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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.

1. Introduction

Over the past few years, environmental problems have reenforced public interest in reuse and recycling. What is new, is the role of industry in this process. More and more, **O**riginal **E**quipment **M**anufacturers 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 **P**roduct **R**ecovery **M**anagement (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. [5].

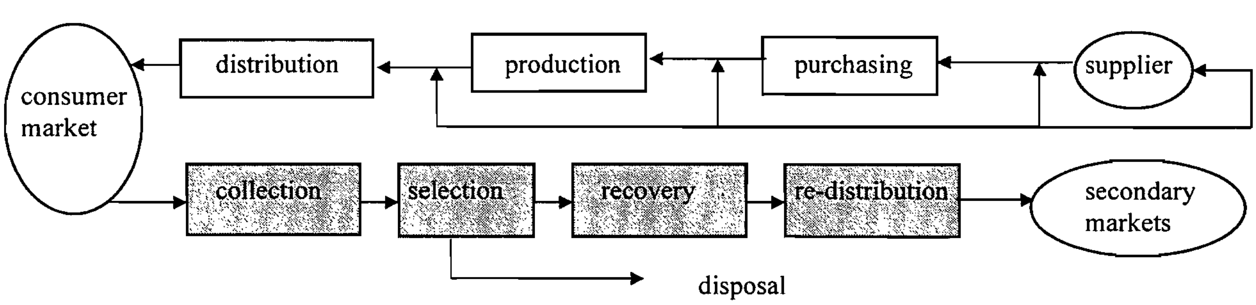

Figure 1. Reverse logistic system in integral supply chain (grey)

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 [4] [5]:

- 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 *physical 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. In addition, it discusses features of reverse logistic systems in comparison with traditional (forward) production-distribution systems. The paper is built up as follows. In Section 2, the problem situation is defined. In Section 3, a mathematical model is presented for determining an optimal multi-echelon network structure. In Section 4, we present a case from the automotive industry. Section 5 is meant for discussion and Section 6 for 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 [4]. 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 5.
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. Model formulation

Next, er give an extended version of some of our earlier work, presented in [1].

3.1. The concept of routes

The core of the model is concept of the *processing route*. As mentioned before, every RD-option assigned in the recovery strategy requires a sequence of facility types. For every facility type, a set of locations is available. Note that in the remainder the terms facility and facility type are equivalent.
Now, an assignment of each facility in the sequence of an RD-options to a location, is called a *processing route* of that RD-option. A set of all possible assignments is generated for each RD-option. Note that a facility -and thus a location- can be part of multiple processing routes. Every 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. If multiple facilities are opened at one location, facility investment costs are charged for every single 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 the 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.

3.2. Construction of an MILP-model

Schematically, the problem with one RD-option r1 with one processing route p1 and three supply and demand points can be represented as in Figure 2.

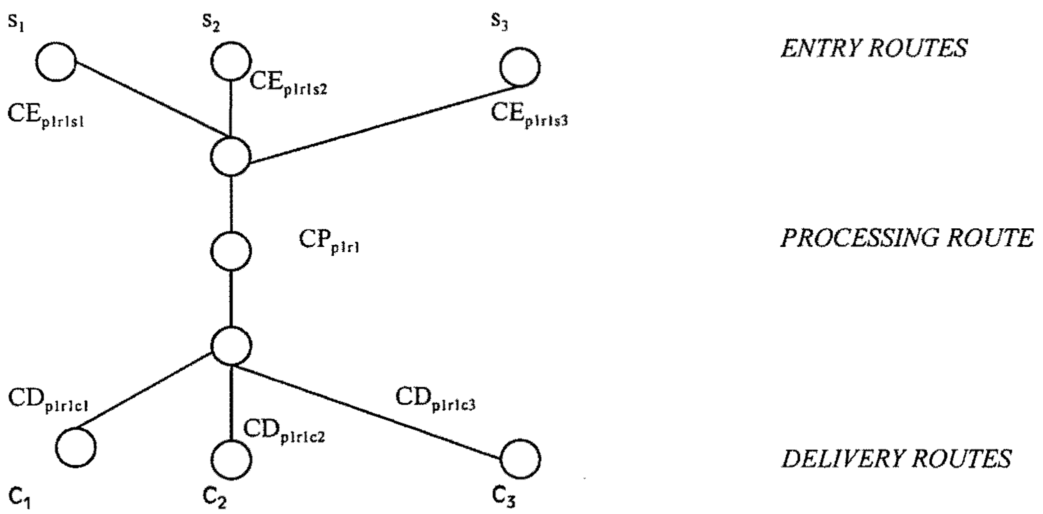

Figure 2. Mathematical representation for one RD-option r1 with processing route p1 and three supply/demand locations

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 cars 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

The decision variables are:

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

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

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

The objective function to be minimised is:

$$\sum_p \sum_r \sum_s CE_{prs} * XE_{prs} \quad + \quad \sum_p \sum_r CP_{pr} * XP_{pr} \quad +$$
$$\sum_p \sum_r \sum_c CD_{prc} * XD_{prc} \quad + \quad \sum_f \sum_{loc} CI_{f,loc} * Y_{f,loc}$$

Constraints:

$$V_{sr} = \sum_p X_{prs} \qquad \forall\, s,r$$

$$\sum_p X_{prc} = V_{cr} \qquad \forall\, c,r$$

$$\sum_p X_{prs} = X_{pr} \qquad \forall\, p,r$$

$$X_{pr} = \sum_c X_{prc} \qquad \forall\, p,r$$

$$X_{prs} * M_{rpfl} <= Y_{fl} * V_{sr} \qquad \forall\, r,p,s,f,l$$

$$X_{prs},\ X_{pr} \text{ and } X_{prc} >= 0 \qquad \forall\, p,r,s,c$$

$$Y_{fl} = 0,1 \qquad \forall\, f,l$$

These constraints are formulated to make sure that:

- all supply is processed correctly
- all demand is satisfied correctly
- recovery strategies are implemented
- all products entering a processing route are taken away from this route
- if a route is used, all locations at this route are opened.

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

4. Automotive case

The case is meant to give an idea of the working of the model. We do not discuss computional results explicitly. Firstly, we shall give a description. Then the data that serve as model input are described. Finally, results are discussed.

4.1. 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.

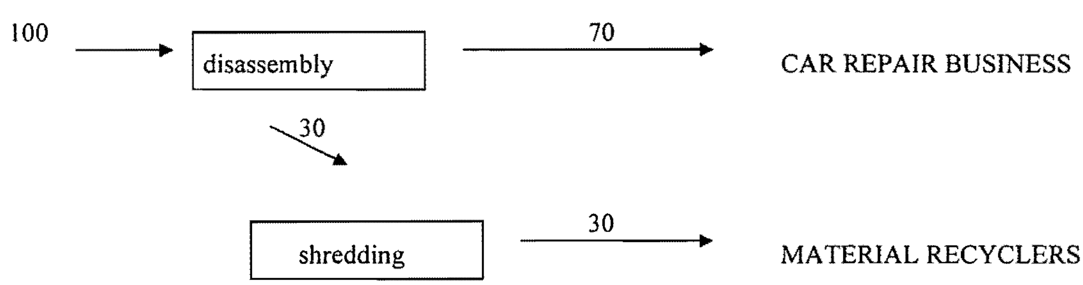

Figure 3. The recovery strategy in the automotive case

4.2. 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.

	supply	*supply*	*supply*	*demand*	*demand*	*demand*
facility loc.	B op Z	Den Helder	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 1. Entry and delivery costs per ton in Dutch guilders

facility location	investment cost shredder	investment cost disassembly line
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 2. Yearly facility investment costs in Dutch guilders

	Enschede	Groningen	Haarlem	Maastricht	Middelburg	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

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

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.

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 4. Yearly supply of cars 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

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

All data are derived from [6]-[15].

4.3. 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 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 lines 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.

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

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

In the Appendix, the flows over entry and delivery routes are given as well as a full check on the cost calculations.
In scenario two, supply and demand are (7,7,7) and (3,3,3) for both RD-option I and II. Now, a disassembly line 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.

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

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

5. Discussion

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, sensitivity analysis might provide interesting insights in the influence of supply, demand and cost functions on the optimal solution and the need for accuracy in parameter estimation.

Forward and reverse logistics compared
Below, we summarise some essential differences forward and reverse logistic systems:

- In reverse logistics there is a supply push and a demand pull, where forward systems (at least for consumer products) are generally pull oriented. We solves this by balancing supply and demand in a predetermined recovery strategy.
- In reverse logistics, there is a major disposal stream that drops out of the system, where in forward systems only some production losses occur.
- Due to a reverse logistic system, closed loops may emerge in an integral supply chain, which increases the number of interactions in the system and hence system complexity.
- In reverse logistics two clients instead of one must be satisfied: the consumer disposer and the consumer re-user.

- In reverse logistics there is often uncertainty with respect to quantity, quality and timing of returns. Gaining control over returns is a notorious problem which increases logistic complexity of the system, especially in closed loop situations where reverse chains connect to forward production-distribution chains.

The above differences are system differences. It remains to be seen whether this has consequences for the modelling of location-allocation problems in reverse chains and integral supply chains. For example, uncertainty in supply may be dealt with by traditional methods in sensitivity analysis, but also new stochastic or probablistic location models may be developed. In addition, 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 algorithms can be used in a branch and bound solution procedure. For a review on general location-allocation models, we refer to [2]. For models specifically developed for reverse logistics, we refer to [3].

6 Conclusions

In this paper, a model was presented to determine an optimal physical design for a multi-echelon reverse logistic system. It can deal with more than two echelons and multiple facility types.
Of course, the model has its shortcomings. To a large extent, this results from the problem definition. 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.

Also, the computation time might strongly increase, when problem instances grow larger than the case we presented in Section 4. 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.

Our future research aims at improvements of the model on the above aspects.

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Appendix Flows and cost calculations for scenario 1

fac.location supply point	Utrecht (disassembly)	Tilburg (disassembly)
Bergen op Zoom	0 (0)	9 (5)
Den Helder	5 (0)	0 (1)
Zwolle	7 (0)	0 (3)

Table a. Entry flows from supply points to facility locations for RD-option I and (II) in 1000 tons

Note, the volumes entered for option II at the disassembly line in Tilburg are also shredded in Tilburg after being disassembled there.

Entry costs: 0*17.9 +(9+5)*10.1+5*19.5+31.5+7*14.4+3*25.3=447.1 * 1000 guilders

Processing costs are assumed to equivalent for all facility locations and thus not of influence on the optimal solution, hence they are set zero in the optimisation.

Yearly facility investment costs: 3.006.750+ 168.750+200.000=3.375.500

fac.location demand point	Utrecht (disassembly)	Tilburg (disassembly)	Tilburg (shredding)
Hoek van Holland	8	2	(4)
Lemmer	4	0	(2)
Roermond	0	7	(3)

Table b. Delivery flows from facility locations to demand points for RD-option I and (II) in 1000 tons

Delivery costs:
8*13.6+4*18.4+0*22.9+(2+4)*17.3+(0+2)*31.4+(7+3)*14.2=491 * 1000 guilders

Total costs:
447.100
3.375.500
491.000
------------------- +
4.313.600

The objective value obtained from the computer is 4.313.660. The difference of 60 guilders is due to round offs in the transportation costs of 0.16/ton/km when calculating entry and delivery route costs.

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