Network design in reverse logistics : a quantitative model

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Network Design in Reverse Logistics: A Quantitative Model

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Abstract. The introduction of (extended) producer responsibility forces Original Equipment Manufacturers to solve entirely new managerial problems. One of the issues concerns the physical design of the reverse logistic network, which is a problem that fits into the class of facility-location problems. Since handling return flows involves a lot of different processing steps, the physical system might consist of two or more echelons. In this paper, a MILP-model is presented that gives decision support in designing the physical network structure of a multi-echelon reverse logistic system. The model is applied to a case from the automotive industry. The general applicability of the model in logistic network design is discussed. Finally, subjects for further research are pointed out.

Keywords. reverse logistics, location allocation, MILP, network design

1. Introduction

Over the past few years, environmental problems have reinforced public interest in reuse and recycling. What is new, is the role of industry in this process. More and more, Original Equipment Manufacturers are held responsible for the take-back and recovery of their own products, both by the consumer and by new environmental legislation. This means that material flows should be closed to obtain an integral supply chain, which is reflected in Figure 1. A new managerial area called Product Recovery Management (PRM) emerges, which can be described as "the management of all discarded products, components and materials for which a manufacturing company is legally, contractually or otherwise held responsible", cf. (Thierry et al., (1995)).

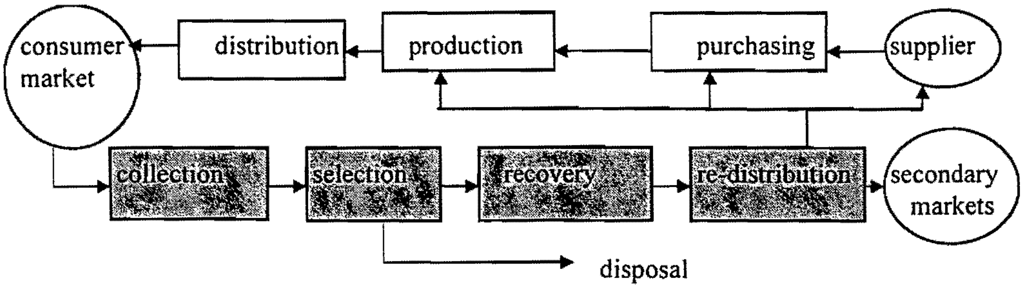

Figure 1. Reverse logistic system in integral supply chain (grey)

As a result, many industrial businesses will compulsorily be confronted with large volumes of discarded or *return* products. A number of managerial problems of an entirely new nature will have to be solved. Some critical problems include the following:

- product design must enable cost effective disassembly and processing as well as high quality recovery
- secondary end markets must be sufficiently developed
- products must be returned in sufficient quantity and quality
- relevant information must be available to decision makers
- a recovery strategy must be determined for return products.

Another key issue concerns the *network design* of a reverse logistic system, i.e., the locations and capacities of processing facilities -such as disassembly stations or shredders- and the optimisation of good flows between facilities. These kind of problems are generally known in OR-literature as facility-location problems. A physical network can consist of one, two or more echelons. A reverse logistic system may involve more than two echelons, due to the high number of (different) processing steps to be performed. This paper discusses a multi-echelon model that can deal with more than two echelons and multiple facility types. The paper is built up as follows. In Section 2, the problem situation is defined. Section 3 discusses literature. In Section 4, a mathematical model is presented for determining an optimal multi-echelon network structure. In Section 5, we present a case from the automotive industry. Section 6 is meant for discussion and conclusions.

2. Problem definition

The problem situation studied in this paper can be described as follows. Return products of a certain type are discarded from the consumer market. The products are collected at a finite number of supply points and from there supplied to the reverse logistic system. Every product is to be processed by a recovery strategy. This strategy gives quality dependent decision rules regarding the degree of disassembly and processing options (reuse, recycling, disposal) applied and hence determines the sequence of processes to be performed (Krikke, (1998)). The aim of a recovery strategy is to regain maximal economical value at minimal economic cost while meeting technical and ecological (legislative) restrictions. We assume that supply and demand for different Recovery and Disposal (RD-) options are balanced in this recovery strategy, so in our physical network design model we can assume that collection volumes and (secondary) demand volumes are equal. The secondary products, components and materials -resulting from applying the recovery strategy- are delivered at customer demand points. As we mentioned, every RD-option requires a sequence of processes, where every process type requires a specific facility type. The reverse logistic system must provide the processing capacity for realising the degree of disassembly and RD-options assigned in the predetermined recovery strategy. This is to be taken into account in the network design.

The following entities are assumed to be known:

- for each supply point: the amount (kg) of discarded products, specified per RD-option
- for each customer demand point: the amount (kg) of secondary products, specified per RD-option
- for each RD-option: the sequence of facility types required to realise this option
- for each facility type: a set of feasible locations plus investment and (constant and variable) processing cost at these locations
- distances between all possible locations plus transportation cost.

For simplicity, we neglect the problems concerning material loss or emissions during the processing. We also assume that there is only *one* problem owner - the OEM - and only *one type* of return product. Of course, in practice many complications might arise. Therefore, we shall discuss extensions of the model is Section 6.

Now, in the physical network design model, it is to be determined for every facility type which location(-s) should be opened and which volumes are handles by which facility. The aim is to minimise the sum of transportation, processing and yearly investment cost while demand and supply constraints are satisfied. Also, the predetermined recovery strategy must be implemented correctly and no capacity constraints are set on the facilities and transportation links.

3. Literature

The use of location-allocation models in reverse logistics is described in a number of studies, mostly related to cases. Below, we give a review of these models.

(Caruso et al., (1993)) consider an Urban Solid Waste Management System (USWMS). They develop a location-allocation model to find the number and locations of the processing plants, given the locations of the waste generators and landfills. For each processing plant, the technology -incineration, composting or recycling-, the amount of waste processed as well as the allocation of service users (waste sources) and landfills (waste sinks) are determined. No more than one facility may be located in one geographic zone and there are maximum capacities for all facilities and landfills. The model is single period and has a multi-criteria objective function, with components for economic cost, waste of resources and ecological impact. Efficient heuristics are developed to solve the problem. The model was applied in a case study for the region of Lombardy (Italy).

(Ossenbruggen and Ossenbruggen, (1992)) describe a computer package for solid waste management (SWAP) based on LP-modelling. The model describes a waste management district as a network, where nodes represent waste sources, intermediary (capacitated) processing facilities and destinations (sinks) on given locations. Sources, sinks and intermediary stations can be of multiple (technology) types. Decision variables are the amount of waste to be processed by each facility and the magnitude of flows between the facilities. Implicitly, the processing paths are determined, where a flow can be split into sub-streams for different processing. Constraints follow from technically allowed processing sequences and capacity limitations. The algorithm finds a cost optimal solution, where the cost function only includes variable costs per waste unit, e.g. kg. These unit costs incorporate tipping fees, shipping costs and revenues from reuse.

(Pugh, (1993)) describes the HARBINGER model, which gives decision support in the long term waste management planning of a city or county. The waste management system involves collection, transportation, treatment and disposal or reuse of a communities waste stream. These systems tend to be very complicated, which explains the need for mathematical analysis. The heart of HARBINGER lies in the multi-period allocation sub-model, which determines the cost-optimal assignment of waste flows from the sources to treatment and disposal facilities on given locations, within constraints set by the user (e.g. for capacity). Optimisation occurs on least cost. Other sub-models of HARBINGER are used to specify the input for the allocation sub-model and for post-optimality analysis. Unfortunately, the model description is not very detailed.

In a study of (Marks, (1969)), the problem of selecting transfer stations is considered. Waste is generated at discrete sources and from there routed via intermediary transfer stations to discrete sinks, representing the disposal locations. The sinks have a demand that varies between a lower and upper bound reflecting minimal throughput requirements and maximum capacities of these disposal locations. At the intermediary transfer stations activities like transfer, packing and sorting can take place. The transfer stations can be located at a number of locations, where capacities are restricted. Each opened location has a fixed cost and linear processing cost. Also transportation cost between sources, intermediary transfer stations and sinks are linear. The problem is formulated as a Mixed Integer Linear Programming problem. A Branch & Bound algorithm, using an out-of-kilter algorithm at the nodes, is developed to find the solution with the least overall cost.

(Gottinger, (1988)) develops a similar, but more extensive regional management model. The model is concerned with the number, location and capacity (expansion) of both intermediary transfer stations and the ultimate disposal locations (sinks) as well as the routing from discrete waste sources through the system to the sinks. There is one type of transfer station and one type of disposal facility. For both types of facilities a set of potential and *existing* locations is given. The concave cost functions are approximated by linear segments, whereby one segment is represented by a pseudo-facility. Each pseudo-facility has a fixed cost and linear processing cost, in compliance with the cost function of the corresponding real life facility, within the capacity range covered by the pseudo-facility. Only one pseudo-facility per location can be opened. Existing locations have a restricted (current) capacity, potential new locations have infinite capacity. In addition, source locations and magnitude of waste flows generated and (linear) transportation costs are given. The aim is to minimise overall cost. A B&B procedure, very similar to the one of (Marks, (1969)), is used for optimisation. Some variations of the model are described, for which special purpose algorithms are developed. The general model is applied in a case study for the Munich Metropolitan Area.

(Spengler et al., (1997)) develop a MILP-model for the recycling of industrial by-products in German steel industry. The model is based on the multi-level warehouse location problem and modified for this case study. It has to be determined which locations will be opened and how flows are routed from the sources through the intermediary facilities to the sinks. The model is multi-stage and multi-product, while it is allowed to transfer sub-streams of interim products from one intermediary facility to another in various ways, before delivering it at a sink. A sink can be either a reuse or a disposal location. Facilities can be installed at a set of potential locations and at different capacity levels, with corresponding fixed and variable processing cost. The type of processes to be installed at the intermediary facilities also have to be determined, hence the processing graph is not given in advance. Maximum facility capacities are restricted and transportation costs between locations are linear. While the amounts of waste generated at the sources are fixed, the demand at the sinks is flexible within a range. This range is set by the minimal required throughput and the maximum capacity of the sink.

(Barros et al., (1998)) present a MILP-model to determine an optimal network for the recycling of sand. In this real life case, sieved sand is coming from construction works, which represent the sources. The sand is delivered at a regional depot, where it is sorted in three quality classes. The first two classes, clean and half clean sand, are stored at the regional depot in order to be reused. The dirty sand is cleaned at a treatment facility, where it is also subsequently stored as clean sand. Both the clean and the half clean sand can be reused in new projects, which represent the sinks. Supply and demand are fixed for the respectively three and two qualities of sand. It has to be determined at which locations regional - and treatment centres must be opened, where locations can be picked from a pregiven set of potential locations. Also the capacities of the facilities and the routing through the system have to be determined, where capacities of both facilities are restricted. Opening a facility incurs a fixed and variable linear processing cost, transportation costs are also linear. The model used is a multi-level capacitated warehouse location model, for which heuristic algorithms are developed.

A huge amount of research has been carried out in facility location theory in general, for a review see e.g. (Domschke and Krispin, (1997)). However, classical models are primarily oriented at classical production-distribution systems and not directly applicable to reverse logistics due to some typical characteristics of reverse chains. Firstly, forward logistic systems are pull systems, while in reverse logistics it is a combination of push and pull due to the fact that there are clients on both sides of the chain, namely the disposer and the reuser. As a result, there remains a logistic design problem quite different from forward problems, because it includes both transhipment and facility location aspects. Secondly, forward logistic models usually deal with divergent networks, while reverse flows can be strongly divergent and convergent at the same time. Thirdly, in reverse logistics, transformation processes tend to be incorporated in the distribution network, covering the entire 'production' process from supply (=disposal) to demand (=reuse). In addition, since only a fraction of return flows is valuable, it is likely that in an efficient design, operations are spread over a high number of echelons. Traditional forward logistics models usually focus on one or two echelons. We conclude that the classical facility location models lack most of the above characteristics, which are typical for reverse logistic systems. Therefore, we only discussed models specifically developed for reverse logistics.

4. Model formulation

Next, we give an extended version of some of our earlier work, presented in (Kooi et al., (1996)).

4.1 The concept of routes

The core of the model is the concept of the *processing route.* As mentioned before, every RD-option assigned in the recovery strategy requires a sequence of processing facilities. For every facility, a set of locations is available.

Now, a processing route represents a sequence of facilities (required for a particular RD-option) all assigned to one location chosen from the set of potential location of that facility. For example, for RD-option „recycling“ a processing route could be (shredder, location 1) -> (melter, location 2) or (shredder, location 3) -> (melter, location 2). A set of all possible processing routes is generated for each RD-option. Note that a facility -and thus a location- can be part of multiple processing routes. Each processing route can be used by return products assigned to the corresponding RD-option, at a certain cost per kg, i.e., variable processing costs per kg of every facility on the route and transportation cost between the facilities (from the first to the last facility on the route). A location must be opened, if at least one processing route is chosen that ‘passes’ through this particular location. For this, investment costs are charged. If multiple facilities are opened at one location, facility investment costs are charged for each facility, hence investment costs are not shared. Facility investment costs are also not capacity dependent.

In addition, we need *entry routes* and *delivery routes.* An entry route is the connection between a supply point and the *first* facility of a processing route. Entry routes can be used at a certain cost, equivalent to the transportation cost between the two locations involved. Analogously, the secondary products are delivered to a customer via a delivery route. The ‘delivery costs’ are equivalent to the transportation costs between the *last* facility of the processing route and the demand point. The model now has to determine an optimal configuration of entry, processing and delivery routes, which is referred to as the optimal reverse logistic network design.

4.2 Construction of an MILP-model

Schematically, the problem with one RD-option r1, one processing route p1, three entry - and three delivery routes can be represented as in Figure 2.

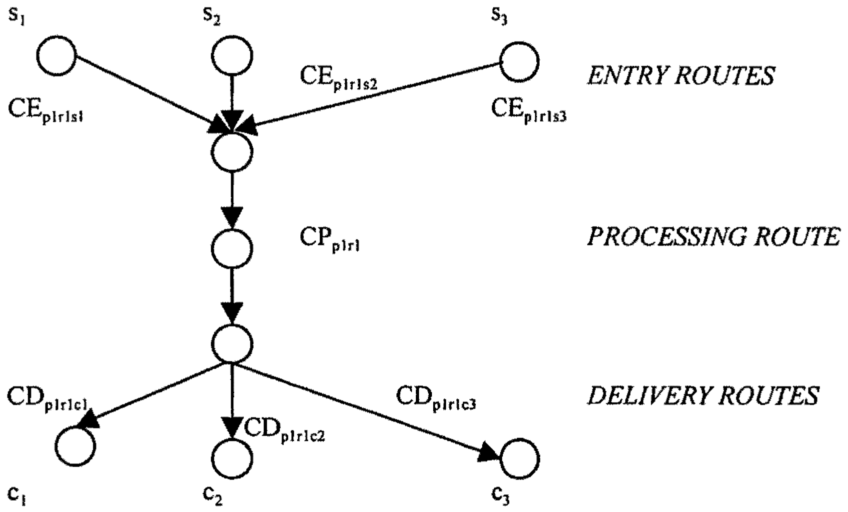

Figure 2. Mathematical representation for one RD-option r1 with processing route p1, three supply points $s_1.s_3$ and three demand points $d_1..d_3$.

To formulate our model we introduce the following notation:

f = facility type, $f=f_1 .. f_F$
loc = location, $loc=loc_1 .. loc_L$
$CI_{f,loc}$ = investment costs of facility type f on location *loc*
p = processing route, $p=p_1 .. p_P$
r = RD-option, $r=r_1..r_R$
s = supply point, $s=s_1..s_S$
c = customer demand point, $c=c_1..c_C$
CP_{pr} = processing costs for RD-option r via route p
CE_{prs} = entry costs of RD-option r via route p for supply from point s
CD_{prc} = delivery costs of RD-option r from route p to customer c
V_{sr} = supply of products assigned to RD-option r at supply point s
D_{cr} = demand at customer demand point c for secondary products, components and materials resulting from RD-option r
M_{rpfloc} = 1 if (f,*loc*) on p for r, else 0

The decision variables are:

- XE_{prs} the amount (kg) of products from supply point s assigned to RD-option r to be processed via route p
- XD_{prc} the amount (kg) of products assigned to RD-option r, processed by route p, delivered to customer c
- XP_{pr} the amount (kg) of products assigned to RD-option r, processed via route p

Note that XP_{pr} is an *implicit* decision variable and dependent on XE_{prs} and XD_{prc}. In other words XP_{pr} is equivalent to $\sum_{s} XE_{prs}$ and $\sum_{c} XD_{prc}$.

- $Y_{f,loc}$ is 1, if location *loc* is open for facility f, else 0.

The MILP-model becomes:

MINIMISE

$$\sum_{p}\sum_{r}\sum_{s} CE_{prs} * XE_{prs} \quad + \quad \sum_{p}\sum_{r} CP_{pr} * XP_{pr} \quad + \quad \sum_{p}\sum_{r}\sum_{c} CD_{prc} * XD_{prc} \quad + \quad \sum_{f}\sum_{loc} CI_{f,loc} * Y_{f,loc} \tag{1}$$

s.t.

$$V_{sr} = \sum_{p} XE_{prs} \qquad \forall\, s,r \tag{2}$$

$$\sum_{p} XD_{prc} = D_{cr} \qquad \forall\, c,r \tag{3}$$

$$\sum_{s} XE_{prs} = XP_{pr} \qquad \forall\, p,r \tag{4}$$

$$XP_{pr} = \sum_{c} XD_{prc} \qquad \forall\, p,r \tag{5}$$

$$XE_{prs} * M_{rpf\,loc} <= Y_{f,loc} * V_{sr} \qquad \forall\, r,p,s,f,loc \tag{6}$$

$$XE_{prs}, XP_{pr}, XD_{prc} >= 0 \qquad \forall\, p,r,s,c \tag{7}$$

$$Y_{f,loc} = 0,1 \qquad \forall\, f,loc \tag{8}$$

The constraints (2) to (8) are formulated to make sure that:

- all waste supplied enters the systems via entry routes (2)
- all demand is satisfied via delivery routes (3)
- all products entering a processing route are taken away from this route (4) (5)
- if a route p is used by any supply point s for any option r, then all locations *loc* at this route are opened (6)
- logical constraints (7) (8) are for possible values of variables

Let us now take a look at the results of the automotive case, which is described in the next section.

5 Automotive case

The case is meant to give an idea of the working of the model. Firstly, we shall give a description. Then the data that serve as model input are described. Finally, results are discussed.

5.1 Description

An OEM of automobiles takes back its family cars. All cars are treated exactly the same, so they can be considered as one type of car. The recovery strategy is as follows:

I. 70 % of all cars is disassembled and reusable parts are reused in the car-repair business
II. 30% of all cars is disassembled and shredded. The shredder fluff is sold to material recyclers, who recycle the materials.

Figure 3 reflects the recovery strategy graphically.

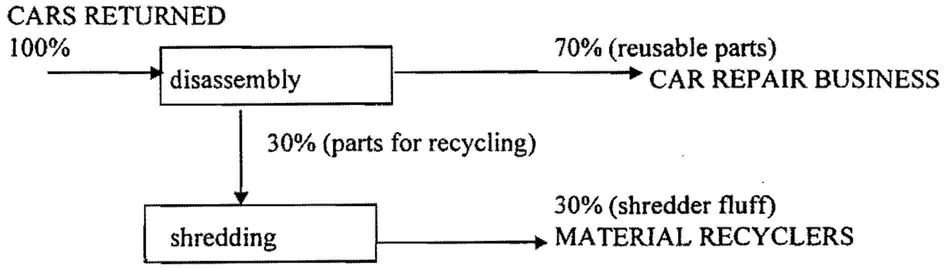

Figure 3. The recovery strategy in the automotive case

5.2 Model parameters

Collection points as well as customer demand points are at three locations. There are seven possible locations for the facilities disassembly stations and the shredders. Facility investment costs are different per location (per facility) due to different landprices. For each facility type, (variable) processing costs are equivalent for all locations, so they have no influence on the optimal solution. Therefore, they are left out of consideration in this case, hence CP_{pr} is now equivalent to the transportation costs between the locations on processing route p (generally, this is not the case!). Transportation costs are calculated by multiplying the distance between locations with a cost of fl. 0.16 per km per ton. Facility investment costs are depreciated linearly in 10 years, without interest. Below, we summarise the data for the cost parameters in Table 1, 2 and 3.

Table 1. Entry and delivery costs per ton in Dutch guilders

facility loc.	*supply*	*supply*	*supply*	*demand*	*demand*	*demand*
	B op Z	Den H.	Zwolle	Hoek v.H.	Lemmer	Roermond
Enschede	38.9	37.8	11.5	35.4	20.3	32.8
Groningen	47.4	24.1	16.6	39.8	12.3	44.3
Haarlem	29.1	12.5	20.8	11.6	19.3	30.1
Maastricht	29.1	46.4	37.1	36.1	46.4	7.2
Middelburg	10.1	43.8	40.8	14.9	45.4	33.1
Tilburg	10.1	31.5	25.3	17.3	31.4	14.2
Utrecht	17.9	19.5	14.4	13.6	18.4	22.9

Table 2. Yearly facility investment costs in Dutch guilders

facility location	*investment cost shredder*	*investment cost disassembly station*
Enschede	3.054.000	177.500
Groningen	3.000.000	167.500
Haarlem	3.030.375	223.700
Maastricht	3.000.000	167.500
Middelburg	2.993.250	166.250
Tilburg	3.006.750	168.750
Utrecht	3.175.500	200.000

Table 3. Transportation costs per ton between facility locations (Dutch guilders)

	E'de	Groningen	H'lem	Maastricht	M' burg	Tilburg	Utrecht
Enschede	X						
Groningen	21.4	X					
Haarlem	28.3	31.4	X		Symmetric		
Maastricht	41.6	53.3	35.5	X			
Middelburg	48.3	57.0	31.7	38.6	X		
Tilburg	29.9	41.4	20.5	19.7	19.7	X	
Utrecht	22.1	30.4	8.5	28.3	27.3	13.3	X

Basically, two situations with different supply and demand parameters are analysed in the case. The supply and demand parameters are reflected in table 4 and 5.

Table 4. Yearly supply of cars in 1000 tons for two scenarios

Collection point	Collected volume RD-option 1.		Collected volume RD-option 2.	
Bergen op Zoom	scenario1: 9	scenario2: 7	scenario1: 5	scenario2: 3
Den Helder	scenario1: 5	scenario2: 7	scenario1: 1	scenario2: 3
Zwolle	scenario1: 7	scenario2: 7	scenario1: 3	scenario2: 3

Table 5. Yearly demand for secondary parts/materials in 1000 tons for two scenarios

Customer demand point	Demand volume RD-option 1.		Demand volume RD-option 2.	
Hoek van Holland	scenario1: 10	scenario2: 7	scenario1: 4	scenario2: 3
Lemmer	scenario1: 4	scenario2: 7	scenario1: 2	scenario2: 3
Roermond	scenario1: 7	scenario2: 7	scenario1: 3	scenario2: 3

5.3. Results

The model was implemented in CPLEX, on a HP 9000/710 workstation. Run times for the case parameter settings were around 5 seconds. The problem complexity for the problem instance chosen is not very high. However, larger problem instances may cause problems. We will come back to this in Section 6. The results are worked out for two scenarios.

In scenario 1, the supply is (9,5,7) and (5,1,3) tons for RD-option I and II respectively, while demand is (10,4,7) and (4,2,3) tons. In this scenario, disassembly stations are opened in Tilburg and Utrecht and a shredder is located in Tilburg only. Overall costs are 4.313.660 guilders per year, variable processing costs not included. The processing flows are given in Table 6.

Table 6: processing flows for scenario 1 for option I and II

facility	location	processing flow
disassembly station	Utrecht	I: 12, II:0
disassembly station	Tilburg	I: 9, II: 9
shredder	Tilburg	I: 0, II: 9

In scenario two, supply and demand are (7,7,7) and (3,3,3) for both RD-option I and II. Now, a disassembly station is opened in Utrecht and a shredder in Haarlem. Overall costs are 4.392.639 guilders per year, again variable processing costs excluded. The flows are given in Table 7.

Table 7: processing flows for scenario 2 for option I and II

facility	location	processing flow
disassembly station	Utrecht	I: 21, II:9
shredder	Haarlem	I: 0, II: 9

Sensitivity analysis

Given the fact that investment costs represent the largest cost component, the depreciation period chosen is therefore of crucial importance to the final solution. To illustrate this, we vary this parameter in a range between 1 and 15 years for scenario 1. The results are in Table 8. Similar results are obtained for scenario 2. Additional sensitivity analysis revealed that the optimality of solutions did only moderately depend on variance in other parameters.

Table 8: Sensitivity analysis for scenario 1- vary depreciation period of fixed costs

depreciation period in number of years	yearly cost (guilders)	optimal solution
1	32.911.520	from year 1 till year 9: disassembly station in Tilburg and shredder in Tilburg
2	17.033.520	
3	11.740.853	
4	9.094.520	
5	7.506.720	
6	6.448.186	
7	5.692.091	
8	5.125.020	
9	4.683.964	
10 (initial choice)	4.313.660	from year 10 till year 15: additional disassembly station in Utrecht
11	4.006.807	
12	3.751.080	
13	3.534.695	
14	3.349.222	
15	3.188.479	

6. Discussion and conclusions

Managerial use of the model

The managerial usefulness of the model can be exploited in scenario analysis, as module in a hierarchical decision process. For example, the management of the OEM might like to know the impact of:

- opening or closing of facilities in an existing network
- changes in transportation costs due to increased tariffs or improved infrastructure
- the implementation of new recovery technologies, resulting in different cost functions or entirely new RD-options
- new supply points or customer locations.

In addition, results of sensitivity analysis might used to compare potential benefits of improved robustness with the cost of gathering additional information or improving logistic control.

Model complexity and computational results

The model complexity is:
$|R|.|S|+|R|.|C|+|R|.|P|+|P|.|R|+|R|.|P|.|S|.|F|.|\sum_f L_f|$ with respect to the number of constraints and $|\sum_f L_f|$ with respect to the number of boolean variables, with L_f the set of locations *loc* for facility f.

Regarding constraints, it is clear that constraint (6) adds most complexity to the problem, namely $|R|.|P|.|S|.|F|.|\sum_f L_f|$ constraints. In order to reduce the complexity, we might use a weak formulation of constraint (6), i.e.:

$$\sum_s XE_{prs} * M_{rpf\,loc} \quad <= \quad \sum_s Y_{f,\,loc} * V_{sr} \quad \forall\, r,p,f,loc \qquad (6')$$

This reduces complexity with a factor $|S|$. One can see that constraint (6') is effective, since all locations at a route are opened if *at least* one supply point s uses route p for an option r. Reducing complexity can also be realised by removing the booleans and using an LP-relaxation to solve the problem. In a reverse logistics situation where supply and demand are balanced and given, we obtain a location problem with transhipment characteristics. This can be used in developing algorithms, e.g. a network flow algorithm can be used in a branch and bound solution procedure or smart heuristics, since an LP-relaxation of the problem can easily be solved as a network flow problem. A general disadvantage of the weak formulation is that we obtain less integer values in the LP-relaxation. The complexity of the case given in Section 5 is given in Table 9.

Table 9: complexity of case problem for various model variants

model variant	number of constraints	number of booleans
strong formulation	9644	14
weak formulation	3214	14
LP-relaxation	9658	0

As we can see, the case problem is small and causes no problems in computational sense (about 5 seconds solving time using CPLEX for the strong formulation). However, in larger problem instances it may be necessary to use an alternative variant of the model, possibly in conjunction with heuristic algorithms.

Also, smart model formulation can be used to reduce complexity of modelling. The problem complexity may be reduced by:

- clustering of supply and demand points
- reducing the set of possible routes by eliminating routes unlikely to be selected.

Computational results were not the first concern in the research, in which it was focused on model formulation.

Subjects for future research

In this paper, the focus was very much on open loop systems. In closed loops an integral supply chain is realised, which increases the number of interactions in the system and hence system complexity. Also, in reverse logistics there is often uncertainty with respect to quantity, quality and timing of returns. Gaining control over returns is a notorious problem. It remains to be seen whether this has consequences for the modelling of location-allocation problems. For example, uncertainty in supply may be dealt with by traditional methods in sensitivity analysis, but also new stochastic or probabilistic location models may be developed. For example, in our automotive case, the parameter V_{sr} might be stochastic, as a result of uncertain return quality, hence the volume of return flows at location s *feasible* for some RD-option r might have some kind of distribution. (Laporte et al., (1994)) provide some interesting insights in stochastic location models. To the best of our knowledge, current stochastic locational models deal with uncertainty in the right hand side 'b' of the constraint matrix Ax=b. This might be applicable to our parameter V_{sr}. Another way of modelling is to introduce a reusability fraction parameter Υ, which would be part of the left hand side 'A'. Future research could focus on dealing with this kind of models.

Moreover, we have restricted ourselves to a relatively easy problem, which might be more complicated in practical situations. Therefore, further model extensions might follow from changes in the problem definition of Section 2. Some examples include problem situations in which:

- supply and demand are not balanced, hence no recovery strategy has been determined
- customers do not take full batches of secondary parts or materials but only parts of it
- the OEM co-operates with other OEMs
- the OEM has to deal with multiple product types
- facility investment costs are capacity related
- the number of facilities is limited per location
- the capacities of facilities are restricted
- minimal throughput for each opened facility is required
- volume reduction, emissions and material loss occur during recovery processes.

This might lead to additional minimal throughput/maximal capacity constraints, piecewise linear cost functions, a volume reduction factor in the balance equations etc. Our future research aims at improvements of the model on the above aspects.

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