Network Designs for LPG Tanks in the Netherlands

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Abstract

This paper presents a case study of a typical reverse logistics problem: the redesign of a recycling system for LPG-tanks. Uncertainty in systems behavior and the difficulty in gathering reliable data are common in reverse logistics network design questions. Especially while the total costs consist for almost 50% of transportation costs, reliable transportation costs estimations are crucial. We used a vehicle routing model to solve this data problem and fed the estimations to a mathematical programming model. The system uncertainty was tackled with sensitivity analysis.

Keywords: Reverse logistics; Network design; Facility location

1. Introduction

Discarded products cause an enormous flow of waste. Policy driven producer responsibility forced industry in many EU countries to set up collection and recycling systems in order to significantly reduce waste (directive 2000/53/EC). In the Netherlands, the producer responsibility is often transferred to sector wide organizations, setting up a collective collection and recycling system because many OEMs are foreign. Auto Recycling Nederland (ARN) is such a branch organization for the collection and recycling of end-of-life vehicles (ELV) in the Netherlands. ARN is the organizer, controller and financer of the system. ARN

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makes use of existing ELV-dismantlers, collection and recycling companies for achieving high-grade recycling of the ELV. Everyone buying a new car in the Netherlands pays a waste disposal fee, currently 45 euro. This disposal fee funds the collection and recycling activities that are not economically self-supporting. Consumers can hand in their end-of-life automobile, regardless of the brand, at one of the 266 ELV-dismantlers affiliated with ARN. Currently about 86% of the weight of the car is recycled. ELV-dismantlers can claim premiums based on the actual number of kilograms, liters or pieces of material dismantled and submitted to the ARN recycling system. An administrative system controls the ELV-dismantlers in the amount of material they can provide, based on the number of wrecks deregistered by the company in the Dutch car register.

The system is operative since 1995 and has recycled almost 1.8 million cars since that time. In 2001 about 285,000 wrecks, which is about 88% of the total number of wrecks that came available in the Netherlands, were collected and recycled by the ARN system for 85% of the average vehicle weight. Van Burik (1998) explains in detail how the concept of ARN was originated. De Koster et al. (2000) describe a system for consumer electronics recycling, very similar to ARN.

1.1 The ARN reverse chain in more detail

Let us now describe the ARN reverse chain in more detail. The recycling process starts with the dismantling of the ELV. 19 Material fractions are separated from the car and are stored for recovery. The remaining body is shredded and separated into different material clusters (e.g. various metals), while the shredder waste is processed thermally. The separate treatment for the 19 materials mentioned earlier is either because they contain hazardous substances, which have a negative environmental impact, or because they possess good opportunities for high-grade recycling. After dismantling, the 19 materials are stored in storage equipment provided by ARN and dedicated for that specific material. Once the ELV-dismantler has a minimal number of filled storage units, the collection company is contacted for collecting the materials. After collection, the materials are bulked up in containers for transport and transferred to the selected recycler for the material in consideration (figure 1). These recyclers are selected by ARN for their quality of recycling, so that the environmental impact is minimized. For example, used oil is recycled into lubricating oil, while tires are recycled to granulated rubber which is used in the production of sport floors and tiles for playgrounds (environmental report 2001, Auto Recycling Nederland B.V.).

figure 1 about here

The ELV-dismantlers are not obliged to hand in all materials to the collection companies. They are free to take out some parts of the wreck for trading. The trade in secondhand parts is a lucrative business for ELV-dismantlers. Demand is created by insurance companies in the Netherlands that offer "green car insurance"; damaged cars are repaired with used parts. The ELV-dismantlers are the main providers of these secondhand parts. However if the parts cannot be sold, the premium offered by ARN makes it attractive to recycle at material level.

This paper deals with a case in which the trade-off between secondary trade (economics) and material recycling (safety) plays a key role. The paper is built up as follows, section 2 describes the problem, section 3 presents the proposed alternatives, section 4 links our research to the literature on reverse logistics, section 5 discusses the methodology, section 6 works out the data collection, implementation, validation and verifications, section 7 presents the results of our analysis, while section 8 presents the final conclusions.

2. Problem description

Although the ARN system is overall considered a success (targets are met within budget), there are concerns about the recycling of LPG-tanks. LPG-tanks are one of the 19 separate materials to be recovered from the ELV before shredding. Approximately six percent of the cars in the Netherlands uses this fuel. The LPG-tank in an ELV has to be degassed, because the remaining gas in the tank can turn the ELV into a small bomb. Degassing of LPG-tanks is obliged before reuse or material recovery can take place. Degassing is a process in which the tank is put under pressure, so that the gas can escape through valve, which is connected into a storage tank. This process guarantees that the LPG-tank is absolutely safe and contains no trace of gas.

In the Netherlands there is only one degassing facility for LPG-tanks, which is part of the ARN-system since 1999. ELV-dismantlers can store dismantled LPG-tanks in a rack with a capacity of 12 tanks, which are collected on call if the rack contains at least 10 LPG-tanks. The collected LPG-tanks are brought to the degassing facility for degassing. The regained gas is reused as fuel; the bad LPG-tanks are traded as scrap, while the good LPG-tanks are traded as secondhand by the degassing company. Hence, degassed tanks are not returned to ELV-dismantlers. The lucrative trade opportunities for LPG-tanks cause the ELV-dismantlers not to hand in their LPG-tanks for degassing. Instead they sell the used tanks, still filled with gas, right away on the market, thereby causing a high safety risk. As a result, a small fraction of the LPG-tanks is degassed and recycled through the ARN-system. Based on data of the Dutch vehicle register one can determine how many LPG-tanks should be degassed. In 2001 there were 17,120 vehicles with LPG-tanks signed off in the register for dismantling by ARN affiliated ELV-dismantlers, while only 6,734 LPG-tanks were handed in for degassing (see figure 2). Although there is some gap in this registration (not all signed off vehicles are dismantled immediately), this gap cannot be of this size and should smoothen out over the years. This means that a large part of the LPG-tanks is traded without degassing, which is likely to result in environmentally unfriendly recycling.

figure 2 about here

ARN wants to solve this by making the system more attractive for ELV-dismantlers. In the new system the degassed LPG-tanks should be returned to the ELV-dismantlers so that they can trade the tanks themselves. The lucrative business for ELV-dismantlers is sustained, while the safety can be guaranteed and the degassing company is compensated for the higher costs. To implement such a system, a few alternative concepts have been worked out. The management of ARN did not wish to make a decision before a thorough quantitative analysis was conducted on alternative solutions and possible strategies. Our analysis will show that solutions can be found that are both safe and economically sound using mathematical optimization.

3. The proposed alternative systems

The new system should be a system with returns of degassed LPG-tanks. However, if the lead-time between degassing and return becomes too long, there is a risk that ELV-dismantlers will not use the degassing service and simply continue trading non-degassed LPG-tanks. The idea is therefore to use a carrousel system: ELV-dismantlers are visited periodically, where in every period a rack with non-degassed LPG-tanks is exchanged for the rack with degassed LPG-tanks from the previous period. From service point of view a period of 3 or 4 weeks is considered to be acceptable by ARN management.

In the current situation the storage racks each have a capacity of 12 LPG-tanks. A typical ELV-dismantler should process more than 2,000 wrecks a year for an acceptable fill-rate of the storage rack, which is not realistic. Hence: underutilization of rack capacity and trucks with fixed collection intervals. A smaller rack with only 6 storage positions might help to improve the efficiency of the operations. Other sizes are not applicable and ARN will only use one type of storage rack, because of handling purposes.

A periodic system is expected to result in transports with a relative low fill-rate, therefore one would like to consider whether it is possible to have a mobile degassing facility built up on a small truck. An engineering company worked this out, and based on a slightly different degassing technique, this turned out to be possible (Auto Recycling Nederland, 2001).

Combining the above two basic strategies are considered:

1. Central strategy. LPG-tanks are collected periodically at the ELV-dismantlers and brought to the current centrally located degassing facility. After degassing the LPG-tanks are redistributed. Degassing takes place at one location.
2. Regional strategy. LPG-tanks are collected to a number of depots located in the Netherlands that are periodically visited by the mobile degassing facility that degas the present LPG-tanks at the depots. Degassing takes place on a (small) number of locations.

In the central strategy the degassing location is known, the current degassing facility. For the regional strategy the number of depots and their geographic location need to be determined. Originally, a third alternative strategy was considered, where every ELV-dismantler was visited periodically by the mobile degassing facility. This option, however, soon turned out to be infeasible, because the Dutch government would not grant licenses for LPG-tank degassing at every ELV-dismantler's site.

Summarizing, the following questions were posed by the management of ARN and need to be analyzed:

- What is the best strategy (central or regional) and in case of the regional strategy what is the optimal number of depots and their geographic location?
- What are the effects on costs for a 3- or 4-week periodic system?
- What are the effects on costs for a storage rack with 6 or 12 positions?

In the next section we relate our work to literature on reverse logistics.

4. Overview of literature in reverse logistics

Reverse logistics is the management of good flows in the opposite direction of the traditional supply chain, with the purpose of value recovery or proper disposal (Rogers and Tibben-Lembke, 1998). Quantitative analyses have proven to be useful in the supply chain management. It is therefore not surprising that operations research is applied frequently in reverse logistics. Fleischmann et al. (1997) give a survey of quantitative models in reverse logistics and distinguish three application areas: distribution planning, inventory management and production planning. Our research is part of distribution planning, with an emphasis on network design for the collecting of LPG-tanks for degassing and redistributing to the ELV-dismantlers for the selection of the appropriate recovery option. Network design models described in literature on reverse logistics are not essentially different from traditional location allocation and facility location models used in forward logistic network design studies. Fleischmann et al. (2000) give an excellent overview on a number of case studies that used mathematical models and derive a characterization of networks. The use of mixed-integer linear programming has been proven to be the dominant technology in nearly all case studies reported on network design. Shih (2001) applies an MILP model for determining the network design for the recycling electrical home appliances. Louwers et al. (1999) and Reallf et al. (2000) address the network design for carpet recycling using a MILP model. Barros et al. (1998) apply a MILP model for the design of a recycling system for polluted sand. Krikke et al. (1999) report on the use of a MILP model for the network redesign for discarded copiers. Spengler et al. (1997) develop a generic MILP model and report on the application in the iron and steel industry. De Brito et al. (2002) give an extensive overview on reverse logistics indicating the critical factors.

Uncertainty is inherent to most reverse logistics systems. In general there are two sources of uncertainty in reverse logistic. First, uncertainty in the behavior of the system caused by the lack of control mechanisms; this includes for example volume, timing, and product compositions of the returns. Second, uncertainty in estimations caused by a lack of data. Many systems have to be setup without having any reference or information of comparable systems: estimated data is used. Errors in input data can have significant impact to the resulting network design. Realff et al. (2000) use a robust optimization framework taking several scenarios into account in the mathematical optimization, other authors often suffice with extensive sensitivity analysis.

In our research we apply a combination of two models for formulating appropriate answers to the questions posed by ARN. A mixed integer linear programming is used to select the depot locations in the regional strategy and the allocation of the ELV-dismantlers to the depots. As an input we needed good estimations for the transportation costs to the different depots. These data are not available at ARN. By modeling the operational transportation activities in a transport model we are able to make reliable estimations and to solve our data problem. The system uncertainty is tackled with sensitivity analysis. The application of a combination of models distinguishes our research from other cases described in literature.

5. The methodology

Our methodology consists of two steps. In the first step, a vehicle routing model is used for estimating the transportation costs for each scenario. Second, an optimization model is performed to minimize the total costs for each scenario and to determine the optimal number of depots and their geographic location in case of the regional strategy.

figure 3 about here

5.1 Vehicle routing model

To evaluate and analyze the influence of the length of the collection period and the size of the storage rack, some additional calculations are made. A collection period is defined as the time between two consecutive visits of the collection truck for collecting and returning storage racks. For each setting of the collection period and the size of the storage rack we need to calculate the volume in number of racks and LPG-tanks per ELV-dismantler. These data are crucial inputs for the vehicle routing model determining the transportation costs for allocating an ELV-dismantler to a certain depot.

A vehicle routing model determines the minimum cost routing of trucks visiting certain locations for delivery and pick-up of load, taking into account practical restrictions. More mathematical: consider a complete undirected graph G = (V, E), where the set V consist of one depot and a number of ELV-dismantlers. The set of edges E, are the connections between the locations, traveling along an edge e incurs a certain costs c_e and a certain traveltime t_e. Find a set of routes starting and ending at the depot visiting all the ELV-dismantlers against minimal costs such that the maximal workday length T and the vehicle capacity C are not exceeded. In fact this is a standard VRP problem.

In total there are 30 locations to which an ELV-dismantler can be allocated for degassing, for all combinations we applied this vehicle routing model in order to estimate the transportation costs accurately. The vertex set V consists of only one depot at a time. To estimate the costs for all depots, the process is repeated.

The complexity of the problem, which is not solvable to optimality in a reasonable amount of time, let us decide to use a heuristic procedure for finding a good instead of optimal solution.

The number of storage racks to be picked up is the same as the number of storage racks to be delivered, so we could apply standard vehicle routing heuristics instead of the more complex pick-up and delivery heuristics, which are more common in reverse logistics (Beullens, 2001).

Our heuristic procedure is constructed by combining some simple heuristics described in literature. We first apply the nearest neighbor heuristic for finding a starting solution and then use local search techniques for improvement of the starting solution. We apply this heuristic for estimating the total transportation costs for the collection truck and the mobile degassing installation for all potential locations: 29 in regional strategy and 1 in the central strategy. The application of more advanced heuristics resulted in might have resulted in lower costs solutions and therefore lower costs estimations, however we aimed at making a realistic estimation and not at finding optimal solutions. The slightly overestimated costs are comparable to practice.

5.2 Optimization model

For minimizing the total costs of the system and determining the optimal locations we used a standard location-allocation model with some additional constraints. We will briefly discuss the mathematical model here, for mathematical details the reader is referred to the appendix. The following decision variables are included:

- Binary variable indicating whether a depot is selected.
- Binary variable indicating whether an ELV-dismantler is allocation to a depot.
- Integer variable representing the number of mobile degassing facilities needed.

Depending on the strategy, there is a binary parameter indicating whether a depot is allowed in the strategy under consideration. Assigning an ELV-dismantler to a certain location occurs with a certain cost and a capacity consummation. The model minimizes the total relevant costs for the system under consideration. The sum of the following cost components determine the total yearly costs of the system under consideration and are therefore the objective function (equation 1) of the model:

- Degassing costs per tank; mobile degassing uses another procedure in which variable costs per LPG-tank are involved.
- Collection costs, the costs for collecting and returning the storage racks with LPG-tanks.
- Storage costs of LPG-tanks, the variable costs of storing one LPG-tank at a certain location.
- Depot costs, the fixed costs for selecting a certain depot for degassing represents the cost of investments needed for suiting the location for LPG-tank degassing. The central degassing facility is also considered as a depot involving fixed costs.
- The costs of storage racks including depreciation and maintenance. The costs of storage racks vary with the size. The number of racks needed varies with the length of the collection period and the size of the storage racks.
- Costs of the mobile degassing installation(s) including depreciation, insurance, maintenance and personal costs.

The objective function is subjected to the following sets of constraints:

- All ELV-dismantlers are allocated to exactly one degassing facility (equation 2).
- ELV-dismantlers only are allocated to degassing locations that are open (equation 3).
- The degassing locations are feasible within the chosen strategy (equation 4).
- The capacity (measured in time) of the mobile degassing installations is not exceeded or extended with an addition installation (equation 5). A mobile degassing installation is available for a limited number of hours in a collection period; the available time is consumed by traveling to the selected degassing locations, setups at a location, the time needed for handling of the storage racks and the actual time needed for degassing.

In case of the central strategy there is no optimization of the number and the geographic location for depots and the allocation of the ELV-dismantlers to the depots. In this case the number of variables reduces to zero and the model suffices with calculating the total costs.

6. Data collection, implementation, validation and verification

Every theoretically good model fails in practice with bad data, incorrect implementation or no proper validation and verification process (Fleuren, 2001). The success in these processes determine the success of the project.

6.1 Data collection

The ARN database provides us with all necessary historical data on the number of wrecks and LPG-tanks dismantled by ELV-dismantlers needed for both the vehicle routing and the location-allocation model. The vehicle routing model makes extensive use of a table with distances and driving times based on zip codes. A specialized company provides us with these tables. In this way we could assure the reasonable estimate of the transportation costs between the possible locations. For the optimization model we need, besides the transportation costs, also data on the potential locations and on the degassing facilities (fixed and mobile). The potential locations for the depots in the regional strategy were obtained by contacting collection companies with a depot certified for storage of hazardous waste. The collection companies provided us a list of 29 potential locations together with an estimation of the rent. Both the engineering company that designed the mobile degassing installation and the company operating the degassing plant provided us with data on the degassing processes required in the location-allocation model.

6.2 Implementation

The models were implemented in AIMMS (Advanced Integrated Multi-dimensional Modeling Software) from Paragon Decision Technology (Bisschop and Roelofs, 2001). AIMMS is an algebraic modeling system with the possibility to easily implement advanced mathematical models, data connections with databases and graphical user interfaces. We used a business version of AIMMS with CPLEX 7.0 as solver for our programming model. While AIMMS is a mathematical programming environment, the implementation of the vehicle routing model in AIMMS was not so obvious, but the integration in the total system made it beneficial.

6.3 Verification and validation

In the verification process we questioned the internal correctness of the models. We made some test runs and did some sensitivity analysis to both the vehicle routing and the mathematical programming model. We varied parameters to explore the extremes of the spectrum to check whether the behavior of the models is in line with our expectations and whether the outcomes were correct.

In the validation process we questioned the external correctness of the models. Does the models give representative descriptions of the real world system. Historical comparison was impossible because of the novelty of the system. Transportation costs coming from the vehicle routing model where validated by comparison with data from collection companies for other materials and whether they met with the expectations of the logistic specialists of ARN. The implementation with a graphical user interface enabled us to provide a simple tool to the ARN management to play around and to get an intuition, which we used in the validation process.

7. Results

In this section we will discuss the results of our analysis. We first discuss the basis scenario, which is based on data of 2000. In the base scenario we vary the parameters for the length of the collection period (3 or 4 weeks) and the size of the storage rack (6 or 12 LPG-tanks). Actually we have 4 base scenarios, representing the alternatives proposed by management, in other words the evaluated parameters settings are controllable for ARN.

Next, to deal with system uncertainty we do some sensitivity analysis on the number of LPG-tanks in the most favorable base scenario. The system's redesign is a strategic decision for several years; the number of LPG-tanks varies over the years. Beside this, it allows us to account for the limit control on the number of LPG-tanks. Yearly volume of LPG-tanks is exogenous.

Finally we perform sensitivity analysis on the collection costs in the most favorable base scenario, because of the potential impact of variations on collection costs. Collections costs account in some situations for almost 50% of the total yearly costs of the system. Besides this, it shows effects of reductions in the collection costs on the systems. The collection costs are exogenous for ARN. Figure 4 illustrates the base scenarios and the resulting cases for sensitivity analysis.

Figure 4 about here

7.1 Base scenario

In table 1, we give an overview of the costs for the central and regional strategy.

Table 1 about here

Comparing both strategies with each other, the central strategy is significantly cheaper for all relevant parameter settings. If a collection period of three weeks is chosen, one mobile degassing installation has got too little capacity and a second installation is needed. This causes a cost jump of about 200,000 euro. This makes the regional strategy 48% and 8% more expensive than the central strategy for respectively collection periods of 3 and 4 weeks. If a collection period of 4 weeks instead of 3 weeks is chosen, only 13 instead of 17 collection rounds will take place, which causes another reduction of the total costs. The effects of using a storage rack of 6 instead of 12 LPG- tanks are small. For a collection period of 3 weeks the storage rack of 6 is about 1% cheaper, while for a collection period of 4 weeks the storage rack of 12 positions is significantly cheaper. This can be explained by the fact that expanding the collection period causes the number of storage racks needed to increase more rapidly when racks with capacity 6 are used instead of racks with capacity 12. For the regional strategy there is a tie whether to select two or three depots. The lowering in collection costs, because of the shorter distances by opening a new depot, compensates the fixed costs involved. The two or three locations selected by the model are nicely spread, covering the

Netherlands. The number of locations to be selected depends on the weight of the collection costs in the total yearly costs. When the frequency of collection (collection period of 3 weeks instead of 4 weeks) is raised, the weight of the collection costs in the total costs increases and are three locations selected to trade the collection costs against higher fixed costs.

7.2 The effects of changes in the yearly volume of LPG-tanks

The calculations in the base scenario are based on volumes of the year 2000 when all LPG-tanks dismantled by ELV-dismantlers affiliated to ARN were handed in. In the new, more attractive system, the number of tanks to be degassed is likely to be close this number. However, there remain some fluctuations in the number of LPG-tanks. Therefore, sensitivity analysis is performed on the yearly number of LPG-tanks in car wrecks assuming ARN to continue the use of storage racks with 12 positions with a collection period of 4 weeks, see figure 5 and table 2.

Table 2 and figure 5 about here

In performing the sensitivity analysis we were confronted with the changes in the number and geographic location of the depots, therefore we decided to analyze both, fixing the optimal locations from the base scenario and keeping it open to the model. Increasing the volume with 10% causes the need for a second mobile degassing installation in the regional strategy. A phenomenon we already have seen in case of a collection period of 3 weeks. In all cases considered, the central strategy seems to be the most attractive solution. A yearly maximum of about 20,000 LPG-tanks is possible with the current facility. If the number of LPG-tanks is below the numbers in the base case, the central strategy is definitely better, without any doubts on the capacity.

7.3 The effects of changes in the collection costs

In some situations the collection costs are close to 50% of the total costs of the system, hence the right estimation of the collection costs is critical. To analyze the influence, we perform sensitivity analysis on the collection costs. Again we were confronted with the changes in the number and geographic location of the depots, therefore we decided to analyze both, fixing the optimal locations from the base scenario and keeping it open to the model. Figure 6 and table 3 represent the change in costs for the case of storage rack with 12 positions and a collection period of 4 weeks.

Table 3 and figure 6 about here

The central strategy is in all situations the most attractive one, however the difference between the central and regional strategy becomes smaller as the collection costs increase. This can intuitively be explained by the fact that one saves on collection costs by adopting the regional strategy with more locations and thereby reducing the total collection costs. Fortunately, the differences between the regional strategy with fixed and free locations are small even when the costs are varied by 30%. This underlines the robustness of the solution found by the model. At the same time, the resulting change in total costs caused by changing the collection costs is significant and thereby justifies the application of a special vehicle routing model for estimating the collection costs accurately.

8. Conclusions & recommendations

Reverse logistics is an area of growing importance. Complex planning and uncertainty are typical. Sources of uncertainty are data estimations and lack of control. We describe an optimization problem for a typical reverse logistic case: LPG-tank degassing.

We applied a special model for estimating the collection costs as accurately as possible. Next we applied an integer-programming model to minimize the total costs and to determine the optimal number and their geographic location of the degassing locations. Although our results are quite robust, the effects of small estimation errors in the collection costs can be large at an absolute level. We have seen this in the case study in the number and the geographic location of the depots in the regional strategy when the volume and collection costs change. But also the uncertainties in other parameter estimations deserve special attention and ways to handle. Research on robust stochastic location models is therefore desirable.

We presented our findings in February 2002 to the management of ARN. Our quantitative analysis played a crucial role in the decision process. The choice for the central strategy could be justified based on quantitative reasons. A few years ago ARN invested in storage racks with a capacity of 12 LPG-tanks. While there is no significant cost benefit for a storage rack with a capacity of 6, the use of storage racks with 12 positions is maintained. A mixed strategy (racks of 6 and 12 LPG-tanks, depending on the ELV-dismantler) is probably a source for potential savings, but more research is recommended. The length of the collection period is unclear yet, but management is inclined towards 4 weeks for all ELV-dismantlers. Further research on the operational aspects is conducted. In July 2002 ARN took the first steps for implementing the new system for the recycling of LPG-tanks, which is expected to be operational finalized at the end of 2002.

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Appendix

The following optimization model is used for determining:

- The costs of the different strategies.
- The number and geographic locations of the depots in case of the regional strategy.
- The number of mobile degassing installation needed.

We first describe the sets, indices, parameters and variables used in the model, before we present the programming model.

Sets and indices

LOC	=	set of degassing locations
		{central, depot A, depot B, …, depot Z}.
loc	=	index referring to the set LOC.
ED	=	set of ELV-dismantlers affiliated to ARN
		{ED-1, …, ED-266}.
ed	=	index referring to the set ED.

Decision variables

$X_{ed,loc}$	=	1 if ELV-dismantler ed is allocated to degassing locations loc,
		0 else.
Y_{loc}	=	1 if degassing location loc is in use, 0 else.
#MOBILE	=	number of mobile degassing installations needed
		(nonnegative integer).

Cost parameters

$degascosttank_{loc}$	=	costs of degassing process per tank if it takes place at location loc.
$degascostrack_{loc}$	=	costs of degassing process per rack independent on the fill-rate of

the rack, if the degassing takes place at location loc.

$colcost_{ed,loc}$ = yearly collection costs for ELV-dismantler ed to location loc.

$storcost_{loc}$ = yearly storage costs of storage racks at location loc.

$depotcost_{loc}$ = yearly cost of rent of space on depot in location loc for degassing.

$transmobilecost_{loc}$ = yearly transportation costs of the mobile degassing installation for visiting location loc.

deprerackcost = yearly deprecation costs of one complete set of storage racks.

mobilecost = yearly total costs of one mobile degassing installation (deprecation, personel, insurance, maintenance).

Other parameters

$\#tank_{ed}$ = the average number of LPG-tanks of ELV-dismantler ed in a year.

$\#rack_{ed}$ = the average number of storage racks supplied by ELV-dismantler ed in a year.

$strategy_{loc}$ = 1 if location loc is feasible in the strategy under consideration, 0 else.

$roadtime_{ed,loc}$ = time to travel from location loc (or in strategy loc) to visit ELV-dismantler ed.

$setuptimerack_{loc}$ = setup time per storage rack for degassing at the mobile installation in location loc.

degastime = degassing time for a LPG-tank for degassing at the mobile facility in location loc.

$setuptime_{loc}$ = time needed for set up the mobile installation at location loc.

minutescp = time mobile installation is available in a collection period.

The integer programming model

minimize

$$\sum_{ed\in ED}\sum_{loc\in LOC}\left(\#tank_{ed}\cdot degascosttank_{loc}+\#rack_{ed}\cdot degascostrack_{loc}\right)\cdot X_{ed,loc}$$

$$+\sum_{ed\in ED}\sum_{loc\in LOC}\left(colcost_{ed,loc}+\#rack_{ed}\cdot storcost_{loc}\right)\cdot X_{ed,loc}$$

$$+\sum_{loc\in LOC}\left(depotcost_{loc}+transmobilecost_{loc}\right)\cdot Y_{loc}$$

$$+2\cdot deprerackcost+mobilecost\cdot\#MOBILE \qquad (1)$$

such that

$$\sum_{loc\in LOC}X_{ed,loc}=1 \qquad \forall ed\in ED \qquad (2)$$

$$X_{ed,loc}\le Y_{loc} \qquad \forall ed\in ED,\quad loc\in LOC \qquad (3)$$

$$Y_{loc}\le strategy_{loc} \qquad \forall loc\in LOC \qquad (4)$$

$$\sum_{ed\in ED}\sum_{loc\in LOC}\left(roadtime_{ed,loc}+setuptimerack_{loc}\cdot\#rack_{ed}+degastime\cdot\#tank_{ed}\right)\cdot X_{ed,loc}$$

$$+\sum_{loc\in LOC}setuptime_{loc}\cdot Y_{loc}\le\#MOBILE\cdot timecp \qquad (5)$$

$$X_{ed,loc}\in\{0,1\} \qquad \forall ed\in ED,\quad loc\in LOC \qquad (6)$$

$$Y_{loc}\in\{0,1\} \qquad \forall loc\in LOC \qquad (7)$$

$$\#MOBILE\in\{0,1,2,\ldots\} \qquad (8)$$

Equation (1) is the mathematical representation of the objective function of the optimization model representing the total yearly costs of the system. Note that there are two sets of storage racks needed. Equation (2) represents the constraints assuring that every ELV-dismantler is allocated to exactly one degassing location. Equation (3) represents the constraints assuring that an ELV-dismantler can only be allocated to a degassing location that is opened. Equation (4) represents the constraints for the user selection of the strategy. The optimization model is used to analyze both strategies. If the user selects the strategy in the developed tool, the parameter $strategy_{loc}$ is automatically adapted to the strategy under consideration; all other parameters keep their value. This could only be realized by taking into account the possible strategies explicitly in the set of degassing locations. Constraint (5) represents the capacity constraint of the mobile degassing installation, expressed in time. The left side of the equation represents all time needed to perform all activities: degassing of LPG-tanks, handling of storage racks, setup of degassing installation at a location and the estimated travel time between location, while the right side of the equation represents the time available per collection period per mobile degassing facility multiplied with the number of mobile degassing facilities needed. Equations (6), (7) and (8) represent simple technical constraints defining the decision variables of the model.

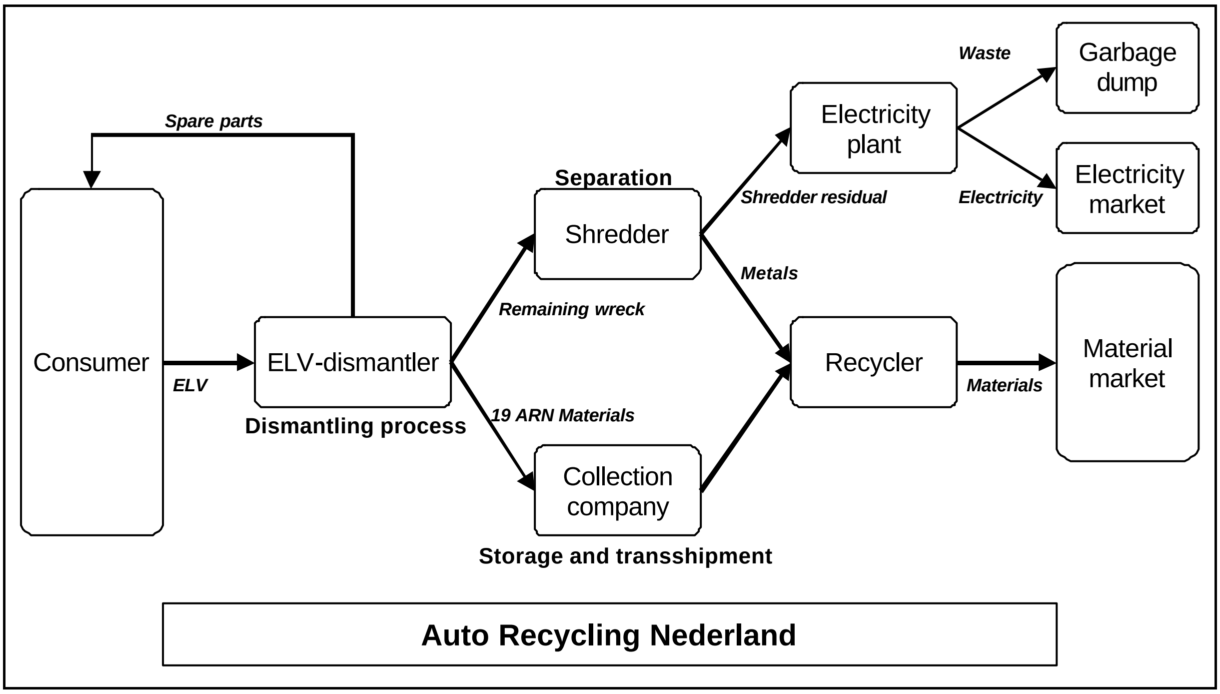

Figure 1. An overview of the ARN chain for the recycling of end-of-life vehicles.

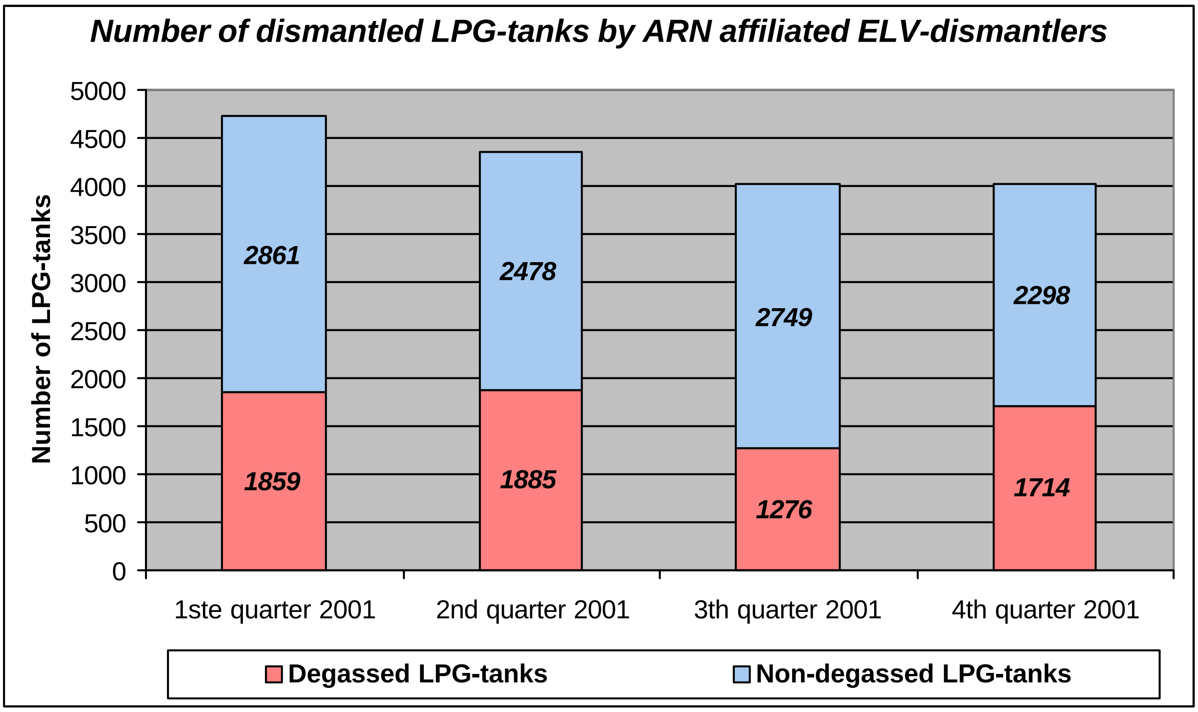

Figure 2: The number of LPG-tanks dismantled by ARN affiliated ELV-dismantlers according to the Dutch car register and the number of collected and processed LPG-tanks by the degassing facility.

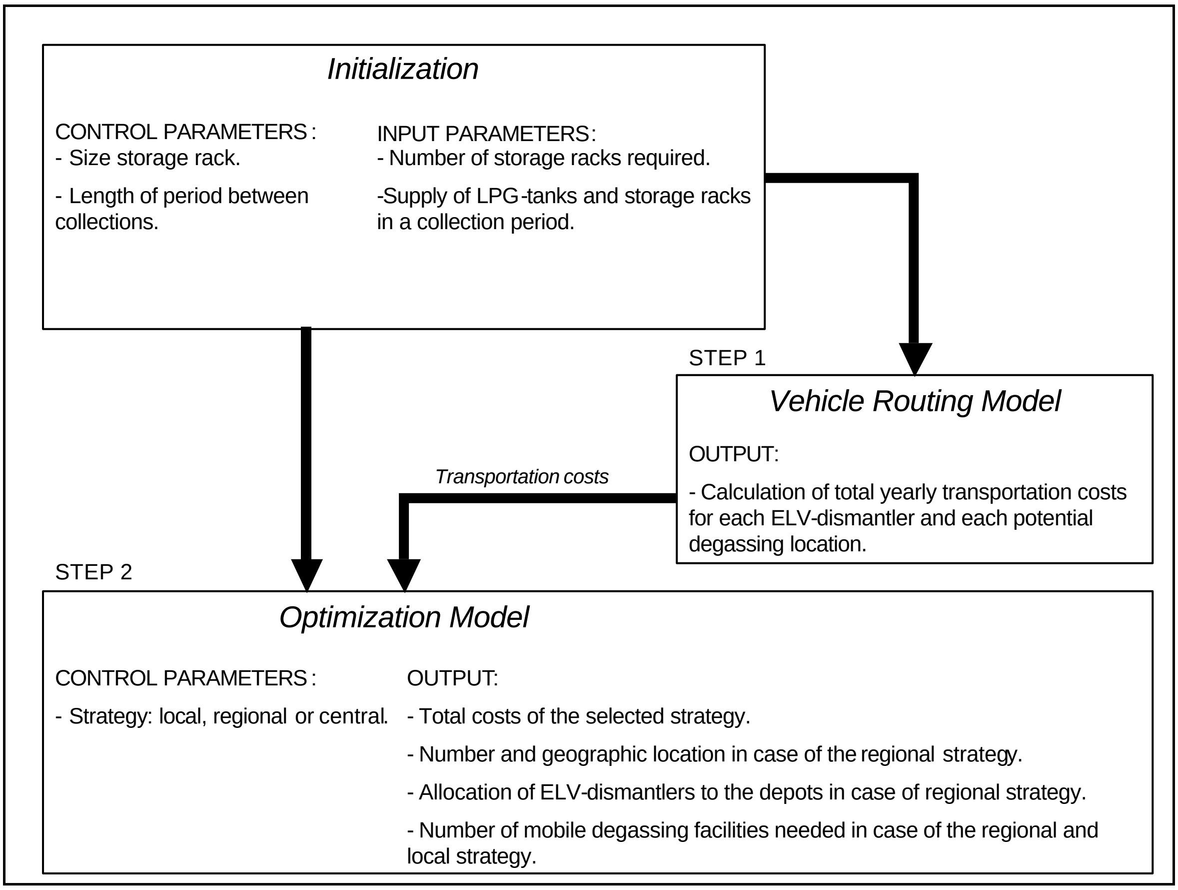

Figure 3: The methodology followed in the research consisted of three steps. The basic calculations and vehicle routing model served as input to the optimization model.

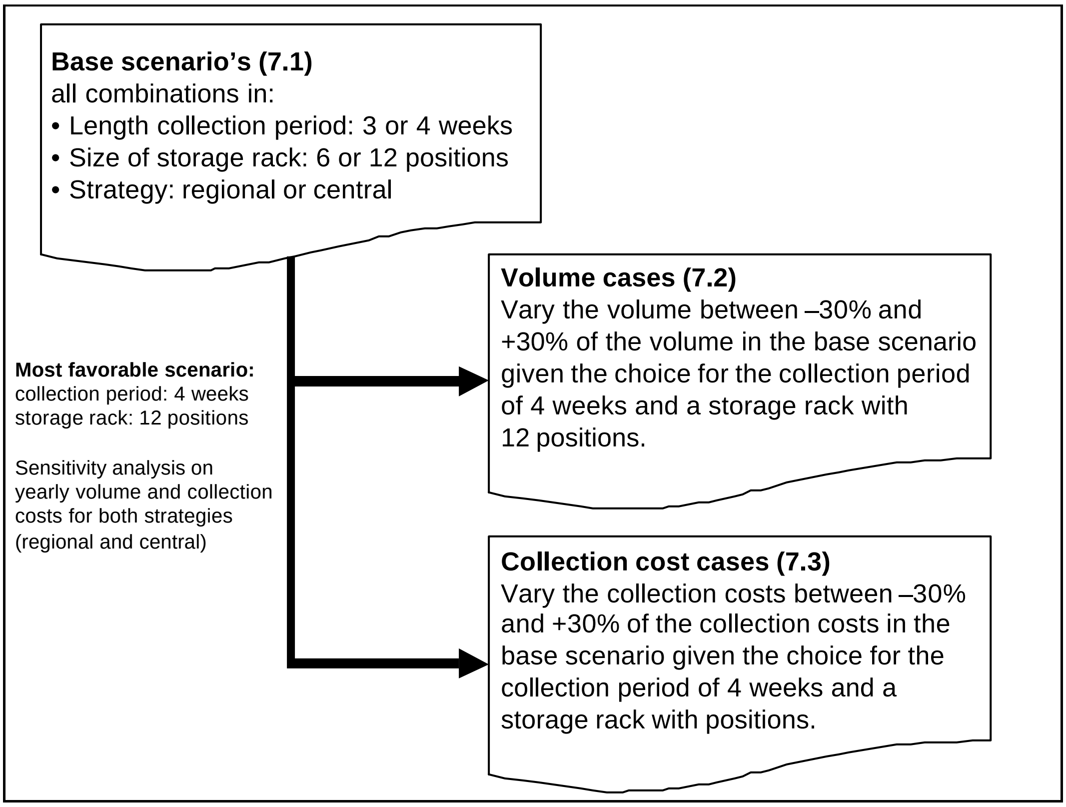

Figure 4: Overview of the base scenarios and the resulting cases for sensitivity analysis.

CENTAL STRATEGY

Length collection period in weeks)	3	3	4	4
Capacity storage rack in LPG-tanks	6	12	6	12
Yearly cost of storage racks	€ 40,000	€ 41,000	€ 45,000	€ 42,000
Yearly collection costs	€ 219,000	€ 224,000	€ 176,000	€ 172,000
Yearly depot costs	€ 200,000	€ 200,000	€ 200,000	€ 200,000
TOTAL COSTS	€ 459,000	€ 465,000	€ 421,000	€ 414,000

REGIONAL STRATEGY

Length collection period in weeks)	3	3	4	4
Capacity storage rack in LPG-tanks	6	12	6	12
Yearly cost of storage racks	€ 40,000	€ 41,000	€ 45,000	€ 42,000
Yearly collection costs	€ 167,000	€ 163,000	€ 134,000	€ 136,000
Yearly depot costs	€ 28,000	€ 42,000	€ 28,000	€ 28,000
Yearly costs of mobile degassing facility	€ 399,000	€ 399,000	€ 200,000	€ 200,000
Yearly degassing costs	€ 29,000	€ 29,000	€ 29,000	€ 29,000
Yearly storage costs	€ 16,000	€ 14,000	€ 18,000	€ 14,000
TOTAL COSTS	€ 679,000	€ 688,000	€ 454,000	€ 449,000

Table 1: Total cost and composition for the central and regional strategy in the base scenario.

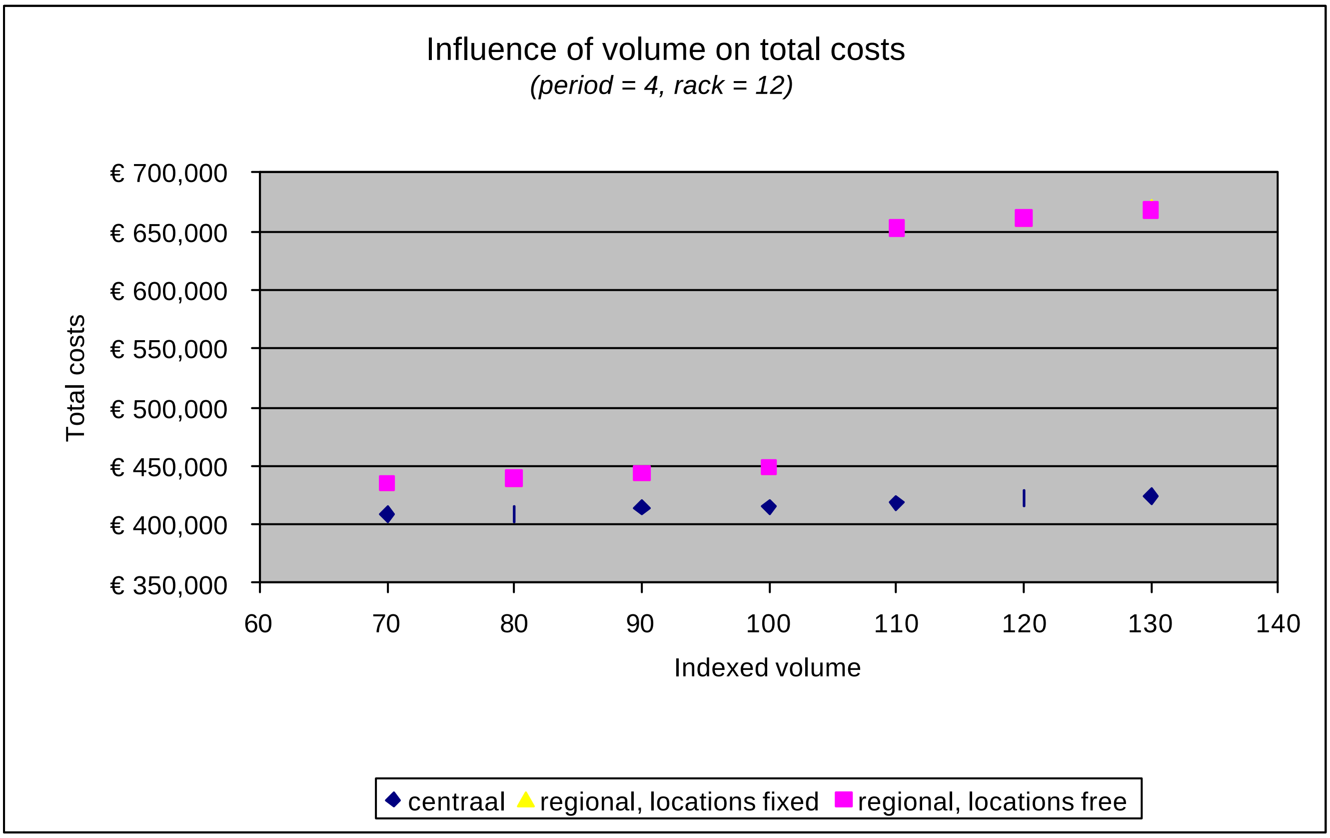

Figure 5: The influence of variations in the yearly volume of LPG-tanks on the total costs for a collection period of 4 weeks and a storage rack of 12 LPG-tanks.

Strategy	Indexed volume	Total costs
Central	70	€ 408,583
Regional locations free	70	€ 435,087
Regional locations fixed	70	€ 435,556
Central	80	€ 408,700
Regional locations free	80	€ 439,227
Regional locations fixed	80	€ 439,227
Central	90	€ 414,575
Regional locations free	90	€ 443,392
Regional locations fixed	90	€ 443,415
Central	100	€ 414,869
Regional locations free	100	€ 448,639
Regional locations fixed	100	€ 448,639
Central	110	€ 418,298
Regional locations free	110	€ 652,924
Regional locations fixed	110	€ 653,901
Central	120	€ 422,579
Regional locations free	120	€ 660,784
Regional locations fixed	120	€ 661,216
Central	130	€ 423,891
Regional locations free	130	€ 667,786
Regional locations fixed	130	€ 670,925

Table 2: The influence of variations in the yearly volume of LPG-tanks on the total costs for a collection period of 4 weeks and a storage rack with 12 LPG-tanks.

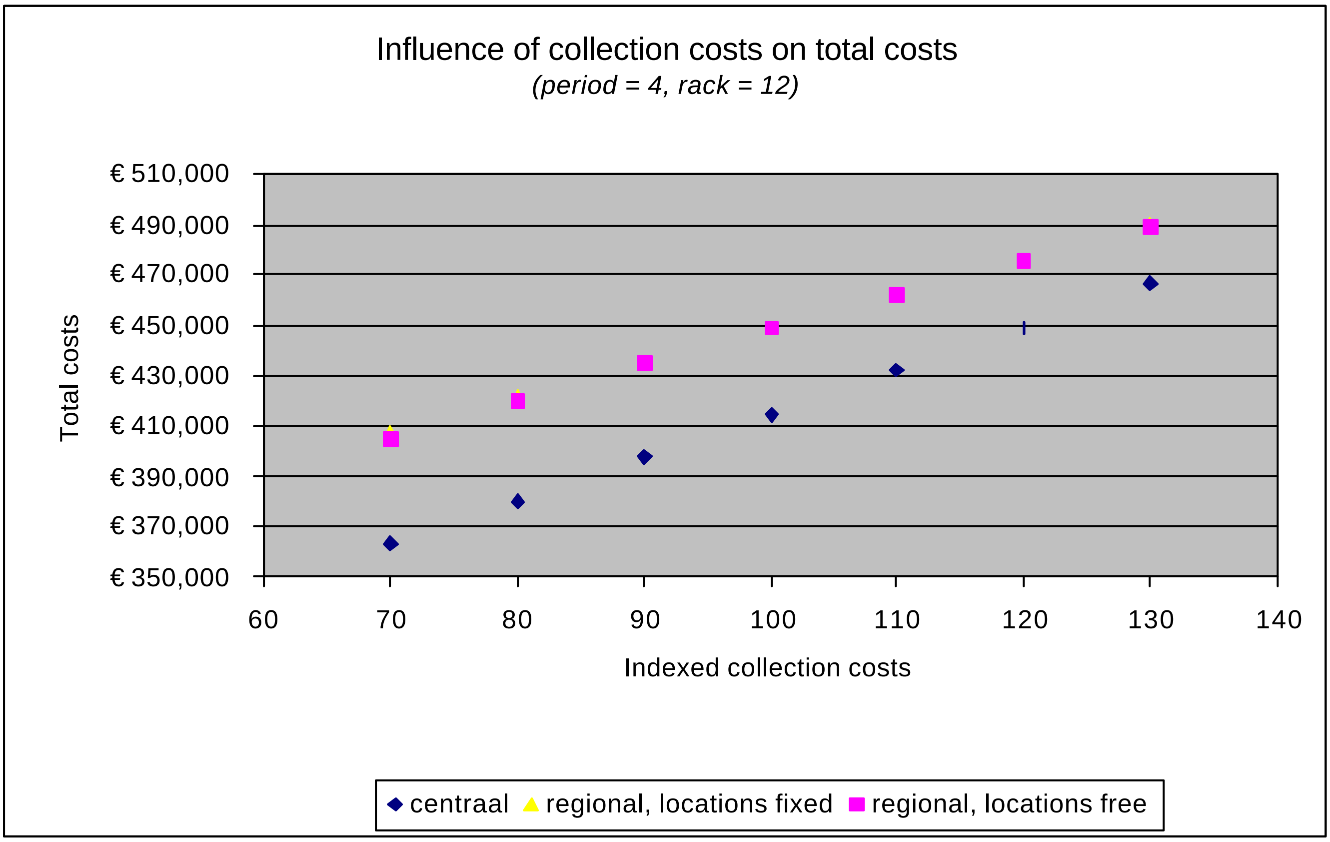

Figure 6: The influence of variations in the collection costs on the total costs for a collection period of 4 weeks and a storage rack of 12 LPG-tanks.

Strategy	Indexed collection costs	Total costs
Central	70	€ 363,145
Regional locations free	70	€ 404,583
Regional locations fixed	70	€ 407,793
Central	80	€ 380,386
Regional locations free	80	€ 419,740
Regional locations fixed	80	€ 421,409
Central	90	€ 397,627
Regional locations free	90	€ 434,897
Regional locations fixed	90	€ 435,024
Central	100	€ 414,869
Regional locations free	100	€ 448,639
Regional locations fixed	100	€ 448,639
Central	110	€ 432,110
Regional locations free	110	€ 462,255
Regional locations fixed	110	€ 462,255
Central	120	€ 449,351
Regional locations free	120	€ 475,870
Regional locations fixed	120	€ 475,870
Central	130	€ 466,592
Regional locations free	130	€ 488,386
Regional locations fixed	130	€ 489,486

Table 3: The influence of variations in the collection costs on the total costs for a collection period of 4 weeks and a storage rack with 12 LPG-tanks.