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Publication date:
2004

CentER

Discussion Paper

No. 2004–103

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October 2004

ISSN 0924-7815

Tilburg University

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Abstract. In this paper we discuss a real-life case study in the optimization of the logistics network for the collection of containers from end-of-life vehicle dismantlers in the Netherlands. Advanced planning concepts like dynamic assignment of dismantlers to logistic service providers are analyzed by a simulation model. In this model, we periodically solve a vehicle routing problem to gain insight in the long-term performance of the system. The vehicle routing problem considered is a multi depot pickup and delivery problem with alternative delivery locations. We solve this problem with a heuristic based on route generation and set partitioning.

Keywords: *Reverse logistics - Closed-loop supply chain management - Vehicle routing - Set partitioning - Distribution planning*
JEL-code: C61, M11, R4

1 Introduction

Concern for environment has led to EU legislation for the recovery and discarding of products. The original equipment manufacturer (OEM), as the creator of the products, is responsible and pays for the reverse chain activities. Extended Producer Responsibility (EPR) is the starting point for all EU legislation on end-of-life waste (Spicer and Johnson, 2004). EPR extends the responsibility of the producer towards the whole life cycle, including end-of-life disposal. The EU directive formulates goals. The way the EPR is implemented is left to the member states. In this paper we address a container case of the national Dutch auto recycling system. In this case we analyze new route planning concepts based on central planning.

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1.1 Developments in end-of-life product recovery networks

The automotive industry is one of the major European industries confronted with a massive amount of end-of-life products. In Europe alone, 14.2 million passenger cars were sold in 2003, which will all be discarded at some time. With the approaching deadline for implementation of the European directive on the recycling of end-of-life vehicles (2000/53/EC), initiatives are taken in many EU member states (ACEA, 2004). EU legislation prescribes a recovery target of at least 85% of which 80% by reuse and recycling by 2006. In some of the EU member states, the national legislation is even stricter. In the Netherlands, the national representatives of the automotive industry, including all car manufacturers, acted together with the foundation of Auto Recycling Nederland (ARN).

ARN is responsible for the funding and the physical operations in order to fulfill the national legislation on EPR for its members. In terms of Spicer and Johnson (2004), ARN is a producer responsibility organization. Under the authority of ARN, certain materials are dismantled at the collections points for separate recovery; administration and reporting are essential. Krikke et al. (2004) describe this type of reverse supply chain as a “control type”. These “control-type” supply chains assure that recovery is performed according to formal prescriptions by reporting mass-balances that show the relationship between inputs, output and the degree of recovery. The costs in the logistic network to collect, consolidate, disposition and transport these materials are high. Pressure from the market, together with harmonization of national legislations, aims for more efficiency in the “control-type” reverse supply chains.

In the case study at hand, we deal with the optimization of the collection of containers that are used for transport of end-of-life materials dismantled from vehicles. Due to pressures from the market, the ARN system has to further improve the reverse chain for the processing of end-of-life vehicles (ELVs). Being the chain director, ARN outsourced the actual processes to existing ELV-dismantlers, shredder companies, recyclers and logistic service providers (LSPs). The LSPs are contracted for a period of three years and are responsible for the logistics activities in a certain district. Their activities include the transportation of the container to a depot, consolidation at the depot and in some cases value-adding activities such as sorting and finally transport to the recycling company.

The current logistic planning activities are decentralized and performed by the individual contracted LSPs. LSPs are assigned to ELV-dismantlers based on district boundaries. In a central planning scenario, transportation orders are not sent directly to the individual LSPs, but collected on a centralized level and assigned in clusters to the LSPs, making use of the cost benefits of combining orders. Allocation of customers to LSPs is no longer fixed, but adjusted regularly based on the optimization of routes on a central level. Cruijssen and Salomon (2004) call this the principle of transportation order sharing and find savings up to 15% in an empirical study depending on the characteristics of the network. In business publications this concept is referred to as fourth party logistics (4PL). Fourth party logistics (4PL) is a term coined in 1996 by Andersen Consulting. It was meant for an entity outside the organization that assembles and integrates capabilities from third parties to achieve transformational efficiencies not attainable by the organization on its own (Bumstead and Cannons 2002). More specific to logistics it is an organization for managing multiple third party logistics service providers, who are performing the physical logistic activities on behalf of the supply chain client (Klaver 2000). A 4PL service provider is not engaged in the day-to-day physical logistic operations. The 4PL is therefore an information based company and typically non-asset (Van Hoek and Chong 2001).

1.2 Outline of the paper

The aim of the present study is to quantify the expected benefits of new advanced planning concepts for the logistic network for containers of Auto Recycling Nederland. The problem and its real-life setting will be discussed in Section 2. We restrict ourselves in this discussion to the part of the recycling network concerning the containers. In Section 3 we discuss literature relating to the problem at hand. Vehicle routing literature describing similar problems is scarce. Due to the special problem characteristics we needed to develop a new heuristic. This heuristic is described in Section 4. In Section 5, the results of the case study are discussed. These results incorporate sensitivity analysis and analysis of alternative scenarios. Finally, in Section 6, the results are summarized and an outlook on further research is given.

A detailed description of the various aspects of end-of-life vehicle recycling will not be given and the interested reader is referred to Püchert et al (1994) for discussion on the business aspects of ELV recycling and for more details on the Dutch system of ARN to Van Burik (1998) and Le Blanc et al. (2004).

2 Problem description and background

2.1 Case study

The case study deals with the manual dismantled, high volume materials stored and collected in containers. An end-of-life vehicle consists for 75% of metals, which are easy to recycle. The remaining 10% to reach the recycling target of 85% has to come from manual removal of other materials before the shredding process. Table 1 gives an overview of the high volume materials that are dismantled manually.

Table 1

An ELV-dismantler who has a full container places a request for collection at the logistic service provider (LSP). Within 5 working days, the LSP visits the dismantler and exchanges the full container for an empty one. Glass, rubber strips and PU-foam are collected in a compartmented container, which is developed specially for ARN. Tires and bumpers are collected in 35m3 containers for all ELV-dismantlers. Tires are transferred to one of the four recycling companies for tires contracted by ARN in the Netherlands either directly or via a consolidation depot. The other materials are sorted, processed and finally transferred in a bulk transport to recyclers, mostly located in neighboring countries. We focus on the planning of the collection requests for containers from ELV-dismantlers. Since the recyclers for materials other than tires are located abroad, the transportation of these materials to the recyclers are usually performed in a linehaul trip. Linehaul trips offer no combination possibilities and the costs of these trips are assumed to be given. Figure 1 gives an overview of the processes in the ARN network.

Figure 1

Currently, two types of lifting mechanisms are in use by the LSPs for loading and unloading of containers on a truck. The first system uses an iron chain to drag up the container onto the truck; the second system uses a pneumatic hook to pickup the container and lay it down on the truck. Both systems work fine, however the systems are not compatible. A container or truck suitable for the hook system is not suitable for the chain system and vice versa. This restriction must be taken into account in planning the trips, since LSPs do not have both lifting mechanisms available. Figure 2 shows the map of the Netherlands with district boundaries and the lifting mechanism in use (hook or chain). There is the feeling that improvement can be found in standardizing the lifting mechanism.

Figure 2

The goal of the study is to analyze and improve the collection system of containers. To this end, we examine the following situations:

- Allowing direct shipment of containers from dismantler to recycler, bypassing the consolidation depot.
- Changing the allocation of dismantlers to LSPs from the current assignment, based on district boundaries, to the optimal fixed assignment or to a dynamic assignment based on optimal routing decisions in each planning period.
- Standardizing the lifting mechanism for loading and unloading containers on a truck.

Although this is mainly a tactical study, we choose to solve the operational problem as well to get a good estimate of transportation costs and performance. The reason for this is that the small nuances in different scenarios cannot be adequately expressed in tactical models; hence we need detailed operational route schemes. The problem resembles an unique multiple logistic service provider vehicle routing model with pickup and delivery allowing alternative delivery locations with small vehicle capacity (2 containers), which has not been described in literature before. We call this the 2-container collection problem. In the next paragraph we give a formal description of the problem.

2.2 The 2-container collection problem

Consider an undirected graph G = (V, E) with V the vertex set and E the set of edges connecting the vertices. The vertex set V consists of vertices for customer sites, depots and recycling facilities, i.e. $V = V^{cust} \cup V^{depot} \cup V^{recycling}$. The distances and travel times along the edges are given in matrices D = ($d_{i,j}$) and T = ($t_{i,j}$) respectively. Let $O = O^{cust} \cup O^{depot}$ be the set of orders consisting of orders to be picked at a customer site O^{cust} and orders to be picked up at a depot O^{depot}. Customer orders can either be delivered to a depot or to a recycling facility, depot orders can only be delivered to a recycling facility. Practical restrictions determine which locations are feasible for each order $o \in O$. Binary parameter $\delta_{o,loc}$ indicates whether order o can be delivered to location $loc \in V^{depot} \cup V^{recycling}$. The decision which delivery location is selected depends on estimated gate fee for dropping the order at a location $profit_{o,loc}$ and the cost of including the delivery location in the route. The costs of a route are built up of a distance component, a time component and the profit or costs of the selected delivery location.

Vehicle capacity in the model is limited to 2 containers and the duration of a route is restricted. We consider each logistic service provider to have an unlimited number of vehicles, since in practice capacity problems never occur. We consider different types of containers. Orders always consist of an exchange of a full and an empty container. At a customer location an empty container is exchanged for a full container, at a recycling facility full containers are exchanged for empty containers of the same type. Orders can have the size of either 1 or 2 containers, all orders concern containers of the same type. Since shortage of containers in practice never occurs, a depot location is assumed to have an unlimited storage of all containers types to exchange.

In the next section we explore relevant literature dealing with similar problems.

3 Literature

Literature on vehicle routing is abundant, see Bodin et al. (1983) and Toth and Vigo (2002). In reverse supply chains, variants of the classical vehicle routing problem occur that are less extensively studied (Dethloff 2001). Beulens (2003) provides an excellent overview of vehicle routing models and the special types of models occurring in reverse logistics.

The problem closest to the situation at hand is the skip problem (SP), as described in De Meulemeester et al. (1997). Vehicles start at a depot and have to deliver empty skips to customers, collect full skips from customers and deliver the full skips to either the depot or one of the disposal facilities. A vehicle has capacity to carry one skip at a time. Skips can be of multiple types and this is a restriction in exchanging full for empty. De Meulemeester et al. (1997) develop two heuristics and an exact procedure for solving this real-life problem. The first heuristic is based on the classical Clarke and Wright savings heuristic. The second heuristic considers the solution of a formulated transportation problem that is a relaxation of the original problem and therefore provides a lower bound to the optimal solution. The solution of the transportation problem is made feasible in some heuristic steps. De Meulemeester et al. (1997) also developed an enumerative algorithm for finding the optimal solution to the problem. In a number of cases this enumerative algorithm was not capable of finding the optimal solution within one hour of calculation time even on relatively small instances. In randomly generated instances the developed heuristics were benchmarked against the obtained optimal solution. On average, the variant of the Clarke and Wright savings algorithm performed best.

Bodin et al. (2000) describe a variant of the skip problem called the rollon-rollof vehicle routing problem (RRVRP). In a RRVRP trip the truck with capacity for one container, or in this paper called trailer, starts at a depot and needs to serve customers who need either a container to be placed, collected or exchanged (full for empty). Two types of trailer exchanges can occur: an empty trailer is attached at the depot and exchanged for a full trailer at the customer, in the other type of trip the full container is attached at the customer, emptied at the disposal facility and returned to the customer. Which type of exchange trip occurs depend on the ownership of the container types. The network consists of only one depot and one disposal facility and all trailers are of the same type. In that sense the model of

Bodin et al. (2000) is a simplification of the real-life case of De Meulemeester et al. (1997). Bodin et al. (2000) develop four types of algorithms. The first algorithm is again an adjustment of the Clarke and Wright heuristic. The second algorithm is a trip insertion and trip improvement heuristic. The third algorithm is a so-called decomposition algorithm, starting with enumerating routes, followed by solving a set covering. The resulting solution is improved with some swaps. The last and most advanced algorithm is a truncated dynamic programming heuristic, generating partial solutions that are completed by adding the not covered orders by solving a bin-packing model. The contribution of Bodin et al. (2000) is theoretical of nature, since they only test the developed heuristics on a set of randomly generated instances. The performance of the dynamic programming algorithm is the best in solution quality, however calculation times are long. The other algorithms are faster, but especially the trip insertion and trip improvement heuristic is not competitive on solution quality.

Archetti and Speranza (2004) describe another variant of the problem, the so-called 1-skip collection problem (1-SCP). As the name already indicates vehicle capacity is again limited to 1 skip or container. Archetti and Speranza consider two types of customers, one type with a fixed visit frequency and one with service request when the skip is full. Since they deal with a real-life problem, several practical restrictions are considered such as multiple container types, time windows, different priorities for different customers and a limited fleet size. Archetti and Speranza developed a three phase algorithm. In phase 1, the set of skips that needs to be collected that day is determined and ranked in priority. In phase 2, a solution for the subset of skips is constructed. In phase 3, the solution is further improved by using local search procedures.

Although some of the models come close to the situation at hand, none of them has the same characteristics. All of these models consider the vehicle capacity to be limited to precisely one skip, trailer or container. In our case, two containers can be loaded on a truck. Extensions of the algorithms described in literature to the situation with two containers are not trivial. Techniques known from more general vehicle routing models should be used, however these techniques do not exploit the feature of having discrete capacity of only two containers. Hence, in this paper we develop a new heuristic for tackling the problem at hand.

4 Description of the heuristic

The heuristic we developed to handle the case described is a two step heuristic. In the first step a large number of candidate routes are generated. In the second step a combination of routes is selected, minimizing the cost making up a complete route scheme, while satisfying all the requirements. This combination of route generation and set partitioning is referred to in vehicle routing literature as the set partitioning approach, see for example Fleuren (1988). More generally, this type of algorithms where a promising set of possibilities is generated and a solution is found by set partitioning is called petal algorithms (Laporte et al. 2000). An alternative way of applying set partitioning in this setting is by using column generation, see for example Agarwal et al. (1989). Since we have a fast set partitioning solver to our disposal and the average number of orders per route is limited in our case, we choose to do an enumeration of a large set of feasible routes.

4.1 Route generation

Goal of the route generation is to construct a set of feasible routes, such that the route selection procedure can make a “good” choice from the set. Since our problem concerns a multi depot pickup and delivery problem with alternative delivery locations, we introduce the concept of root and sub-orders to handle this type of problems. This is described in Section 4.1.1.

While the number of feasible routes grows exponentially we suffice with the generation of a promising subset of routes. To restrict the number of route candidates that are generated we use the concept of order neighborhoods, this is the topic of Section 4.1.2.

Finally, the route generation procedure is described in Section 4.1.3.

4.1.1 Root and sub-orders

A vehicle routing model with pickup and delivery heuristic with alternative delivery locations and selection of logistic service providers comes along with a number of difficulties in the algorithm. To handle this efficiently, we split the transportation order into two parts; a general part, the root-order, and a delivery location specific part, the sub-order. Since each sub-order has a unique pickup and delivery location and logistic service provider, our algorithm can proceed similar as standard pickup and delivery heuristic with some additional constraints on the combination of sub-orders (never two sub-orders of the same root-order).

Example

ELV-dismantler WreckRec has a container with tires that needs to be transported to either the tire recycler TireRec or to a depot of a logistic service provider. There are two competing logistic service provider with a depot: LogOpt and LogCheap. This single root-order results in four sub-orders as shown in Table 2.

Table 2

4.1.2 Neighborhoods

While the total number of feasible routes can be very large, we use the concept of neighborhoods to limit the set of candidate routes. Every order has a set of neighbors, ordered on distance, and when we add orders to a route, we only consider orders that are in the neighborhood of the route, which is the union of neighborhoods of the orders in the route.

Formally, we can describe this as follows. At the start of an empty route, every sub-order can be inserted. For each sub-order we define a set of neighboring sub-orders belonging to different root-orders. Let nb_subord_{so} denote this set of neighboring sub-orders for sub-order so. $RouteSubOrders_r$ denotes the set of suborders in route r. The neighborhood of a route r, denoted as nb_route_r, is the union of the neighborhoods of the sub-orders in a route, i.e. $nb\_route_r = \bigcup_{so \in RouteSubOrd_r} nb\_subord_{so}$.

To determine the neighborhood of a sub-order we need a distance measure. Consider two sub-orders so_A and so_B, with p_{so} and d_{so} denoting the respectively the pickup and the delivery location of sub-order so. Our distance measure is based on the best way to combine two orders instead of driving the driving them separate. Mathematically this criterion is given in [1].

$$
\begin{aligned}
dist_{so\_A,so\_B} = \min\{ & d(p_{so\_A}, d_{so\_A}) + d(d_{so\_A}, p_{so\_B}) + d(p_{so\_B}, d_{so\_B}), \\
& d(p_{so\_A}, p_{so\_B}) + d(p_{so\_B}, d_{so\_A}) + d(d_{so\_A}, d_{so\_B}), \\
& d(p_{so\_A}, p_{so\_B}) + d(p_{so\_B}, d_{so\_B}) + d(d_{so\_B}, d_{so\_A}), \\
& d(p_{so\_B}, d_{so\_B}) + d(d_{so\_B}, p_{so\_A}) + d(p_{so\_A}, d_{so\_A}), \\
& d(p_{so\_B}, p_{so\_A}) + d(p_{so\_A}, d_{so\_B}) + d(d_{so\_B}, d_{so\_A}), \\
& d(p_{so\_B}, p_{so\_A}) + d(p_{so\_A}, d_{so\_A}) + d(d_{so\_A}, d_{so\_B})\} \\
& - d(p_{so\_A}, d_{so\_A}) - d(p_{so\_B}, d_{so\_B})
\end{aligned}
\qquad [1]
$$

For each sub-order, we list the distances to all suborders belonging to a different root order and include the nearest nb_size sub-orders in nb_subord_{so}. Experiments with the required size of the neighborhood to find good solutions indicated that nb_size = 6 performs well; in the remaining of this paper we use this value. In Figure 3 the diminishing improvements found by extending the neighborhood size is shown for a representative sample of 25 real-life instances consisting of on average 54 root-orders and 114 sub-orders. Further increasing the neighborhood size will marginally improve the solution and causes large increase in the route generation times. Note that after a certain threshold the route generation is not restricted anymore and all feasible combinations are generated.

Figure 3

4.1.3 Outline of the route generation algorithm

Goal of the route generator is to create a large number of attractive feasible routes. As stated in Section 4.1.2, we restrict the enumeration of routes by only appending orders from the neighborhood. A route is feasible if the maximum time allowed for one day and the maximum vehicle capacities during the route are not exceeded. At all pickups of full containers at an ELV-dismantler, an empty container of the same kind must be exchanged. If this is not possible, the route is infeasible. To systematically generate the routes we make use of a recursive function implementation. The function RouteGenerator describes the main idea behind the route generation algorithm.

```
Function RouteGenerator
IF (Route empty)
        RouteNeighborHood := Set of all SubOrders
ENDIF;
FOR (SubOrder in RouteNeighborHood) DO
        InsertSubOrder( SubOrder )
        UpdateRouteNeighborhood
        IF (RouteFeasible) THEN
                WriteRouteToRouteSelectionProblem
                RouteGenerator
        ENDIF
        RemoveSubOrder
        UpdateRouteNeighborhood
ENDFOR
```

Inserting a sub-order in a route is the same as inserting the pickup stop and the delivery stop of the sub-order in the route. Since we deal with the pickup and delivery situation, we find for each possible position to insert the pickup stop (StopP), the best position to insert the delivery stop (StopD). The function InsertSubOrder desribes the main ideas behind the insertion of of a sub-order in a route.

```
Function InsertSuborder( SubOrder )
FOR (Position in Route) DO
        Insert StopP
        FOR (Position in Route after Stop P) DO
                Insert StopD
                UpdateRoute
                IF (BestInsertion AND RouteFeasible) THEN
                        StoreBestInsertionPosition
                ENDIF
                Remove StopD
        ENDFOR
        Remove StopP
ENDFOR
IF (BestInsertionExists) THEN
        Insert StopD and StopP at best position
        UpdateRoute
ENDIF
```

Although the number of routes that is generated is restricted by the size of the order neighborhood, the number of routes generated can still be very large in some cases. Occasionally, it happens that over 2,5 million routes are generated.

When then number of routes exceeds 2.5 million, we reduce the maximum allowed size of the neighborhood with one and restart the route generation.

4.2 Route selection

The problem of finding the optimal combination of routes such that all orders are performed against minimal cost is formulated as a set partitioning problem. After introducing some notation, the problem is given in equation [2] to [4].

Parameters

$\delta_{so,ro}$ = 1 if sub-order so belongs to root-order ro, 0 otherwise.

$a_{so,r}$ = 1 if sub-order so is contained in route r, 0 otherwise.

c_r = denotes the cost of driving route r.

p_r = denotes the cost or profit of route r as a result from the chosen delivery locations for the orders in route r.

Variables

X_r = 1 if route r is selected, 0 otherwise.

The route selection problem

$$\min \quad \sum_r (c_r - p_r) \cdot X_r \qquad [2]$$

$$\text{s.t.} \quad \sum_r \sum_{so} (\delta_{so,ro} \cdot a_{so,r}) \cdot X_r = 1 \qquad \forall ro \qquad [3]$$

$$X_r \in \{0,1\} \qquad \forall r \qquad [4]$$

Note that $\sum_{so} \delta_{so,ro} \cdot a_{so,r}$ is either 0 or 1 by construction of the route generator and therefore the route selection problem is a pure set partitioning problem. To exploit the special structure of the set partitioning problem we make use of a special set partitioning solver, instead of more generic mixed-integer linear programming solver as for example Cplex (www.ilog.com). We use the solver developed by Van Krieken et al. (2004). This solver uses Lagrangean relaxation and dual heuristics for determining the lower bound and branch and bound for finding the optimal solution. Furthermore, several problem reduction techniques are used to reduce the number of variable and constraints in the problem. The solver is very effective in solving the set partitioning instances under consideration, even if the amount of variables grows very large. Problems with over a million variables are solved in a couple of minutes on a normal desktop computer and several times faster than Cplex.

4.3 Validation and verification

To assure the value of a model, we extensively validated and verified the models correctness. In the verification process we have analyzed the internal consistency. During this phase we checked whether the routed constructed by the heuristic are logical and whether the model behaved as we expected it to behave.

During the validation process, the external correctness of the model was questioned, i.e. does the model give a representative description of the real world? We have compared the results with data coming from collection companies. Furthermore, logistic specialists of ARN have examined the outcomes of the model and compared them with their expectations. Finally, we were able to conclude that the model with its assumptions was representative.

5 Structure of the analysis

5.1 Simulation

We have used a simulation model to analyze the performance of the system. To obtain representative results, each simulation run consisted of 10 replications of 1 year. In the simulation, the operational vehicle routing problem was solved twice a week for a planning horizon of 3 working days. This means that over 1000 set partitioning problems were solved per simulation run.

Orders generated during a certain collection period are planned and executed the next planning period. For containers with tires brought to the depot, the orders for shipping the containers to the recycler are also issued in the beginning of the next planning period. This prevents the simulation for creating dependency within a planning period that cannot be handled.

5.2 Data and scenarios

The scenarios are constructed in cooperation with the logistic experts of ARN and in cooperation with the logistic service providers hired by ARN. Distances and driving times used in the analysis were obtained from Evo-IT (www.evo-it.nl). The cost figures used were obtained from the NEA (2004), which is an authority on traffic and transportation issues in the Netherlands. The data used for simulating the processes at the ELV-dismantlers is empirical data available in the corporate databases of ARN. A detailed description of these data can be found in Schreurs (2004).

Scenarios are defined along three dimensions:

- The lifting mechanisms used by the LSPs:
  - The current situation: two different lifting mechanisms are used
  - The standardized situation: all LSPs use the same lifting mechanism
- The assignment of transportation orders to the logistics service providers
  - Current fixed assignment: ELV dismantlers are assigned to LSPs and recyclers based on district boundaries.
  - Optimized fixed assignment: ELV-dismantlers are assigned to the closest LSP/recycler based on a distance criterion.
  - Central planning: no fixed assignment exists: the LSP with the best combination possibilities executes the transportation order.
- The allowed routes for containers with tires:
  - No direct shipment: all tire containers pass the depot.
  - Direct shipment: in case it is advantageous to ship tire containers directly to a tire recycler instead of the depot this is allowed.

These possibilities result in 12 scenarios as shown in Figure 4.

Figure 4

The current assignment of ELV-dismantlers to depots and recyclers is based on district boundaries, for historic reasons. In many cases, this assignment is far from efficient, since districts can have irregular forms. We resolve this by simply assigning each ELV-dismantler to the nearest depot with the right lifting mechanism. In the central planning scenario, the effect of a fixed assignment is analyzed by losing this restriction altogether and dynamic planning on a central level.

Currently, nearly all tire containers are transported to the recycler via a depot, since the container must be weighed at the depot. Nowadays, recyclers also have accurate weighing facilities for trucks, such that the stop at the depot is not necessary. Direct shipment of containers with tires is possible as long as the date of delivery is communicated.

6 Results

6.1 Current logistic network

The results for the current logistic network with LSPs having different types of lifting mechanisms are presented in Table 3. Due to confidentiality reasons the cost figures are indexed. A comparison of the various scenarios for the key variables, the yearly indexed cost and the number of routes, is also presented in Figure 5. For our convenience we have assigned a scenario ID to each scenario and we refer to this ID instead of giving a full description of the scenario.

Allowing the logistic service providers to ship tire containers directly from ELV-dismantlers to recyclers, results in cost savings ranging from 6.3% to 9.1%, depending on the type of assignment of ELV-dismantlers to LSPs. The average route length both in time and distance increase, since it is more attractive to make a small detour to drop tire containers at a tire recycler instead of bringing them first to the depot and then to the recycler. This phenomenon is causing the drastic decreases in the number of routes driven, since most tire containers are transported only once. Implementation of direct shipment is fairly easy and only requires additional arrangements with the recyclers.

Optimizing the assignment of ELV-dismantlers to depots and recyclers results in cost decreases ranging from 4.4% to 4.7%. This effect is small, since the diversity in container lifting mechanisms only allows little freedom for optimization. Changing to another fixed assignment is fairly easy and only requires renegotiation of contracts with LSPs.

Compared to the optimal fixed assignment, the extra savings of dynamic allocation by central planning are limited, ranging from 0.6% to 3.6%. These marginal costs savings do not counterbalance the change required in the planning and control mechanisms to implement this dynamic assignment.

Table 3

Figure 5

6.2 Network with uniform lifting mechanism for containers

The differences in lifting mechanisms in use by the logistic service providers are likely to cause inefficiencies. ARN is lobbying for standardizing container lifting mechanisms at the logistic service providers. In Table 4, this situation is compared to the current situation. Currently, the assignment of dismantlers to depots and recyclers incorporates the differences in lifting mechanisms. Therefore, the standardization of the lifting mechanism only makes sense for the situation where the assignment is changed. We compare the current situation with the optimized assignment and central planning scenarios with uniform lifting mechanism.

Table 4

Using the optimal fixed assignment, the costs savings of standardizing the lifting mechanism are about 8.7% when we allow direct shipments. If direct shipments are not allowed the costs savings are 8.5%.

The costs savings of standardizing the lifting mechanism in the case of central dynamic planning are 8.3% in the case where direct shipment is not allowed and 6.1% when direct shipment is allowed. Given standardized lifting mechanisms, the costs savings of dynamic central planning over optimized fixed assignment are less than 1%, whether we allow direct shipment or not, which does not counterbalance the costs of the organizational changes. Standardizing the lifting mechanism is comparable with increasing the network density for the LSPs. Improving the combination possibilities in a dense network has a marginal effect on the cost, since, in a dense network, there are already abundant combination possibilities. These results on central planning are supported by the findings of Cruijssen and Salomon (2004), who showed that the benefits of central planning are limited, when orders are large compared to the vehicle capacity. Furthermore, our orders are not randomly assigned to depots, but by using district boundaries. Although district boundaries are far from optimal as shown, it has still some logic and is much better than a random assignment as was initially the case in Cruijssen and Salomon (2004).

When we optimize the assignment of recyclers to LSPs, standardizing the lifting mechanism results in considerable cost savings that justify the necessary investment to implement this in the chain of ARN.

7 Conclusions and outlook

In this paper we describe a real-life project in optimizing the logistic network for containers with materials coming from end-of-life vehicles. The underlying vehicle routing model is a unique multi-depot pickup and delivery with alternative delivery locations model. The heuristic we use is based on generating a set of promising routes and selecting the optimal combination of routes by solving a set partitioning problem.

The limited research on this type of problems is probably caused by the fact that it is considered to be a typical reverse logistics problem where waste or cores for recycling are collected, bundled and brought the a central recovery center. We are not aware of forward logistic problems with similar characteristics. Although we developed a new heuristic and the heuristics described in literature stem from problem instances that are typically product recovery or waste disposal networks, we do not feel that the mathematical techniques differ. Relating this project to earlier projects in the same recycling network we conjecture that, although logistic concepts differ from forward logistics, the mathematical techniques and models in this network are not fundamentally different.

From a business point of view, we analyzed the consequences of better assigning waste generators to logistics service providers and making routing decisions by central planning. Furthermore, we analyzed the influence of a policy not allowing the direct shipment of waste generator sites to recycling facilities and the effects of the different lifting mechanisms for containers in use.

Considering the assignment of recyclers to logistics service providers, we recommend to change the current fixed assignment, based on district boundaries, to the optimal fixed assignment. Efforts to implement the dynamic assignment option would be considerable, while the additional savings over the optimal fixed assignment are limited. Since the study shows that allowing direct shipment will results in costs savings and the organizational burden is not very large, we recommend allowing direct shipment of tires to recyclers. Considering the lifting mechanism, the study shows that standardizing will result in significant costs savings, worth the effort to standardize the lifting mechanism in the ARN network. The total percentage costs savings of the recommended new system with standardized lifting mechanism, possible direct shipments and the optimal fixed assignment are over 18% compared to the current system.

In popular literature the term fourth party logistics is frequently used. We favor the term of central planning, since the exact meaning of fourth party logistics term is not crystallized yet. Our concept of central planning as the coordination of multiple third-parties, i.e. logistic service providers, implies the same as the concept of fourth party logistics as defined by Van Hoek and Chong (2001). In our case study the concept of a central planning is not effective.

Since cost reductions in closed-loop supply chains for EOL product are crucial; it can make the difference between recycling for profit or for loss. In the last case, OEMs will not recycle as long as they are not forced by legislation. The best way to proceed towards the sustainable society is driven by business motivations. Since we are just at the start in setting up and designing product recovery networks, there are great opportunities for operations research to assist with offering advanced planning systems from an operational to a strategic level.

Acknowledgements. The authors would like to thank Roelof Reinsma and Annemieke van Burik of Auto Recycling Nederland for their assistance and support during the project.

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Appendix: figures and tables

Material	Average amount per wreck	Application of the recovered material
Tires	27.9 kg	High quality: retreaded and sold as tire Low quality: paving tiles and insulation mats
Bumpers	5.6 kg	Engine covers and wheel arches
Glass	25.4 kg	Bottles and glass fibre
PU-foam	6.7 kg	Car seat padding and mattresses
Rubber strips	7.7 kg	High purity: as roll container wheels Low purity: as fuel in cement kilns

Table 1. The materials collected in containers with their applications after recycling

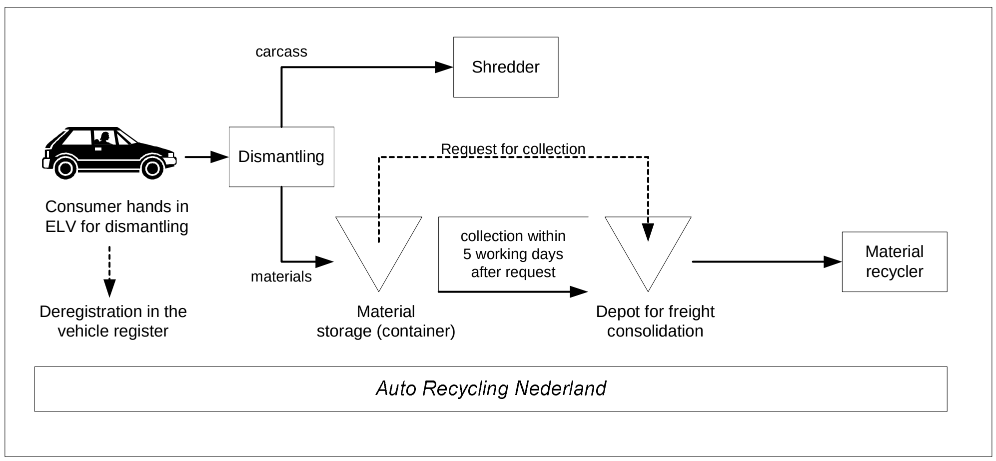

Figure 1. An overview of the processes in the ARN network for the recycling of ELVs

Figure 2. Overview of the ARN network indicating the two lifting mechanism (hook and chain) in use per district.

Sub-order	LSP performing the order	Pickup location	Delivery location
1	LogOpt	WreckRec	LogOpt depot
2	LogOpt	WreckRec	TireRec
3	LogCheap	WreckRec	LogCheap depot
4	LogCheap	WreckRec	TireRec

Table 2. The sub-orders in the example of WreckRec.

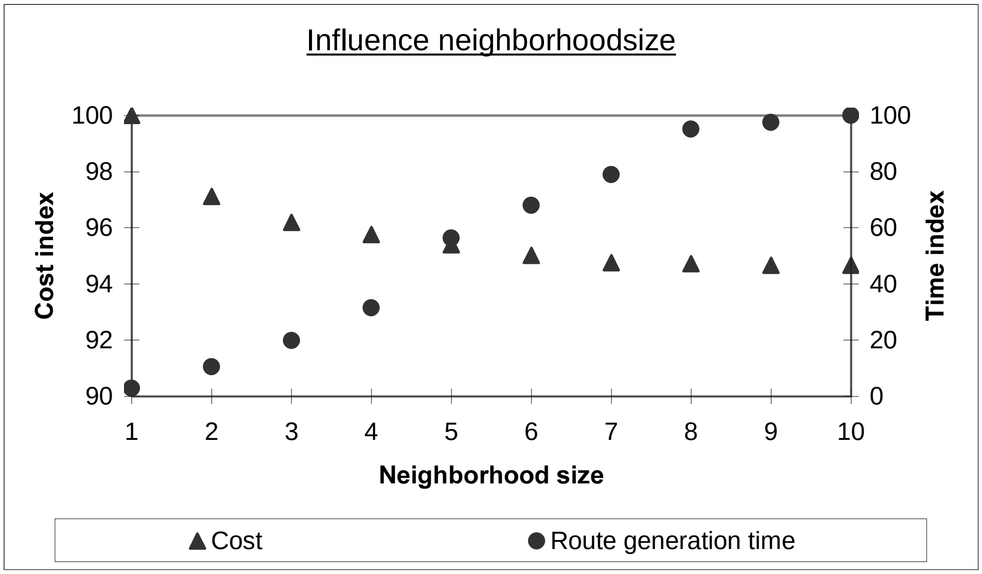

Figure 3. The influence of changing the size of the neighborhood on the quality of the solution based on representative sample of 25 real-life instances.

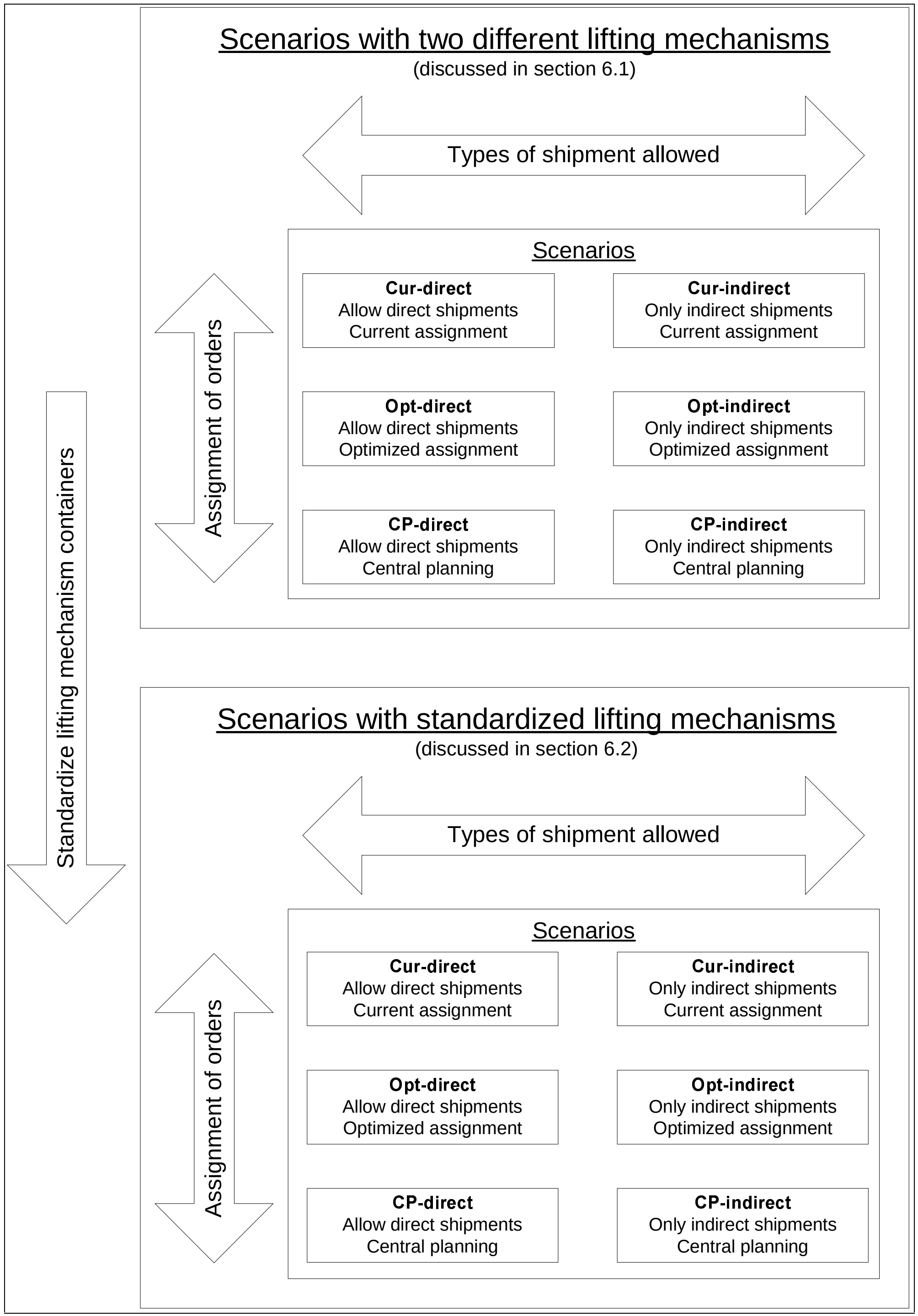

Figure 4. An overview of the scenarios.

Scenario ID	Cur-indirect	Opt-indirect	CP-indirect	Cur-direct	Opt-direct	CP-direct
Assignment	Fixed, current	Fixed, optimized	Free, central planning	Fixed, current	Fixed, optimized	Free, central planning
Type of shipments for tires	Only indirect	Only indirect	Only indirect	Allow direct	Allow direct	Allow direct
Average cost per year (indexed)	100	95.3	94.8	93.4	89.3	86.1
Average distance per year (km)	505,779	471,610	467,188	483,092	458,972	433,735
Average number of routes per year	2,887	2,906	2,907	2,346	2,336	2,226
Average number of containers per route	2.45	2.44	2.44	2.39	2.32	2.42
Average route distance (km)	175.2	162.3	160.7	205.9	196.4	194.8
Average route duration (min)	291.0	277.6	276.1	331.3	319.7	325.4
Average driving time per route (min)	177.1	164.3	162.8	208.7	198.4	198.2
Average load and unloadtime per route	114.0	113.3	113.3	122.6	121.3	127.1

Table 3. Results for the current network with restrictions on the lifting mechanisms (Case 1).

Scenario ID	Cur-indirect	Opt-indirect	CP-indirect	Cur-direct	Opt-direct	CP-direct
Assignment	Fixed, current	Fixed, optimized	Free, central planning	Fixed, current	Fixed, optimized	Free, central planning
Type of shipments for tires	Only indirect	Only indirect	Only indirect	Allow direct	Allow direct	Allow direct
Average cost per year (indexed)	100	87.2	86.9	93.4	81.6	80.8
Average distance per year (km)	505,779	411,893	408,954	483,092	402,125	394,886
Average number of routes per year	2,887	2,891	2,876	2,346	2,254	2,280
Average number of containers per route	2.45	2.45	2.47	2.39	2.39	2.36
Average route distance (km)	175.2	142.5	142.2	205.9	178.4	173.2
Average route duration (min)	291.0	258.8	259.4	331.3	306.6	301.1
Average driving time per route (min)	177.1	145.1	145.0	208.7	181.4	177.2
Average load and unloadtime per route	114.0	113.7	114.4	122.6	125.1	123.9

Table 4. Results for the current network with losening the restrictions on the lifting mechanisms (Case 2)

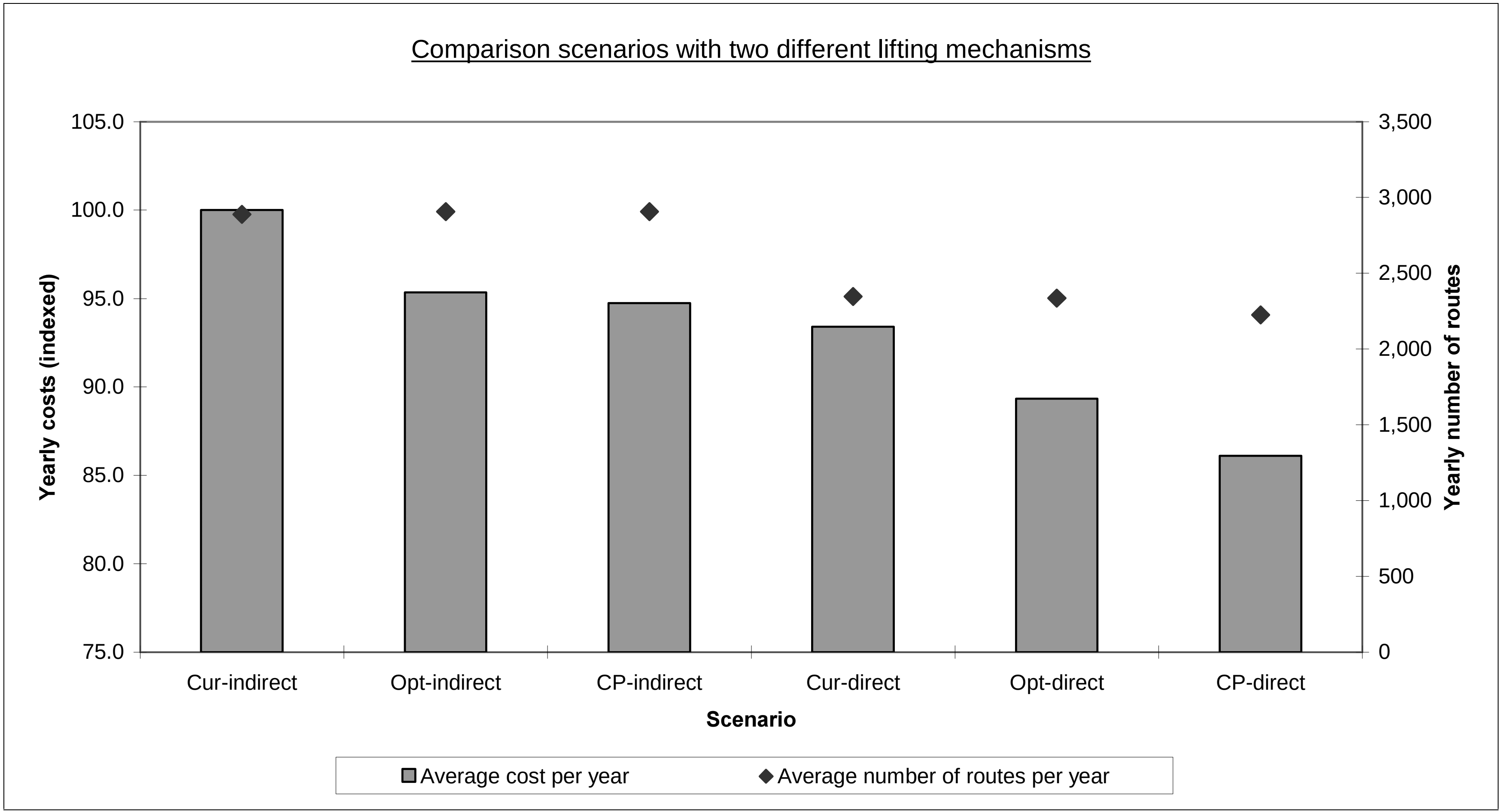

Figure 5. Comparison of scenarios with different lifting mechanisms for the key variables total yearly cost and the number of routes.