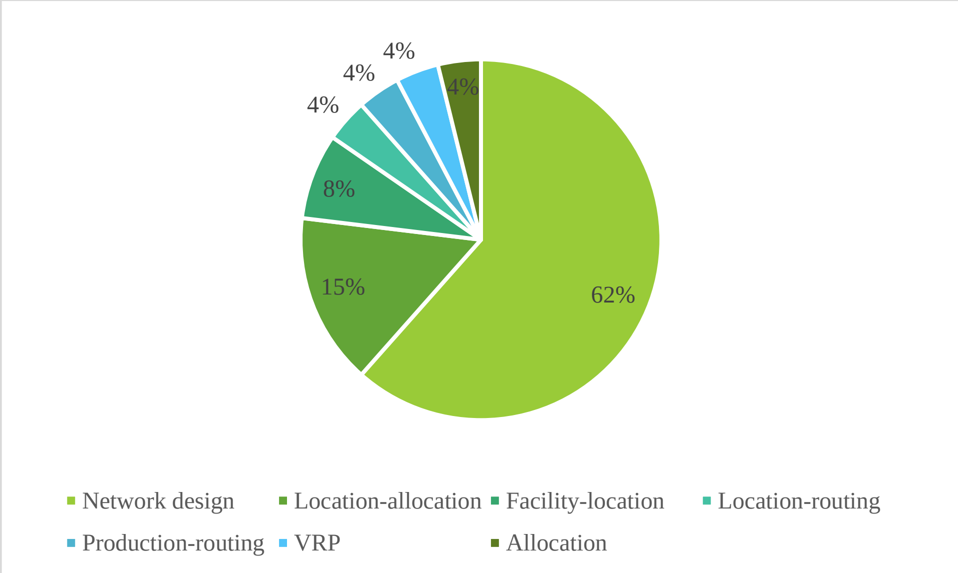
Figure 4
Distribution of Network Structure



Seven (27%) papers consider a closed-loop supply chain (CLSC). In addition, one (4%) paper considers both the forward and reverse network, without closing the chain. In Zarbakhshni et al. (2019) a single-period, multi-stage, multi-product, and multi-objective MILP model for the network design of household appliances is studied. The network consists of forward flows of materials used for the manufacture of the appliances and reverse flows of products returned by customers for remanufacturing, recycling, or disposal. The epsilon-constraint method is used to solve the model to minimise costs and simultaneously minimise carbon emissions.

Figure 5 shows network design is the most frequent problem type considered. Out of the 26 papers, 16 (62%) consider network design for their model (e.g., Sadrnia et al., 2020; Prahaks et al., 2017; Sing et al., 2022; Huo & Wang, 2011; Zarbakhshnia et al., 2019).

Figure 5
Distribution of Problem Type



Location-allocation problems are modelled in four (15%) papers. Yanik (2015) models a single-period, single-echelon MILP location-allocation problem for the reverse logistics of large household appliances in Turkey. Locations of collection centres and treatment facilities are determined for the minimisation of costs. Wan & Zhang (2008) develop a MINLP model for the location-allocation of household appliances to the second-hand market in China. A genetic algorithm is used to solve for the minimisation of costs.

Yang et al. (2022) proposes a MILP model for the location-routing problem of waste from household appliances for recycling. A fuzzy population density algorithm is used to determine the optimal locations for and routing between collection-, recovery- and treatment centres considering risks and uncertainty in the supply chain for the minimisation of costs. Furthermore, Che et al. (2022) develop a MILP model for a facility-location problem for the recycling of materials from household appliances in China. Capacity restrictions are considered, and a decomposition-and-expansion heuristic is used to determine the optimal location and capacities to maximise profit.

A vehicle routing problem (VRP) is modelled for the recycling of household appliances in China by Wei & Lv (2018). Moreover, Shuang et al. (2019) propose a production-routing problem with remanufacturing and pickup and delivery for the reverse flows of household appliances. In addition to a MILP model with deterministic demand, two-stage stochastic model with uncertain demand is formulated and solved for the maximisation of profit.

2.4.3 Indicators

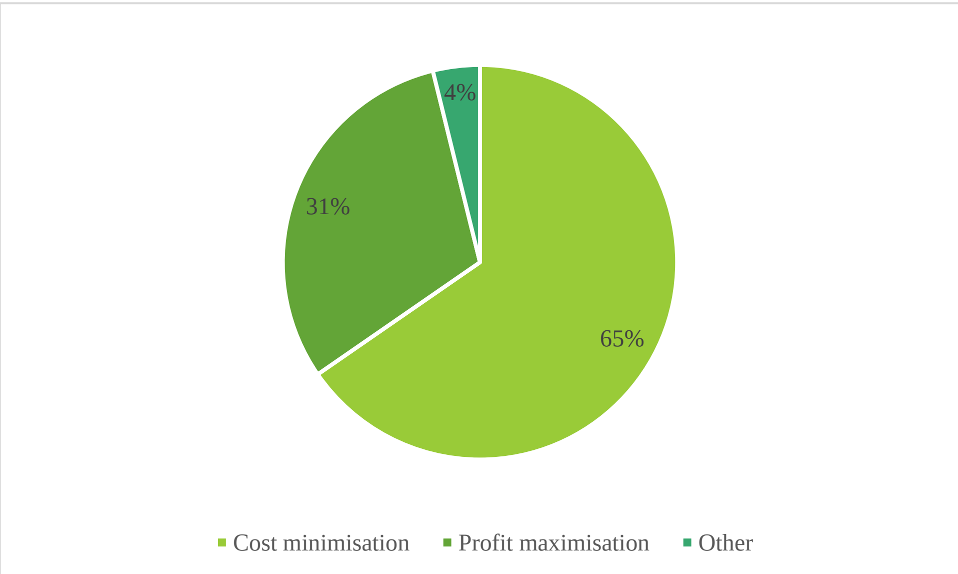
From the 26 papers, 21 (81%) consider a single objective. For all papers, this is an economic objective. The other five (19%) papers consider multiple objectives, which for all papers is an economic and environmental objective. An overview of the indicators used can be found in Table 3.

Table 3
Summary of Indicators

	Number of papers		Total
	Single objective	Multi-objective	
Economic	21	5	26
Cost minimisation	12	5	17
Profit maximisation	8	-	8
Other	1	-	1
Environmental	-	5	5
Carbon emission minimisation	-	5	5
Total	21	5	

Figure 6 shows the economic indicators used in all papers. Out of all 26 papers, 17 papers (65%) use cost minimisation as the economic indicator. Out of 21 papers which consider a single objective, 12 papers consider cost minimisation (e.g., Sadrnia et al., 2020; Prahaks et al., 2017; Sing et al., 2015; Yanik, 2015; Yang et al., 2022; Huo & Wang, 2011; Wan & Zhang, 2008).

Figure 6
Distribution of Economic Indicators



Another frequently used economic indicator is profit maximisation, which is used in eight (31%) of the 26 papers. Chen et al. (2015) develops a two-stage stochastic model for the CLSC network design for house appliances with uncertainty in market size, return volume and quality of return. In the first stage, the model is solved for the maximisation of expected net profit considering expected sales profits and subtracting fixed establishment costs of facilities. In stage two, operating profit is maximised. Operating profit consists of the sales revenue from remanufactured products minus the costs for transportation, handling, sorting, and disposal. In addition, Ali et al. (2020) proposes a MILP model for the reverse logistics of air conditioners with uncertain demand. The model is optimized so total expenses are minimised by subtracting revenue of sales from spare parts from the costs. This is similar to the maximisation of profit. Costs considered are transportation, purchasing, operation, facility, and inventory costs. In addition, environmental costs are included.

One (8%) paper uses another economic indicator than cost minimisation or profit maximisation. Özcelick et al. (2020) propose a robust optimization model for a reverse logistics network of household appliances. The model considers ripple effects on the supply chain caused by disruptions to the environment or systems. The model is solved so the number of total recovered products is maximised.

Notably all papers which consider multiple objectives use cost minimisation as the economic indicator. Mogale et al. (2022) propose a MINLP multi-echelon, multi-period, and multi-product model for the CLSC network design of household appliances. The model considers price-sensitive demand, consumer's incentives, and accounts for variations in quality level of the products. A non-dominated sorting genetic algorithm and Co-Kriging approach is used to solve the model for cost minimisation and emission minimisation. The costs minimised are production, disposal, processing, technology, location, transportation, incentive, and inventory costs. Emissions considered in minimisation are production, disposal, processing, and transportation emissions.

In addition, Bal & Satoglu (2018) develop a multi-facility, multi-product, and multi-period goal-programming model for the reverse network design of electronic waste products from household appliances. The epsilon-constraint method is used to determine pareto-efficient solutions for the minimisation of costs and minimisation of carbon emissions. The costs include recycling, labour, transportation, and penalty costs for uncollected products. Emissions minimised are carbon emissions from transportation and facilities.

2.4.4 Processes

From the 26 papers, 11 processes in the supply chain design are identified which are summarised in Table 4.

Table 4

Summary of Processes

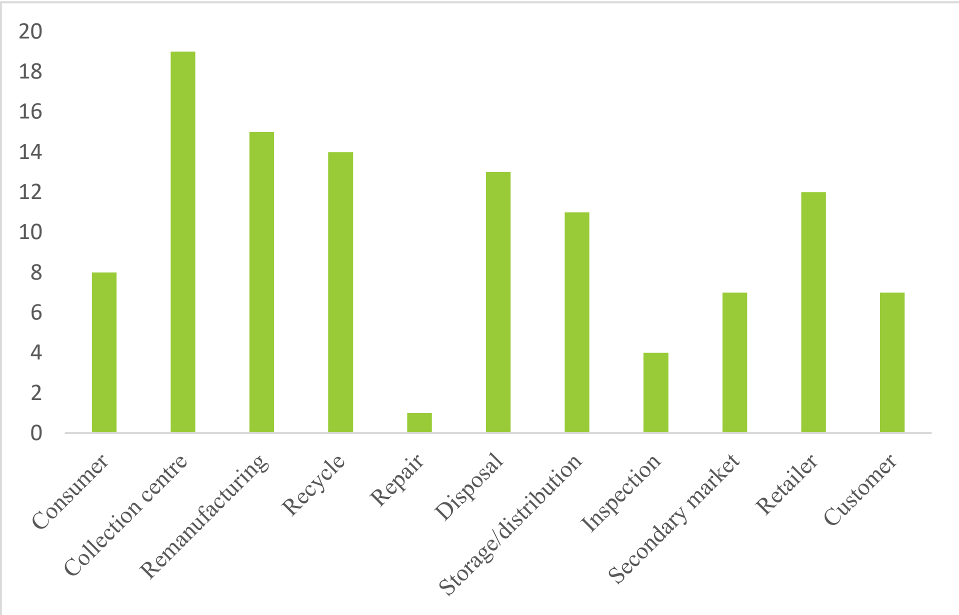
Reference	Consumer	Collection	Remanufacturing	Recycling	Repair	Disposal	Storage /Distribution	Inspection	Secondary market	Retailer	Customer
Accorsi, Manzini, Pini, & Penazzi, (2015)		✓	✓	✓		✓	✓			✓	✓
Ali, Paksoy, Torgul, & Kaur, (2020)	✓	✓	✓	✓		✓			✓	✓	
Alshamsi, & Diabat, (2017)		✓	✓	✓			✓	✓	✓		
Alumur, Nickel, Saldanha-da-Gama, & Verter, (2011)		✓	✓					✓	✓		
Bal & Satoglu, (2018)	✓	✓		✓		✓			✓		
Che, Lei & Jian, (2022)		✓		✓						✓	
Chen, Kucukyazici, Verter, & Sáenz, (2015)			✓				✓				✓
Chu, Lin, Sculli, & Ni, (2010)		✓	✓			✓				✓	
Huo & Wang, (2011)	✓		✓			✓	✓	✓		✓	

Kazancoglu, Yuksel, Sezer. Mangla, & Hua, (2022)		✓	✓				✓		✓		
Lin, Chen, Tseng, Chiu, & Ali, (2020)	✓		✓			✓				✓	
Meng & Mu, (2010)				✓		✓	✓			✓	
Meng & Zhang, (2009)			✓	✓			✓	✓		✓	
Mogale, Ghadge, & Aktas, (2022)		✓	✓			✓	✓			✓	✓
Özcelik, Yilmaz & Yeni, (2021)	✓	✓		✓							
Prakahs, Soni & Rathore, (2017)	✓	✓				✓	✓				
Sadrnia. Langarudi, & Sani, (2020)	✓	✓		✓	✓	✓			✓	✓	
Shuang, Diabat & Liao, (2019)			✓							✓	✓
Singh, Kumar, Bhandari & Soni, (2015)						✓	✓				✓
Soleimani & Kannan, (2015)		✓	✓			✓	✓			✓	✓
Wan & Zhang, (2008)		✓		✓					✓		

Wei & Lv, (2018)				✓			✓
Yang, Guo, Zhang & Li, (2022)	✓	✓		✓	✓		
Yanik, (2015)		✓	✓				
Zarbakhshnia, Soleimani, Goh, & Razavi (2019)		✓	✓	✓		✓	
Zhao, Liu, Fan & Ci, (2007)		✓	✓				

Figure 7 shows the distribution of processes used in the 26 papers. Eight (31%) out of 26 papers started its reverse supply chain design at customers. These customer points are often generated, such as in Alumur et al. (2011). A multi-period, multi-commodity reverse logistic network design is modelled for the remanufacturing of washing machines and tumble dryers. The products are collected from the generated customers points and transported to a collection centre after which it is inspected, remanufactured, and sold on the secondary market. The authors find that a specific facility for inspection is costly, and costs are reduced when inspection is combined with another process (collection, remanufacturing) at the same facility. Four (15%) of the papers included inspection as a specific process whereas for other papers it was either not included or performed at the collection centres.

Figure 7
Overview of Processes



In 19 (73%) of the 26 papers, a collection centre is used. Collection centres are either the starting point of the network or the second step in case primary consumers are included. When collection is not included, the supply chain starts at the treatment facility. For example, Meng & Mu (2010) develop a MINLP for household appliances. The network starts at the recycling facility where usable components are retrieved. Components are then stored in warehouses to be sold. Some form of storage is implemented in 11 (42%) of the papers, usually after the product has received treatment (recycle, remanufacture, repair). Accorsi et al. (2015) model a CLSC for furniture in Italy. The reverse flow start at the collection centre whereafter the furniture is transported to be recycled, remanufactured or disposed of. Remanufactured items are stored at distribution centres and transported to retailers to be sold.

Remanufacturing and recycling are most often included in the supply chain design. Out of 26 papers, 15 (58%) include the option for remanufacturing whilst 14 (54%) include recycling. In 5 papers, both options are included. Alshami and Diabat (2017) develop a MILP facility location model for household appliances in the Gulf Cooperation Council. Reusable parts of the product are used for remanufacturing whilst damaged part are recycled for materials. Remanufactured products are then sold at secondary markets. Repair of the product is only implemented in the supply chain design of one (4%) paper (Sadrnia et al., 2020).

2.5 Conclusion

In this literature review, an analysis is conducted on 26 papers focusing on products, modelling approach, network structure, problem type, indicators for objective, and processes. As expected, few papers considered specifically a reverse supply chain design for furniture. Most of the research on furniture develop a CLSC design, except for one paper by Lin et al. (2020). A MILP is the most common modelling approach. Considering all papers, networks including only reverse flows are most often modelled. Thus, in the limited literature on reverse logistics for furniture, reverse flows are considered more frequently simultaneously with forward flows compared to reverse logistics for household appliances. Overall, the design of these reverse flows is primarily on the (strategic) level of network design with few papers focussing on tactical or operational decision-making.

Few papers account for the environmental impact of the reverse logistics. The majority of the papers consider a single economic objective with some papers including environmental costs in the economic objective. The subset of papers that explore multi-objective problems all consider the same two objectives: cost minimisation and emission minimisation. Notably, the majority of the papers integrate remanufacturing or recycling within the supply chain design. Little focus, however, is on the repair and subsequently reuse of the product.

Chapter 3: Discarded Furniture in the Netherlands

This chapter presents the results of interviews with stakeholders on the current disposal of furniture in the Netherlands and the barriers in the implementation of a reverse network. First, the methodology for the interviews is described. The outcomes from the interviews are described in five themes: logistics, flow and materials, consumer behaviour, costs and data availability. A gap in data on the flow of discarded furniture is identified. Therefore, a data analysis is conducted to estimate the current flow and volume of discarded furniture.

3.1 Interview methodology

Limited literature exists on the current disposal system of furniture in the Netherlands. Therefore, interviews with stakeholders are conducted to gain an overview of the current system. Two aims for the interviews are identified:

1. Gain an understanding and overview of the existing disposal system for furniture in the Netherlands.
2. Identify bottlenecks for the implementation of reverse logistics system.

3.1.1 Participant selection

Participants were selected in collaboration with *het Groene Brein*, a key partner in the development of this research and member of the ReUse Alliance. Most participants are part of the Reuse Alliance, a movement in the furniture sector that is focused on preventing the disposal of furniture (ReUse Alliance, 2023). The network of *het Groene Brein* was used to contact members of the ReUse Alliance. The selection process was designed to capture a broad view of the furniture sector, considering a variety of stakeholders. Participants were selected to represent different stakeholder in the industry, including:

1. **(Online, Second-Hand) retail**: professionals involved in the retail of furniture, including major furniture chain, thrift stores and online (second-hand) retail.
2. **Logistics**: professionals involved in the logistics and transportation of furniture.
3. **Waste Management**: professionals involved in the collection and processing of disposed furniture.
4. **Government representatives**: professionals involved in the regulation and policies influencing the furniture sector.
5. **Research professionals**: professionals with research on furniture, the circular economy and consumer behaviour.
6. **Knowledge platforms**: professionals focused on informing consumers on sustainable choices or furniture specifically.

3.1.2 Interview Guide

The aim of the interview is to gain an understanding of the current disposal of furniture in the Netherlands and identify potential bottlenecks in the implementation of a reverse system. The interview methodology is semi-structured, which includes predetermined themes with room for additional questioning (Kahlio et al., 2016). The flexibility of a semi-structured interview ensures all knowledge of the participant is captured. The following five themes are identified:

1. **Logistics**: current system of disposal, available infrastructure, bottlenecks within furniture disposal process.
2. **Flow and materials**: quality, quantity and categorisation of furniture in the disposal process.

3. **Costs**: financial aspects of furniture disposal and identification of bottlenecks.
4. **Consumer**: consumer behaviour towards disposed and second-hand furniture.
5. **Available data**: availability and accessibility of existing data and identification of data gaps.

An interview guide is developed based on the five themes. The interview guide is personalised for each interviewee based on their knowledge and expertise to ensure questions are relevant and provide meaningful insight. Duration of the interviews were 45 minutes to an hour.

3.1.3 Analysis

Interviews are conducted online and recorded with the consent of the participant for documentation purposes. Following the interview session, the recorded material is reviewed. A summary of every interview is made, based on the recording and additional notes taken during the interview. The summary serves as the basis for the analysis focused on the five predefined themes. Each interview is examined individually to gain insight on the themes relevant in the interview. In addition, insights are compared to identify commonalities and disparities across stakeholders. The findings from the interviews are shared during a stakeholder session to allow feedback.

3.2 Interview Results

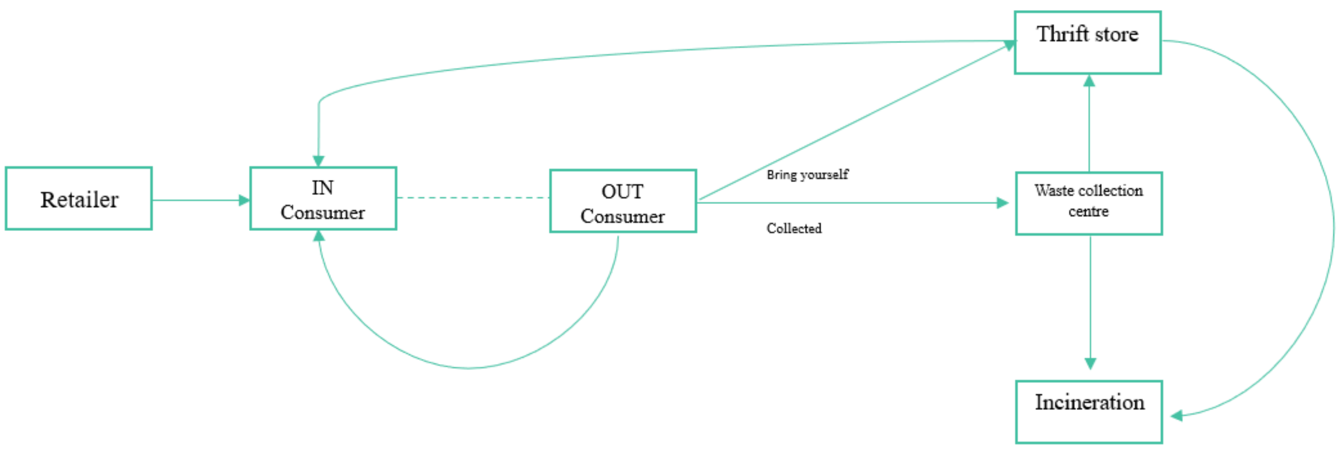
A total of 10 interviews are conducted. Summaries of the interviews can be found in Appendix A. In the following section, the results are discussed per theme. References are provided when data or findings from the research were discussed in the interviews.

3.2.1 Logistics

At the moment, there is no system dedicated specifically to the reverse logistics of furniture for consumers. There are some developments, however, regarding office furniture but this is organised by the companies themselves.

The current system for the disposal of furniture can be seen in Figure 8.

Figure 8
Current flow of discarded furniture



Consumers have several options for disposing their furniture. First, they can choose to give the item away to acquaintances, donate to thrift stores or sell it through platforms like *Marktplaats* thereby enabling the furniture to be acquired by another consumer.

Furthermore, various methods exist for furniture to reach the municipal waste collection centre (*milieustraat)*. Consumers can personally transport the furniture to the collection centre using their own vehicle. In some municipalities, scheduled collection routes or the option to arrange appointment for pick up exist. The advantages and disadvantages of these methods can be seen in Table 5.

Table 5

(Dis)Advantages of Transportation Methods for Disposed Furniture to the Collection Centre

Method		Advantage	Disadvantage
Bring yourself		Assumption that the furniture retains a better condition	A car is needed since, often, furniture is heavy and big – creates a barrier.
Municipality			
	Fixed routes at fixed times	Low barrier – consumer only must move the furniture to the street. 'Easy' logistics – route and time are already fixed	Chance that furniture gets damaged by weather (e.g., rain) or inattentive retrieval.
	Appointment	Easier for consumer compared to transporting the item themselves. Smaller chance furniture is damaged by weather or inattentive retrieval.	Not as flexible for the consumer in comparison to move it to the street. High costs due to the individual and single routes that must be taken.

At the collection centre, materials get separated if the product has been disassembled. However, most of the furniture typically ends up as bulky waste, after which it is incinerated.

Similarly, consumers have the option to transport furniture to the thrift store personally or arrange for the thrift store to collect the items through a scheduled appointment. Thrift stores, however, encounter a storage problem due to high supply of second-hand products. Furniture occupies a significant amount of space which makes a quick turnover time necessary. Thrift stores already implement a stricter acceptance policy for furniture, however, even with the stricter policy a portion of furniture in thrift stores remains unsold. Unsold furniture must make room for new furniture and is offered for recycling or incineration.

3.2.2 Flow and Materials

Koch & Vringer (2023) investigate the current behaviour and openness towards 'circular' consumer behaviour for several product categories, including furniture. A survey is used to question consumers about the last furniture item the respondent bought or disposed of.

The research finds that approximately 55% of disposed furniture is of good quality, indicating that it is not damaged or worn out. This is the highest share of valuable products being disposed compared to other product categories: smartphones (40%), apparel (37%), small household appliances (30%) and washing machines (15%). Furthermore, the average lifespan of a furniture item is approximately 14.5 years – like the 7 to 17 years that Intven et al. (2022) find. Thus, more than half of furniture will be disposed of by a consumer before the end of its lifespan.

From the furniture of good quality (55%), a majority (79%) are passed on to acquaintances or donated to thrift stores. The remaining 21% is discarded on the street or brought to collection centre. In addition, it can be assumed that the 45% of the furniture that is in poor condition follows a similar path, being discarded on the street, or brought to the collection centre.

Thrift stores receive 94% of the furniture directly from the consumer, whilst 6% comes through the waste collection centre. Due to the limited storage capacity, 40% of furniture in thrift stores remain unsold. To make room for new furniture, the unsold furniture is offered for recycling (19%) or incineration (21%) (Van den Heerik & Schootstra, 2021). It must be noted that the 19% of furniture is only offered for recycling and no data are available on whether the furniture offered for recycling is actually recycled or incinerated instead.

3.2.3 Consumer behaviour

The research by Koch & Vringer (2023) finds that the most common reason for furniture disposal is related to aesthetic concerns. For 52% of disposed furniture of good quality, the consumer simply expresses a change in their aesthetic preference. Other reasons for disposal of furniture include the item no longer being necessary (18%), lack of space (17%), moving house (4%) or other (9%).

In the survey by Koch & Vringer (2023), 91% of respondents indicate a willingness to sell or donate their furniture as second-hand items. This contrasts with buying second hand furniture, which 11% of respondents have done. Nevertheless, 70% of respondents express openness to buying second-hand furniture in the future. However, hygiene and quality function as two important barriers. Consumers perceive second-hand furniture as potentially unclean, while also maintaining the notion that new furniture is of better quality compared to second-hand alternatives.

Furthermore, several interviewees highlight the importance of establishing an accessible and affordable disposal system of furniture for consumers within the context of implementing a reverse logistics network. Consumers are reluctant to incur additional costs associated with the logistics of furniture disposal.

3.2.4 Costs

For the high-end segment of furniture, reverse logistics is less of a problem. The retrieval and repair of the furniture is often part of the service the retailer provides. However, the interviews highlight that this is not the case for the lower- and midsegment.

High logistic costs, especially transportation, make the business case for reverse logistics difficult. Repair is often not profitable due to transportation costs. Retailers would incur losses in case they absorb these costs. Alternatively, costs could be transferred to consumers through a price increase on new furniture. However, accessibility of furniture is extremely important for retailers in the mid and lower price segment. Therefore, logistic costs should not drive up the price of the new furniture.

3.2.5 Available data

The interviews highlight the limited availability of data on disposed furniture. Empirical data concerning the quality and quantity of disposed furniture is scarce. In addition, there is little data on aspects such as materials, costs and repairs.

3.2.6 Conclusion

There is no dedicated reverse logistics system for discarded furniture. In the current system, furniture often becomes bulky waste and is incinerated, raising environmental concerns. Thrift stores encounter storage issues due to an oversupply of second-hand furniture and resort to recycling or incineration of furniture.

Despite the consumer willingness to donate or sell their furniture, concerns about hygiene and quality hinder the sale of second-hand items. High logistic costs are identified as a bottleneck for the implementation of a reverse logistic system, which emphasises the importance of cost minimisation. Finally, interviewees highlight the scarcity of available data, emphasising the need for more empirical data.

3.4 Data Analysis: Flow and Volume of Discarded Furniture

The interviews highlight the scarcity of information regarding the flow of discarded furniture, emphasising its critical role in obtaining an understanding of the magnitude of the problem. Initially, a flow was estimated based on data from Intven et al. (2022). However, during a stakeholder session, concerns were raised about the underestimation of consumer-to-consumer transactions and the overestimation of flow from collection centres to thrift stores. Therefore, a more comprehensive data analysis is conducted, incorporating additional sources such as Koch & Vringer (2023), Van den Heerik & Schootstra (2021) and unpublished data from Rijkswaterstaat (RWS).

Research from RWS (2023) [1]estimate that a total of 5,674,458 items of furniture are reused annually. Using this data and data from Koch & Vringer (2023), the amounts of furniture are estimated in Table 6.

Table 6
Estimation of Amount Discarded Furniture in the Netherlands

	Good condition		Poor condition		Total	
	%	#	%	#	%	#
Reuse	43.45	5,674,458	0	0	43.45	5,674,458
Discarded	11.55	1,508,400	45	5,876,884	56.55	7,385,285
Total	55	7,182,858	45	5,876,884	100	13,059,742

Note: in the calculations, it is assumed only the furniture of good quality are reused and thus all furniture in poor condition is disposed of.

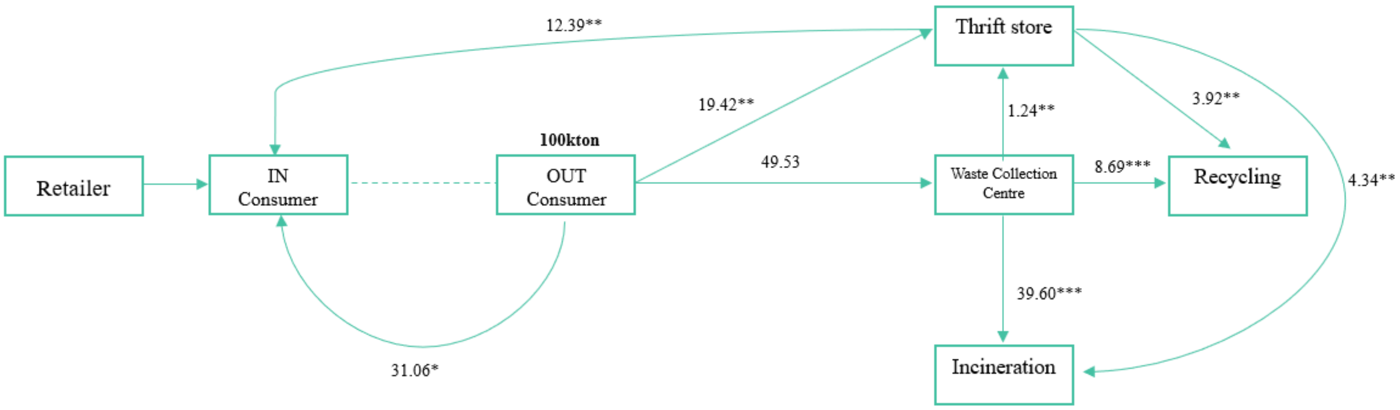
Table 6 shows that the annual disposal of furniture by consumers in the Netherlands amounts to 13,059,742 items. Among these, 5,674,458 items (43.45%) are reused, while the remaining 7,385,285 items (56.55%) are discarded and subsequently incinerated (or recycled). Notably, 1,508,400 items of the discarded furniture are of good quality prior to their incineration, which constitutes approximately 20% of total furniture incinerated.

[1] Data is from research by Rijkswaterstaat on the reuse of furniture which is not published at the time of writing. Data was shared by the researchers in a meeting.

Limited data exists on the flow and volume of discarded furniture. Intven et al. (2022) have estimated the flow of discarded seating furniture. However, discrepancies arise when comparing data from Intven et al. (2022) with that of RWS (2023) and Van den Heerik & Schootstra (2021). For instance, Van den Heerik & Schootstra (2021) report that 6% of furniture received by thrift stores originates from waste collection centres, with the remaining 94% being sourced directly from consumers. Intven et al. suggest that as much as 56% of the furniture received by thrift stores originates from waste collection centres. Given that the data by Van den Heerik and Schootstra (2021) is directly sourced from thrift stores, whereas Intven et al. (2022) acknowledge uncertainty in their data, in the following analysis the data concerning thrift stores is based on Van den Heerik and Schootstra (2021).

Figure 9

Estimation Flow of Discarded Furniture in the Netherlands



* RWS (2023)
** Heerik & Schootstra (2021)
*** Intven et al. (2022)

Based on data from RWS (2023), Van den Heerik & Schootstra (2021) and Intven et al.(2022) the flow for 100kton discarded furniture in the Netherlands is estimated in Figure 9. Within this estimate, 12.61kton is opted for recycling, with 43.93 kton are incinerated. However, it is important to note that not all 12.61kton designated for recycling may necessarily be recycled, potentially resulting in larger quantity of furniture being incinerated. From Table 6, it is estimated that 20% of furniture received by the collection centre is of good quality. Based on the flow of 100kton in Figure 9 approximately 9.91 kton received by the collection centre is of good quality. No data are available on the quality of items based on the destination (thrift store, recycling, incineration). Therefore, the following assumptions for the flow of good quality discarded furniture are made:

1. 100% (1.24kton) of the items offered to the thrift store by the collection centre are of good quality.
2. 50% (4.34 kton) of the items offered for recycling by the collection centre are of good quality.
3. 10 % (4.34 kton) of the items offered for incineration by the collection centre are of good quality.
4. 100% (4.34) kton of items offered for incineration by the thrift store are of good quality.

Thrift stores implement a strict policy for accepting furniture, which implies only items of good quality are accepted. Therefore, the items offered to thrift stores are assumed to be of good quality. Similarly, it is assumed that the items offered by the thrift stores for incineration are of good quality. Insights from the interviews reveal that the decision to offer items for recycling is primarily based on the materials rather than the quality of the item. Therefore, it is assumed that an equal quantity of good quality furniture is allocated towards recycling and for incineration. Under these assumptions, 8.68 ktons of furniture offered for incineration is of good quality. This constitutes 20% of furniture that is incinerated.

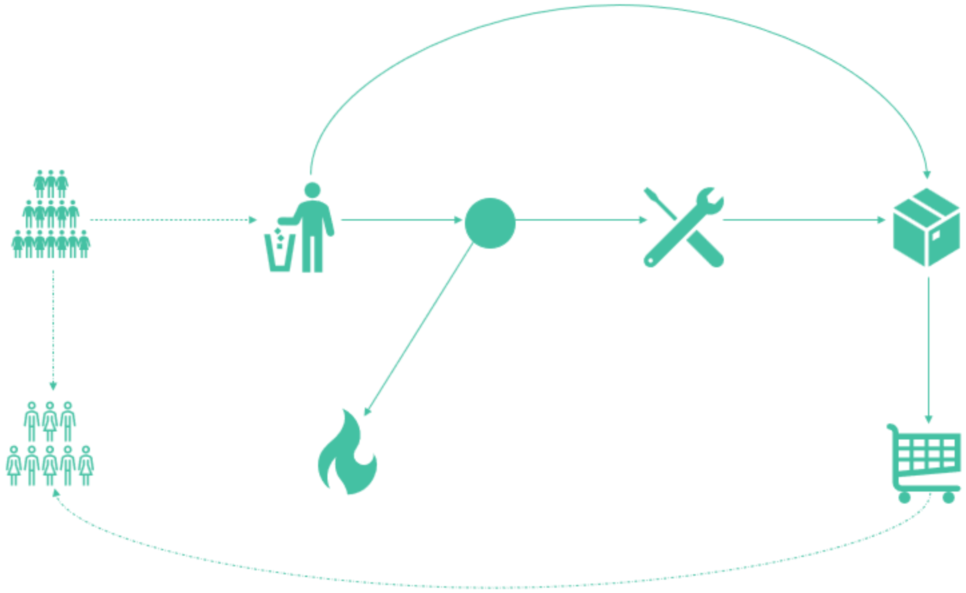
This data analysis provides estimates for the volume (Table 6) and flow (Figure 9) of discarded furniture in the Netherlands. Using the data from Koch & Vringer (2023), Van den Heerik & Schootstra (2021), RWS (2023) and Intven et al. (2022), it is calculated that approximately 43% of furniture disposed of by consumers is reused whilst at least 44% is incinerated. In addition, potentially 13% of furniture is recycled, although it is likely that this figure is lower with more incineration. Therefore, a minimum of 80% of furniture received by waste collection centres is incinerated, whilst a minimum of 21% of furniture received by thrift stores is incinerated. In addition, it is estimated that 20% of furniture that is incinerated is of good quality.

Chapter 4: Methodology

This chapter presents the methodology used in the research. First, the conceptualisation of the reverse logistics network design for discarded furniture is introduced, based on insight from the literature review and interviews. The mathematical formulation for the mixed integer linear programming (MILP) model is provided and the ε-constraint method is described. Finally, the chapter presents an overview of the scenarios for which the model will be solved.

Based on the literature review in Chapter 2 and the interview results in Chapter 3 the design of the reverse logistics network for furniture is depicted in Figure 10.

Figure 10
Reverse Network Design for Furniture



Discarded furniture is collected at the collection centre (*milieustraat*). At the collection centre, the furniture is inspected and then transported to either the incineration plant, repair facility or directly to the storage centre. Furniture that has reached the end of its life cycle is typically incinerated at the waste incineration plant (*Afvalverbrandingsinstallatie (AVI))*. Second, if repair is necessary, the furniture is transported to a local repair facility (*circulair ambachtcentrum*). After repair, it is then transported to a storage centre. If the item of furniture at the collection centre is determined to be in excellent condition, the furniture can directly be transported to a storage centre. Ultimately, furniture is transported from the storage centre to the retailer.

Decisions to be made comprise of the locations and size of the storage centres (central, decentral, or mixed system) and network flow of the furniture. The model is solved and optimised for two objectives: (1) cost minimisation and (2) carbon emission minimisation. A trade-off between the two objectives will be found through the ε-constraint method (see Section 4.1.3).

The flow of furniture from original consumer to the collection centre and flow from retailer to end-consumer is outside of the scope of the model.

In addition, the following assumptions for model formulation and data are made:

1. Locations for collection centres, incineration plants, repair facilities, storage centres and retailers are known and given.
2. The rate of incineration, repair and direct reuse is fixed and not a decision in the model. Several scenarios with different rates are defined in Section 4.2.
3. There is no maximum of repair facilities, storage facilities or retailers to be used.
4. There are no fixed costs directly associated to the use of a facility.
5. Either a central storage facility, multiple decentral storage facilities or both can be used.
6. The central storage facility can only be used if the lower bound is exceeded. The lower bound is equal to the maximum capacity of the decentral storage facilities.
7. All collection centres receive the same number of products of each type.
8. The central storage facility has higher capacity and lower storage and holding costs than the decentral storage facilities.

In practice, the actual supply of products to collection centres will vary. However, due to a lack of available data, a uniform distribution of supply among the centres is assumed. In addition, fixed costs are not considered directly. However, recognizing the overall lower investment costs associated with the use of central facilities compared to decentral facilities, the assumption is made that variable costs (storage and holding) are lower for the central facility and higher for the decentralised facilities. Recycling is not included in the model due to scarcity of data. Stakeholder sessions, however, also emphasised focus should be on reuse and repair instead of recycling. In addition, it can be assumed that items offered for recycling are also suitable for repair.

4.1 Mathematical formulation

To formulate the model, the following notation is introduced.

Indices and sets

m	Set of collection centres	$m \in M$
d	Set of disposal sites	$d \in D$
k	Set of local repair facilities	$k \in K$
s	Set of all storage centres	$s \in S = Sl \cup Sc$
• s_l	Set of local storage centres	$Sl \subset S$
• s_c	Set of central storage centre	$Sc \subset S$
r	Set of retailers	$r \in R$
n	Set of all locations	$n \in N = M \cup D \cup K \cup S \cup R$
p	Set of products	$p \in P$

Where the available flows in the network are:

$A = M \times (D \cup K \cup S) \cup K \times S \cup S \times R$

Parameters

Opm_p	Estimated supply (units) of product *p* at a collection centre
Ca_n	Maximum capacity (m^2) of location *n*, where n in N
LB_s	Lower bound of capacity (m^2) at storage centre *s*
CL_k	Capacity of labour (hrs) for repair at repair facility *k*
Dm_r	Demand (units) for retailer *r*
V_p	Area (m^2) of product *p*
Wp	Weight (kg) of product *p*
DC_p	Disposal costs (€/unit) of product *p*
TC_p	Transportation costs (€/kg*km) for product *p*
HC_{pn}	Holding costs (€/unit) for product *p* at location *n*
SC_{pn}	Storage costs (€/unit) for product *p* at location *n*
RC_p	Material costs (€) for repair for product *p*
LC	Labour costs (€/hr) for repair
RL_p	Labour use (hr) for repair for product *p*
DE_p	Emissions from disposal (CO_2 kg eq./kg) for product *p*
TE_p	Emissions from transportation (CO_2 kg eq./kg*km) for product *p*
RE_p	Emissions from repair (CO_2 kg eq./RC_p) for product *p*
$Dist_{ij}$	Distance (km) from location *i* to location *j* where $(ij) \in A$
RD	Rate of disposal
RU	Rate of direct reuse
RR	Rate of repair
	Where $RD + RU + RR = 1$

Decision variables

X_{pij}	Flow of product p from location i to location j where $(ij) \in A$
F_s	Whether storage centre s is open or not $\{0,1\}$

4.1.1 Objective function

The economic performance of the network is assessed through cost equation (1). The total costs consist of five components: transportation costs (TC), disposal costs (DC), repair costs (RC), holding costs (HC) and storage costs (SC).

$$Minimise\ Total\ Costs = TC + DC + RC + HC + SC \tag{1}$$

The cost components are calculated through equations (1a)-(1e). Transportation costs (1a) are determined by the amount of product and distance travelled. Disposal costs (1b), holding costs (1d) and storage costs (1e) are directly proportional to volume (and type) of product flow. Repair costs (1c) are determined by the costs for material and labour required for the repair. Material costs are based on the original price of the furniture (Russell et al., 2023).

$$TC = \sum_p \sum_i \sum_j TC_p Dist_{ij} X_{pij} \tag{1a}$$

$$DC = \sum_p \sum_m \sum_d DC_p X_{pmd} \tag{1b}$$

$$RC = \sum_p \sum_m \sum_k (RL_p LC + RC_p X_{pmk}) \tag{1c}$$

$$HC = \sum_p \sum_m HC_{pm} Opm_p + \sum_p \sum_i \sum_j HC_{pj} X_{pij} \tag{1d}$$

$$SC = \sum_p \sum_m SC_{pm} Opm_p + \sum_p \sum_i \sum_j SC_{pj} X_{pij} \tag{1e}$$

The environmental performance of the network is assessed through the emission equation (2). The total emissions consist of three components: transportation emissions (TE), disposal emissions (DE) and repair emissions (RE).

$$Minimise\ Total\ Emissions = TE + DE + RE \tag{2}$$

The emission components are calculated through equations (2a) -(2c). Transportation emissions (2a) are determined by the amount of product and distance travelled. The distance matrix will be generated as Euclidean distance in the model. Disposal emissions (2b) are proportional to the amount and type of products incinerated. Emission from repair (2c) come from new material used in repair. These emissions are based on the price of the material costs for repair (Kanyama et al., 2021).

$$TE = \sum_p \sum_i \sum_j TE_p Dist_{ij} X_{pij} \tag{2a}$$

$$DE = \sum_p \sum_m \sum_d DE_p X_{pmd} \tag{2b}$$

$$RE = \sum_p \sum_m \sum_k RE_p X_{pmk} \tag{2c}$$

4.1.2 Constraints

Initially, seventeen groups of constraints are formulated for the model.

$$\sum_p Opm_p V_p \leq Ca_m \qquad \forall\, m \tag{3}$$

$$\sum_p \sum_m X_{pmd} W_p \leq Ca_d \qquad \forall\, d \tag{4}$$

$$\sum_p \sum_m X_{pmk} V_p \leq Ca_k \qquad \forall\, k \tag{5}$$

$$\sum_p \sum_m X_{pmk} RL_p \leq Cl_k \qquad \forall\, k \tag{6}$$

$$\sum_p \sum_m X_{pms} V_p + \sum_p \sum_k X_{pks} V_p \leq Ca_s\, F_s \qquad \forall\, s \tag{7}$$

$$\sum_p \sum_m X_{pms} V_p + \sum_p \sum_k X_{pks} V_p \geq LB_s\, F_s \qquad \forall\, s \tag{8}$$

Constraints (3) – (7) are capacity constraints which ensure that the maximum capacity of each facility is not exceeded. In addition to a maximum capacity of space available, the number of labour hours for repair available are restricted. Constraint (6) ensures the maximum number of hours available for repair per repair facility are not exceeded.

In Constraint (7), the capacity of the (central or decentral) storage centres are dependent on whether the facility is open or not. Constraint (8) ensures that a storage facility can only be used if the lower bound is exceeded to maintain a suitable utilization rate. This is especially important for the central facility.

$$\sum_{m} RDOpm_p = \sum_{m} \sum_{d} X_{pmd} \qquad \forall\, p \qquad (9)$$

$$\sum_{p} RDOpm_p = \sum_{p} \sum_{d} X_{pmd} \qquad \forall\, m \qquad (10)$$

$$\sum_{m} RROpm_p = \sum_{m} \sum_{k} X_{pmk} \qquad \forall\, p \qquad (11)$$

$$\sum_{p} RROpm_p = \sum_{p} \sum_{k} X_{pmk} \qquad \forall\, m \qquad (12$$

$$\sum_{m} RUOpm_p = \sum_{m} \sum_{s} X_{pms} \qquad \forall\, p \qquad (13)$$

$$\sum_{p} RUOpm_p = \sum_{p} \sum_{s} X_{pms} \qquad \forall\, m \qquad (14)$$

Constraints (9) – (14) are flow constraints for the collection centres. These ensure that all the furniture at collection centre is collected for the correct treatment (disposal, repair, direct storage).

$$\sum_{m} X_{pmk} = \sum_{s} X_{pks} \qquad \forall\, k,p \qquad (15)$$

$$\sum_{m} X_{pms} + \sum_{k} X_{pks} = \sum_{r} X_{psr} \qquad \forall\, s,p \qquad (16)$$

Constraints (15) and (16) ensure the flow of furniture for every type of product for the repair and storage facility, respectively. The flow constraints ensure that the flow of incoming products is equal to the outgoing flow.

$$\sum_{s} \sum_{p} X_{psr} \geq D_r \qquad \forall\, r \qquad (17)$$

Constraints (17) ensures that the incoming flow in the retailer at minimum meets the demand of the retailer.

$$X_{pij} \geq 0 \qquad \forall\, p, i, j \quad (18)$$

$$F_s \in \{0,1\} \qquad \forall\, s \quad (19)$$

Finally, Constraints (18) and (19) ensure all flow variables are non-negative and that the decision variable that determines which storage centre(s) to use, is restricted to be binary.

4.1.3 Epsilon(ε) -constraint method

For a multi-objective model, no single optimal solution exists. Instead, multiple Pareto optimal solutions are generated. Pareto solutions are solutions for which the value of one objective function cannot be improved without a decline in the value of the other objective (Mavrotas, 2009). Since there is a large number of pareto optimal solutions, a solution method that accounts for user preferences must be adopted to get a single solution (Marler & Arora, 2010). Two common methods to generate the Pareto set are the *weighting sum* method and the *ε-constraint* method.

In the weighted sum method, the multiple objectives are assigned weights and combined into one single objective function which is then optimised to provide a single optimal solution. The model is then optimised for several different values of the weights assigned to provide a convex approximation of the frontier of pareto optimal solutions (Marler & Arora, 2010; Kim & de Weck, 2005). An advantage of the weighted sum method is that a single optimal solution can be determined. However, this solution is dependent on the weights that are selected by the user and is therefore subjective (Ooi et al., 2017).

In the ε-constraint method, no single optimal solution can be determined but rather multiple pareto optimal solutions are generated. One objective function is optimised while the other objective is transformed into a constraint. The model is then solved as if it is a single-objective problem.

Comparing the two methods, the ε-constraint methods have several advantages (Mavrotas, 2009). First, in the weighted sum method results are influenced by the scale of the objective functions making normalization necessary. In the ε-constraint method, normalisation is not required since objective functions are not combined into one single function. Furthermore, the ε-constraint is regarded to be more efficient than the weighted sum method. For continuous problems, the ε-constraint produces different pareto optimal solutions every run whilst the weighted sum method can produce identical solutions with different weights. In addition, for (mixed) integer problems, the ε-constraint method can produce unsupported efficient solutions, whilst this is not possible with the weighted sum method.

In this study, the ε-constraint is therefore used to retrieve the Pareto set. Specifically, the AUGMECON method by Mavrotas (2009) since it is found to perform better than the conventional ε-constraint method.

The following ε-constraint model is then proposed:

$$Minimise\ f_1 + eps * s_2 \quad (20)$$

s.t.

$$f_2 + s_2 = f_{min2} + \alpha(f_{max2} - f_{min2}), \quad (21)$$

$$where\ 0 \leq \alpha \leq 1$$

$$Constraints\ (3) - (19)$$

In this formulation, f_1 corresponds to the "Total Costs Function" (Equation 1) and f_2 corresponds to the "Total Emissions Function" (Equation 2) and s_2 describes the slack variable. The minimum (best) and maximum (worse) value correspond to f_{min2} and f_{max2}, respectively and are taken from the pessimistic and ideal points. The α dictates the relaxation of the emission constraint with incremental steps of 0.1, starting from 0 and progressing to 1. When α is set to 0, it corresponds to emission minimisation, whereas a value of 1 corresponds to cost minimisation.

4.2 Scenarios description

The model will be solved for two types of scenarios: the logistical system for storage (1) and the rate of total reuse (2).

Storage capacity is highlighted as a bottleneck in Chapter 3. Therefore, storage is an important aspect to incorporate and consider in the implementation of a reverse logistics network design. The influence of three storage scenarios is considered in the model. These logistical systems for storage are described in Table 7.

Table 7
Description of Storage Scenarios

System	Description
Central storage	A central storage facility with high capacity and lower holding and storage costs.
Decentral storage	Multiple smaller decentral facilities with lower capacity and higher holding and storage costs.
Mixed storage	A central storage facility with high capacity and lower holding and storage costs AND multiple smaller decentral facilities with lower capacity and higher holding and storage costs.

The model will be run for the three systems to compare its costs and emissions. Furthermore, five scenarios with different rates of incineration, direct reuse and repair are considered (Table 8). The different rates were determined in consultation with *het Groene Brein*. A comparison of the scenarios can give an understanding of the influence of incineration, reuse and repair on costs and emissions.

Table 8
Description of Reuse Scenarios

		Total reuse	
Scenario	Incineration (%)	Direct reuse (%)	Repair (%)
1	75	20	5
2	50	20	30
3	25	20	55
4	80	20	0
5	100	0	0

The direct reuse rate is the same for all scenarios, except Scenario 5. Scenario 5 describes a state in which all furniture that is collected at the collection centre is incinerated which is the closest to the current situation. Scenario 4 describes a case in which the incineration of the 20% of furniture that is in excellent state is prevented and instead reused, but no repair is implemented. Scenario 1 to 3 describe situations in which the incineration of the 20% of furniture of good quality is prevented and reused. In addition, a percentage of furniture is repaired and reused instead of incinerated.

Chapter 5: Results

This chapter presents the research findings, highlighting the outcomes of the model in terms of the logistic system and reuse scenarios. A detailed examination of costs and emissions is provided with a description of the distribution patterns. The chapter also describes the Pareto frontier and concludes with the results of the sensitivity analysis, describing the effect of an increase in transportation and disposal costs.

The model is executed for all combinations of logistic scenarios and reuse scenarios. The model is solved on a personal computer (through MyWorkspace) with FICO IVE-Xpress 8.9 64-bit using an Intel ® Core, 1.60 GHz processor with 8GB RAM under a Windows 11 (education) operating system. Average CPU time is around 120 seconds for all scenarios. An overview of data and assumptions made can be found in Appendix B. Table 9 shows the costs and emissions for all combinations of logistic system and reuse scenario.

Table 9

Results for Costs and Emissions per Furniture per Day

	Costs (€ furniture per day)				Emissions (kg CO2 eq. furniture per day)			
Scenario	Central	Decentral	Mixed (a)	Mixed (b)	Central	Decentral	Mixed (a)	Mixed (b)
1	250,537	252,473	250,005	252,473	347,065	343,826	345,403	343,826
2	568,106	571,374	566,954	571,374	263,695	256,518	260,288	256,518
3	895,262	900,010	893,140	900,010	181,326	170,381	176,418	170,381
4	187,245	188,777	186,793	188,777	363,995	361,385	356,760	361,385
5	198,939	198,939	198,939	198,939	451,655	451,655	451,655	451,655

(a) - Cost minimisation

(b) - Emission minimisation

5.1 Logistic System

For all reuse scenarios, the optimal choice remains consistent. In terms of cost minimisation (a), the mixed system gives the lowest cost. However, when it comes to the minimisation of emissions (b), the mixed system aligns with the decentralised system. This indicates that for the reduction of emissions, the mixed system effectively transforms into a decentralised system, rendering the central storage facility unused.

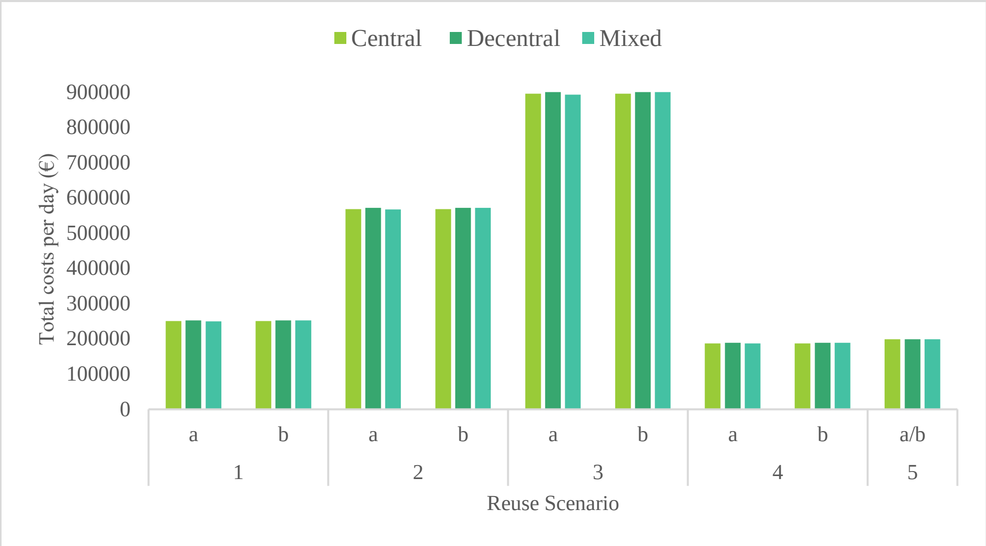
There is no distinction between cost minimisation (a) and emission minimisation (b) for the centralised and decentralised systems. Since all storage centres within the system have identical capacities and costs, there is no trade-off between greater distance and lower holding- and storage costs.

A decentralised system, while incurring the highest costs, gives the lowest emissions due the reduced travel distance. The central system gives lowers costs than a decentralised system, but higher costs than the mixed system for cost minimisation (a). For emission minimisation (b), the centralised system gives the lowest cost for all scenarios. However, it does give the highest emissions among all three systems.

5.2 Reuse Scenarios – Mixed System

The differences between logistic systems are small. However, the difference between reuse scenarios is more apparent. Comparing the reuse scenarios for total costs, Figure 11 shows that, in general, the scenarios with higher percentage of total reuse have higher costs. For the mixed system, Scenario 3 gives a cost increase of +349% (+352%) in case of cost (emission) minimisation compared to Scenario 5. Meanwhile, Scenario 4 gives a -6% (-5%) reduction in costs for cost (emission) minimisation compared to Scenario 5. This result shows that a 20% decrease in furniture incineration, replaced by the reuse of furniture, results in a cost reduction compared to the existing situation.

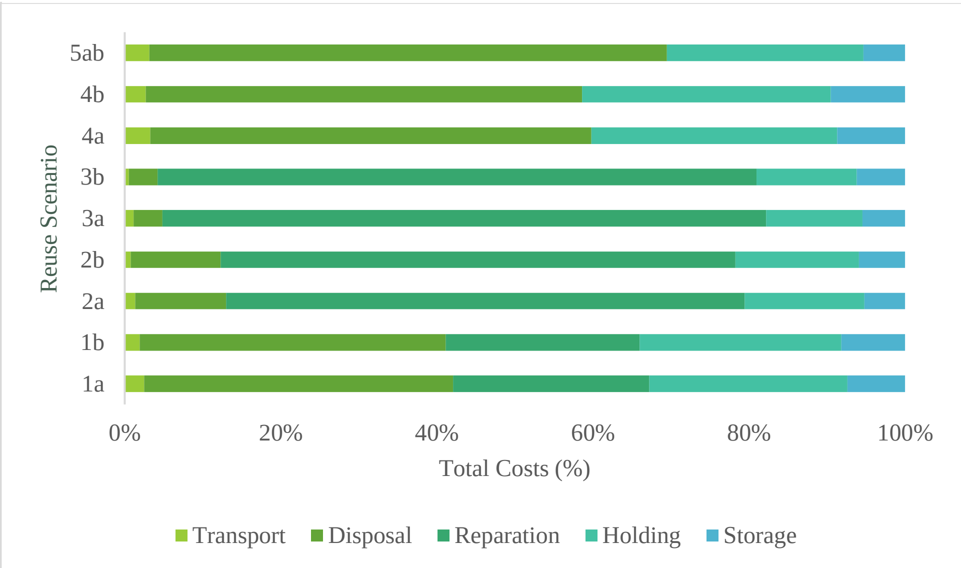
Figure 11
Total Costs for Furniture per Day



(a) - Cost minimisation
(b) - Emission minimisation

Figure 12 illustrates the distribution of costs within a mixed system for both cost minimisation (a) and emission minimisation (b). Repair costs constitute the largest share of the total costs in scenarios involving repair, especially Scenario 2 and 3. In scenarios with a high level of incineration, disposal costs represent the largest share of the total costs.

Figure 12
Distribution of Costs for a Mixed System



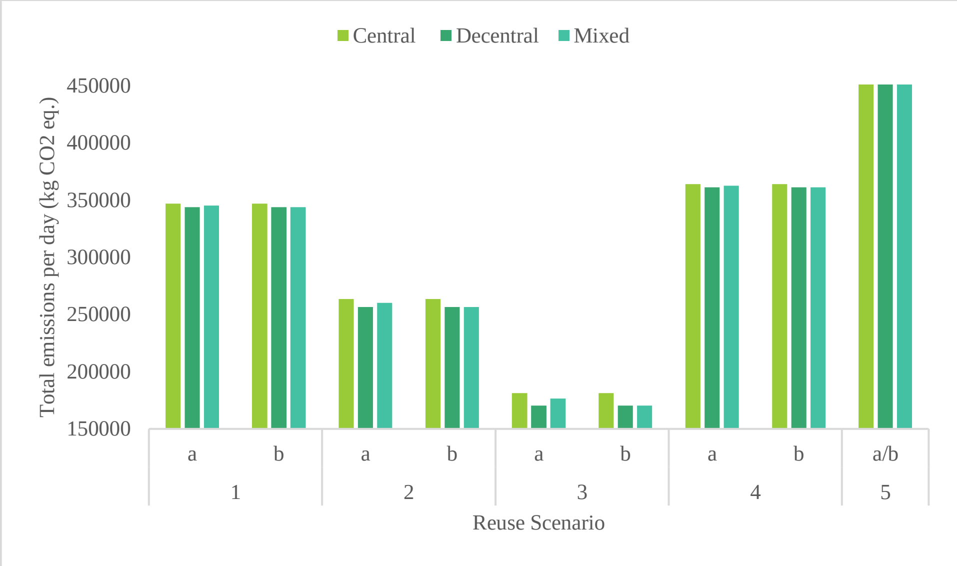
(a) - Cost minimisation
(b) - Emission minimisation

Although the share varies, the transportation costs remain a minor contributor to overall costs for all scenarios, with a more substantial share in scenarios with a higher level of incineration.

Furthermore, a comparison of costs between the two objective functions shows a difference in transport, holding and storage costs. In the context of cost minimisation, the use of the central facility leads to a higher proportion of transport costs with a reduced share in holding and storage costs compared to emission minimisation. For the minimisation of emissions, only decentralised storage facilities are used, resulting in shorter travel distances but increased costs for storage and holding relative to cost minimisation.

Figure 13 shows the total emissions for every combination of reuse and logistic scenario. Again, the differences between logistic systems are relatively small whilst the differences between reuse scenarios are more apparent.

Figure 13
Total Emissions for Furniture per Day



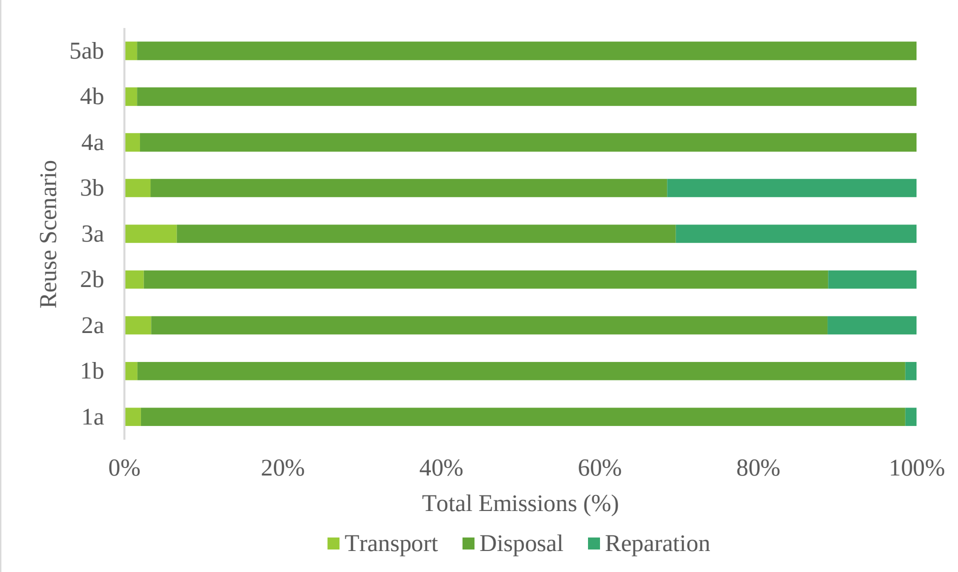
(a) - Cost minimisation
(b) - Emission minimisation

Comparing the reuse scenarios for total emissions, Figure 13 shows that as the percentage of total reuse increases, the overall emissions decrease. In the mixed system, Scenario 4 gives a -20 (-20%) reduction in emissions for cost (emission) minimisation compared to Scenario 5. Additional to direct reuse, scenarios with higher percentage of repair give a larger reduction in emissions compared to Scenario 5. Scenario 3 gives the lowest total emissions with a reduction of -61% (-62%) for cost (emission) minimisation compared to Scenario 5.

Figure 14 illustrates the distribution of emissions within a mixed system for both cost minimisation and emission minimisation. Disposal emissions constitute the largest share of total emissions for all reuse scenarios, even Scenario 3. The share of repair emissions is larger for scenarios with a higher percentage of repair. Furthermore, transport emissions are a minor contributor to the total emissions for all reuse scenarios, although its share is more substantial in scenarios with a higher level of overall reuse. Finally, comparing transportation costs constitute a larger share of the total emissions in the context of cost minimisation compared to emissions minimisation.

Figure 14

Distribution of Emissions for a Mixed System



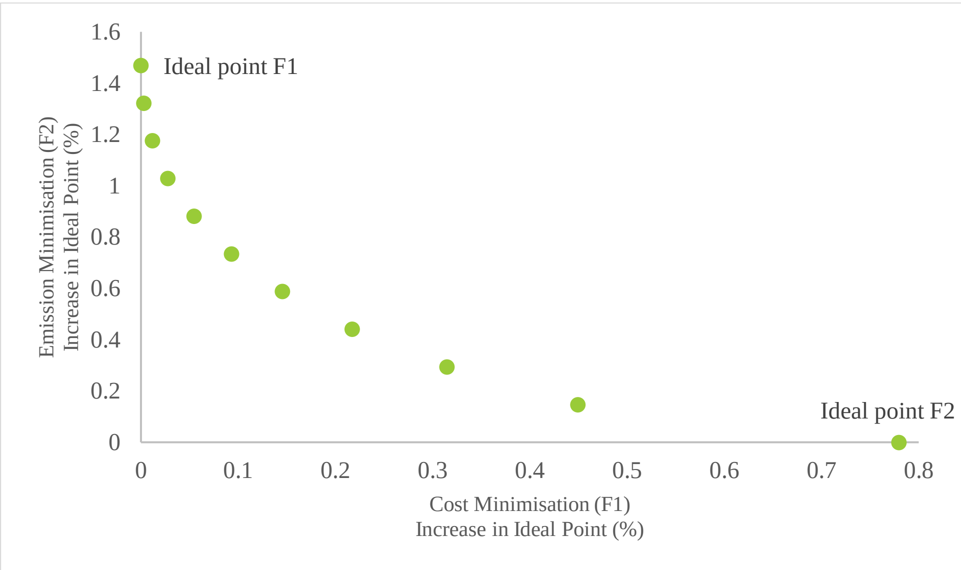
(a) - Cost minimisation
(b) - Emission minimisation

5.3 Pareto Efficiency

As described in Chapter 4.1.3, the ε-constraint method was used to find the set of pareto optimal solutions. The pareto solutions are exclusively found for the mixed system since there is no distinction between the two objectives for the centralised and decentralised system.

Figure 15

Pareto Frontier



Pareto solutions are identified for all Reuse Scenarios 1 – 4, with the same pattern observed across all four scenarios, as depicted in Figure 15. In the process, incremental steps of 0.1 are taken, beginning at a value of 1 (cost minimisation). With each incremental step of 0.1, a similar quantity of emissions is reduced. However, the associated additional costs increase for every step. This indicates that the reduction in emissions from 1 to 0 compares to the reduction from 0.1 to 0, although the additional costs are substantially lower for the transition from 1 to 0 compared to the transition from 0.1 to 0.

5.4 Sensitivity Analysis

A sensitivity analysis is applied to several parameters to examine changes in the objective functions.

The effects of an increase in transport costs (*5 and *10) are examined for Scenario 1-3. Figure 17 and Figure 16 show the total costs for the logistic systems and reuse scenarios 1-3. With an increase in transportation costs, total costs increase for all systems and reuse scenarios. The central system now gives the highest costs for all scenarios. The difference in costs between the mixed and decentral system under cost minimisation decreases, however, the mixed system still gives the lowest cost.

Figure 17
*Sensitivity Analysis with Increased Transport Costs (*5)*

Figure 16
*Sensitivity Analysis with Increased Transport Costs (*10)*

(a) - Cost minimisation
b) - Emission minimisation

Implementing a 50% increase in disposal costs, Figure 18 shows a comparison of the total costs between the base level and the cost increase. Total costs increase for all reuse scenarios; however, the increase is relatively larger for the scenarios with higher incineration percentage. Although there is the decrease in the difference in costs between the reuse scenarios, Scenarios 4 and 5 remain the lowest in cost.

Figure 18

*Sensitivity Analysis with Increased Disposal Costs (*1.5)*

(a) - Cost minimisation
(b) - Emission minimisation

Similar results are found for sensitivity analysis conducted for an increase in storage capacity and storage costs. The optimal choice remains similar for all scenarios.

Chapter 6: Discussion

This chapter presents a discussion of the results of the study. First, the data analysis from Chapter 3.4 is examined. Then the results from the scenarios are analysed and compared to literature. The implications for policymaking are discussed. Finally, the chapter provides an assessment on the limitations of the study and offers recommendations for further research.

6.1 Data Analysis: Flow of Discarded Furniture in the Netherlands

One of the objectives of this study was to address the data insufficiency regarding the reverse flow of furniture in the Netherlands. Whilst extensive data exists of the forward flows of furniture, little data exists on its reverse flows in the Netherlands. This is also found by Intven et al. (2022), which served as the sole source of data on reverse flows in the initial stages of this study. This report, however, is focused exclusively on large seating furniture. In addition, the authors acknowledge that the data of the reverse flows is of poor quality, in contrast to the reliable data on the forward flow. During a stakeholder session, a participant highlights the underestimation of the share of consumer to consumer in the reuse of discarded furniture. Furthermore, the difference between the data provided by Intven et al. (2022) and that from Van den Heerik and Schootstra (2021) on the flow of furniture from collection centre to thrift shop highlighted the need for a more comprehensive data collection. Therefore, in this study the flow of discarded furniture is estimated using data from Van den Heerik and Schootstra (2021), RWS (2023), Koch and Vringer (2023) and Intven et al. (2022). In addition, this study presents the scale of furniture waste in the Netherlands by providing an estimation of the annual volume of discarded furniture in the country, a data point that has not been quantified before.

6.2 Analysis of Scenarios

The aim of this research was to introduce a network design for the reverse logistics system focusing on the reuse of discarded furniture. The research involved the development and implementation of a MILP model for several logistic systems and reuse scenarios. The analysis reveals that the mixed system is the most cost-effective while a decentralised system is optimal for minimising emissions. In case of emission minimisation, the mixed system behaves like a decentralised system, rendering the central facility unused. The central system is found to be more cost-effective compared to decentralisation but results in the highest emissions due to increased transport distances.

Centralised facilities often emerge as the preferred option for cost minimisation over decentralised facilities, primarily due to their lower investment costs (e.g., Du & Evans, 2008). However, Agrawal et al. (2015) suggest that in context of reuse systems, decentralisation might be preferred due to high transportation costs. This study did not incorporate investment costs directly, however, lower variable costs for the central facility effectively replicate the cost difference between the two systems. The results of the study support the initial notion, where a central system is more cost effective compared to decentralisation. A mixed system, however, proves to be the most cost-effective. This indicates that the lower variable costs with the central facility does not entirely offset the additional transportation distance (and thus costs). Consequently, in the mixed system there appears to be a trade-off between reduced variable storage costs with the increased transportation costs. Furthermore, the sensitivity analysis conducted in the study shows that variations in transportation costs, variable storage costs, and capacity of decentralised facility does not influence the optimal choice for the logistic system. Although changes in data thus do not result in differences in optimal choice, the systems overall perform relatively similar with marginal differences in terms of costs and emissions.

However, substantial differences are observed when examining the reuse scenarios. Considering the mixed system, scenarios with higher percentage of reuse are associated with higher costs but also lower emissions. The increased costs are primarily attributed to substantial repair expenses, with a relatively small contribution from transportation costs. Scenarios with high percentage of disposal have the highest emissions which can be attributed to high disposal emissions. Furthermore, the Pareto Frontier shows the trade-off between costs and emissions within the network design. The results indicate that the costs of emission reduction increase disproportionally.

Thus, the implementation of a reverse logistic system for discarded furniture entails a significant increase in costs compared to the current disposal system. However, the findings suggest that the direct reuse of furniture within a reverse logistic system can mitigate both financial costs and environmental emissions compared to the disposal of furniture. Notably, the increased costs of the network design primarily stem from the (labour and material) costs of furniture repair. This is in line with findings in the report by Forrest et al. (2017), which highlights the difficulty and high cost of repair for furniture. However, existing literature on reverse network design specifically, fail to mention repair as a bottleneck for the implementation of a reverse network. The literature review in Chapter 2 highlights the limited implementation of repair practices within reverse network designs for household appliances. Instead focus within these frameworks is on recycling and/or remanufacturing of used products. Notably, the only study implementing repair practices (Sardnia et al., 2020) does not highlight repair costs as a bottleneck for the reverse network design or as a substantial contributor to overall costs.

Furthermore, despite transport costs being suggested as a bottleneck for the implementation of reverse logistics for furniture, the outcome of the research shows transportation costs constitute a minor fraction of total costs. From this it can be inferred that there exists a disparity between the perceived bottleneck, namely logistic (transportation) costs, and the actual primary expense which is repair costs. One explanation for this disparity might be the lack of emphasis of repair in reverse network planning. In addition, it is possible that stakeholders are primarily concerned with costs they are responsible for. While producers and retailers would be responsible for logistic costs, such as transportation, costs of incineration are covered for by the consumer and government. As a result, these costs are not accounted for by the industry.

6.3 Practical Implications

The findings of this study also hold significance for policy makers. The results of the study highlight the importance for policy makers to reconsider the allocation of costs from discarded furniture in the implementation of an Extended Producer Responsibility (EPR) for furniture. For example, a policy where the producer is responsible for incineration costs also gives the producer an incentive to prevent disposal of furniture. In addition, if Dutch policy makers adopt the French ERP framework, retailers would be obligated to sell a fixed percentage of reused furniture (Vernier, 2021; Forrest et al., 2017). This study's findings provide insight into the environmental and economic impact associated with various percentages of reuse.

Furthermore, the study offers valuable insight for practices that can be promoted to reduce emissions from the furniture sector. The findings highlight that direct reuse can decrease both costs and emissions compared to incineration of furniture. Policy should therefore focus on measures to promote direct reuse of furniture. In addition, strategies to limit the costs of repair should be considered. For example, encouraging consumers to repair minor fixes themselves (DIY) can reduce labour costs. Another approach is to lift the value-added tax (VAT) on labour, as is done for repair services in Sweden (Forrest et al., 2017).

6.5 Limitations and Recommendations

This study offers insight into the flow of discarded furniture, the design of a reverse network and its association costs. Yet, some limitations and opportunities for improvement should be considered.

First, due to the lack of data on discarded furniture, this study heavily relies on estimations from several sources, including survey data from Koch & Vringer (2023) and RWS (2023). The data from these surveys reflects consumers assertions rather than actual behaviour. Therefore, the volume of discarded furniture calculated in this study should be thus seen as an approximation. Since this volume is a crucial data input, substantial deviations from the estimated volume can have a significant impact on the results. Thus, to improve accuracy of the data and therefore the model, more empirical data regarding e.g., volume, quality (state), type, materials is required.

Second, the study assumes supply is certain and uniform for all collection centres. In reality, supply will fluctuate since furniture disposal commonly occurs in situations such as house renovations or moving. This uncertainty in supply is also key characteristic of reverse network designs (Fleishmann et al., 2004). In addition, supply will be varied across collection centres in the country influenced by factors such local population density and demographics. To improve the model, it can be transformed from a deterministic to a stochastic model by including supply uncertainty to accommodate for the impact of seasonality and variable supply among collection centres.

Furthermore, the current model does not incorporate the sale of the (repaired) furniture. Thus, value-added from repair, such as profit from the sale of repaired furniture, is not included. Therefore, it is possible that the actual economic impact of repair, and thus overall reuse, is overestimated in this study. In addition, only the direct impact on emission reduction is considered, while the potential indirect effect of preventing new furniture production is neglected. Thus, emission reduction from reuse and repair is possibly underestimated in the study. Future research could incorporate the effect of the sale of (repaired) furniture to provide a more comprehensive understanding of the economic and environmental impact.

Finally, in the scope of the study, the initial consumer is excluded with a focus on the activities after collection instead. However, Chapter 3 highlights the challenges of furniture transportation by the consumer. Flexibility and low costs are most important for the consumer in the discarding of their furniture. Minimal effort by consumers and municipal collection services often lead to damage in the collection of discarded furniture, thereby reducing the quality. Further research can expand the model to include the initial consumer and explore the optimal approach of furniture collection to prevent damage.

Chapter 7: Conclusion

This study presents a reverse network design for the reuse and repair of discarded furniture in the Netherlands. The estimation of furniture flows offers insight into the volume of discarded furniture, which has previously been unquantified. The research involved the development and implementation of a MILP model for several logistic systems and reuse scenarios. The model's findings show that incineration of furniture proves to be more cost-effective than repair. However, a shift from incineration towards direct reuse can reduce costs. Furthermore, the promotion of furniture reuse will be crucial for the reduction of emissions.

The study highlights repair costs as the primary expense in the context of furniture reuse. While initially transportation costs were emphasised as the major bottleneck, the findings demonstrate that their contribution to overall costs remains relatively minor. Therefore, a disparity between perceived challenges and actual cost driver is identified, which calls for policy intervention to reallocate the responsibility of costs from discarded furniture. Furthermore, policy measures should prioritise the promotion of direct reuse and strategies to limit repair costs.

Several limitations of the study point to the need of further research. Addressing data insufficiencies, incorporating supply uncertainty and include the value-added aspect are potential areas for exploration. Finally, the inclusion of the first consumer and the evaluation of furniture collection systems can provide further insight into the effective implementation of a reverse logistics network for furniture.

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