Remanufacturing Network Design Modeling: A Case of Diesel Particulate Filter

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Abstract

In the last decade, in order to increase the customer satisfaction, companies faced with challenges like scarce resources and costs during the production process. Reverse logistic approach helps companies to cope with those difficulties by using different operations. Remanufacturing of used products enables companies to decrease production costs and also reduce raw material costs. This common problem is materialized in a famous heavy truck producer who wants to enter European market with a new product which is a diesel particulate filter. This study aims to design and develop a Reverse Logistic Network System that contains remanufacturing processes for the heavy truck manufacturer. The objective is to determine optimal geographical locations of remanufacturing centers considering economical and environmental impact as a cost function in the mathematical model based on Capacitated Facility Location Problem approach.

Keywords: Reverse Logistics; Remanufacturing Network; Modeling; Environmental Impact; Heavy Truck Industry

1. Introduction

Previously, companies used to reuse materials and products or partial equipments. However the main objective was not the environmental matters or sustainable development. The primary concern was scarcity of resources. After the exploration of cheap materials and technological innovations, companies begun to mass consumption and routine throw away. In 1970s, the study for the Club of Rome stated there is a limit to the growth. The report claimed that mankind was going to disintegrate around 2050 [1]. During the following decades, academicians, politicians and media addressed the disasters to such issues in general. Especially in Europe, since 1995, regulations forced companies for green products and materials via reverse logistics (RL) processes.

The mains motivations of RL can be examined into three headlines such as economics, ecologic and legislation. The economical driver of reverse logistics regards profits from recovery actions because of reduced costs, decrement on the use of materials and savings of valuable spare parts. The primary ecological driver is scarcity of resources. Existing legislation that emerges after depletion of landfill and incineration capacities leads producers to recover their products or to accept them-back. Another important driver for product recovery is related with growing environmental concern among customers. Customers increasingly expect companies to reduce the environmental burden of their activities and products. Therefore, a “green” image has become an important marketing element [2]. Producers keep on green line with their process in order to satisfy expectation of customers. In this aspect the main goals of producers are obtaining the customer appreciation [3,4].

This study aims to design and develop a Reverse Logistic Network System that contains remanufacturing processes for the heavy truck manufacturer. The objective is to determine optimal geographical locations of remanufacturing centers considering economical and environmental impact as a cost function in the mathematical model based on Capacitated
Facility Location Problem approach. The manufacturer wants to have a remanufacturing system for a recently developed innovative product. The product is called diesel particulate filter (DPF) which transforms certain pollutant substances into the less pollutant substances before releasing. The price of a new DPF is high because it is composed of expensive materials such as Platinum, Palladium and Rhodium.

Currently, at the end of its lifetime the DPF is destroyed. However, the valuable components of DPF are not completely degraded to be destroyed and it will be worthwhile to exploit them again. For cost and environmental savings, the manufacturer has envisaged the remanufacturing of DPF. However, RL processes may not be as beneficial as we think. RL processes require energy consumption even if they reduce the use of raw materials. On the other hand transportation process generates a significant amount of carbon dioxide. In fact, all processes in RL involve both economic and environmental costs.

The remainder of the paper is organized as follows: Section 2 present a literature survey on RL and RL Network Design. In Section 3, the current situation of the company and the main characteristics of Capacitated Facility Location Problem (CFLP) are explained in detail and its general mathematical formulation is presented. In the fourth section, experimental results of proposed model are presented. The conclusions and possible directions for future research are given in the last section.

2. Literature survey

2.1. Reverse logistics

RL appeared in the beginning 1990s simultaneously in Germany and in the USA. In the USA, it was pushed by environmental consciousness of consumers who wanted the recycling of packaging and product in end of life, while in Germany and Europe, RL emerged because of regulatory constraints [4].

Reverse Logistics is defined in [5] as "The management of the organization of material resources obtained from customers". Fleischmann et al. indicate that the reverse logistics "contains the logistics, to the end, used for products that are no longer required by the users to the products that can be reused in the market"[6]. The definition focuses on distribution planning, inventory management and production planning.

In the end of the 90s, Rogers and Tibben-Lembke describe Reverse Logistic as "The process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for purpose of recapturing value or proper disposal"[7].

A reverse logistics system comprises a series of activities, which form a continuous process to treat return-products until they are properly recovered or disposed of [8,9].

One important issue is to determine suitable locations for these processes. On the other hand, RL has a number of risks and uncertainties. These are related to quality, quantity, timing and variety of returns; decisions about resolution for product returns and cost of coordination along the reverse supply chain; estimation of operation and cost related parameters for reverse logistics networks. Therefore, RL operations and supply chain activities are more complex than traditional manufacturing supply chains [10].

Over the past twenty years, considerable numbers of case studies were published related with the design of reverse logistics networks. Three aspects can be mentioned to justify reverse activities: economic aspects [11], government legislative directives [12, 13] and consumer expectation [14]. Goal of those studies is to determine appropriate locations and capacities for required new centers taking into account investment, processing and transportation costs. Generally, in the literature on RL Network Design, case studies are product-oriented [10, 12, 15] or process oriented [2, 16, 17]. The most frequent mathematical solution that is admitted by scientists is the Mixed Integer Linear Programming (MILP). Construction of mathematical model changes depending on the problem characteristics (one product or multi product, one period or multi-time, the problem size and considering stock level). If the problem size is big, it means that optimal solution founding takes a long time, the authors prefer to use heuristics methods, LP-relaxations [18] or Lagrangian relaxation [19] applications.

Facility Location Problem (FLP) is a specific area in MILP for determination of geographical location of new centers. FLP has been used in reverse logistics network design area since 1997. In this recent field [20] much of the subsequent research is encouraged by the early articles by Barros et al. [12], Fleischmann et al. [6] and Jayaraman et al. [21].

A general FLP involves a set of customers and a proposed set of facilities to serve customer demands. The objective of general facility location problems is to define the optimal geographical locations of new facilities whereby satisfying the demand of clients while minimizing the sum of the fixed setup costs and the variable transportation cost between facilities and clients.

Possible processes in the reverse distribution channel are collecting, testing, sorting, transportation and processing. Specific facilities often support the reverse logistic processes. Collection centers (i.e., available service points will be used for collection of returned products) and remanufacturing facilities (i.e., remanufacturing centers will be established to realize remanufacturing process) are required facilities in this case study. In this manner, extending the network structure with transportation links is needed for return flows from service points to sites where remanufacturing activities take place [20].

In order to setup the simplest version of the FLP, select p facilities to minimize costs or the total (weighted) distances for supplying customer demands. It is called that the P-Median Problem [20]. Arbitrary number of customers can be connected to a facility; in this case the problem is called Uncapacitated Facility Location Problem (UFLP). If there exists a limit for each facility on the number of customers it can serve, name of the problem becomes a Capacitated Facility Location Problem [15]. Capacitated Facility Location Problem (CFLP) focuses on the distribution and production of
a single commodity over a single time period, during which demand is assumed to be known with certainty. Customer zones and facility location are considered as discrete points on a plane [22]. However, the multi-commodity, multi-echelon and dynamic versions also exist in the literature. To approach situations in which parameters change over time in a predictable way, multi-period location problems have been proposed. The aim is to adapt the configuration of the facilities to these parameters. Thus, a planning horizon divided into time periods is considered [23]. The inclusion of stochastic components in facility location models [24] is regarded in another important extension. Uncertainty can often be associated with some of the parameters such as future costs and customer demands. This extension is motivated by uncertainty [25].

3. Capacitated Facility Location Problem formulation and current network

3.1. Capacitated Facility Location Problem (CFLP)

Specific facilities often support reverse logistic processes. Specifically, in this study, the company needs to open remanufacturing centers. Because of capacitated model convenience to real life situation and frequency in the literature CFLP model is chosen among facility location models [24] is regarded in another important extension. Uncertainty can often be associated with some of the parameters such as future costs and customer demands. This extension is motivated by uncertainty [25].

Mathematical model allows answering:

- How many remanufacturing centers are required?
- Where should be the geographical location of manufacturing centers?
- What should be the capacity of remanufacturing center?
- Which service point should be served from which remanufacturing center?
- What is the amount of investment?

Let $I = \{1, ..., n\}$ be a set of facilities and $J = \{1, ..., m\}$ be a set of clients. Let $G(I \cup J, A)$ be a complete bipartite graph where $A$ is a set of arcs $(i, j)$ with $i \in I$ and $j \in J$. Let $D_{ij}$ be the $j$-th client demand, let $c_{ij}$ be the cost of sending one unit of flow from facility $i$ to client $j$ and let $f_{ij}$ be the fixed cost of opening facility $i$. Every facility $i$ has a capacity $s_i$. Let $y_{ij}$ be the binary variable associated with condition of each facility $i$. If it equals to 1, facility $i$ is open $\hat{S} \subset I$ otherwise facility $i$ is close. $\hat{S}$ is a feasible subset $\hat{S} \subset I$ of open facilities. Let $x_{ij}$ be a continuous variable expressing the fraction of client $j$’s demand satisfied by facility $i$. CFLP choose a feasible subset $\hat{S}$ minimizing the sum of opening and transportation cost. The formulation of CFPL is:

$$\begin{align*}
\text{Min} \sum_{i \in I} \sum_{j \in J} c_{ij}(D_{ij})x_{ij} + \sum_{i \in I} f_{ij}y_{ij} \\
s.t.
\sum_{i \in I} x_{ij} = 1 \quad j \in J
\end{align*}$$

Constraints (2) ensure that the whole demand of each client must be satisfied. Capacity constraints (3) ensure that the total demand supplied from a facility does not exceed its capacity. Variable upper bounds (4) ensure that no client can be supplied from a closed facility. Constraints (5) are responsible of the non-negativity and constraints (6) give binary values to $y_{ij}$ variables.

3.2. Current situation

The case study involves a major international manufacturer of truck industry. Customers of manufacturer are the users of trucks (truck type may be highway, distribution or construction trucks) utilized by thousands of transportation firms around the world. The manufacturer is preparing to enter the European market with a recently developed innovative Diesel Particulate Filter (DPF) which prevents from releasing noxious small particles into the air. The manufacturer has 6 manufacturing center all over the world: 2 in the USA, 1 in Switzerland, 1 in France, 1 in China and 1 in Japan. However, production and remanufacturing of DPF is only available in the USA. The manufacturer has 307 service points in France and needs to open remanufacturing centers to carry the reprocessing operations. Fig. 1 gives a graphical representation of the returned product processes. The used product should be gathered in the service points. Service point is responsible for easy processes like disassembling and manual testing. Commonly, these processes do not need machine interaction. If the product passes the first inspection, it means that the product is ready for the next stage with name transportation.

During the transportation stage, used products are carried to remanufacturing center. Before the remanufacturing processes, the second inspection is conducted to determine the damage caused during the transportation. If the product is not able to pass inspection stage, next stage will be recycling stage. If the product passes the inspection, it proceeds to remanufacturing process. The first remanufacturing operation starts with oven. Up to a certain degree the product is heated and the physical particles are burned. After the oven stage the product waits for cool down. In the cleaning stage, the burned particles are removed from the product. The last testing is realized by machine and if the repaired product passes inspection, it is ready to reuse but it waits the transportation. If the last testing stage cannot be passed, it will be send to recycling.

The costs are represented by two indicators: financial amount and carbon dioxide emissions. The required data for the model are: demand of each service point, opening cost of new remanufacturing center, transportation cost and reprocessing cost. Previous turnover data is considered to determine the demand estimation of each service points. Constant annual demand is handled after the balance of
remanufacturing system and the division of each service point demand is calculated by their turnover percentages. Opening cost depends on the opening probability which includes the purchasing cost of the required new machines and the purchasing cost of the required space to receive these machines. The capacity of the remanufacturing centers drives the calculation of the required machines in it. In turn, the number of machines drives the surface required for the shop floor. In our case, as reprocessing cost depends on the number of product treated in each remanufacturing center, it could be integrated into the cost called “transportation cost” in CFLP literature. Finally, it will be called generalized transportation cost which includes:

- The transportation cost of a product is calculated with parameters like the capacity of trucks and fuel consumption of trucks.
- The reprocessing cost. This amount consists of energy consumption of each reprocessing element. The energy consumption of each machine is given. It is assumed that there are no economies of scale in the energy consumption for reprocessing. Under this assumption the reprocessing cost only depends on the annual demand.

4. Case study results

4.1. Problem statement and model reformulation

The model is an extension of the single-product problem model that is defined by Feldman and al. [18]. To formulate the problem the following notation are defined:

- \( I \): set of remanufacturing centers, indexed by \( i \in \{1, \ldots, n\} \)
- \( J \): set of service points, indexed by \( j \in \{1, \ldots, n\} \)
- \( K \): set of remanufacturing centers’ capacity, indexed by \( k \in \{1, \ldots, m\} \)
- \( y_{ij}^k \): the fraction of service point \( j \)'s demand satisfied by the facility at \( i \)

\( f_i^p \): installation cost of a new remanufacturing center \( i \) depending on the change in capacity \( k \)

\( s_i^p \): \( h \)th capacity of a new remanufacturing center \( i \)

\( D_i \): demand at service point \( j \)

\( RR1 \): return rate after first inspection (0.19)

\( RR2 \): return rate after second inspection (0.05)

\( RR3 \): return rate after third inspection (0.06)

For the calculation of the transportation cost, we need to clarify the quantity on flow chart. Fig. 2 shows us amount of material flow. There exist a decrease in the amount of product that caused by return rate such as \( RR1 \) and \( RR3 \).

\( URC \): unit remanufacturing cost

\( UTC \): unit transportation cost of used product per kilometer

\( d_{ij} \): distance between remanufacturing center \( i \) and service point \( j \)

\( UTC_{ij} \): unit transportation cost between remanufacturing center \( i \) and service point \( j \)

\[
UTC_{ij} = (UTC) d_{ij} 
\]

\( i \in I, j \in J \) (7)

For the calculation of unit transportation cost between \( i \) and \( j \) \( (UTC) \), the multiplication of the distance between \( i \) and \( j \) \( (d_{ij}) \) and unit transportation cost are used which is illustrated in Formula (7).

\( UIC \): unit testing and inspection cost

\( c_k(D_i) \): generalized transportation cost that consists of transportation and reprocessing cost which is illustrated in Formula (8).

\[
c_k(D_i) = (URC + UIC) D_i + UIC D_i \left[ \frac{1}{1 - RR2} \right] 
\]

4.2. Proposed mathematical model

\[
\text{Min} \sum_{i} c_k(D_i) y_{ij} + \sum_{k} f_i^p y_{ij}^k 
\]

\( i \in I, j \in J \) (9)

s.t.

\[
\sum_{i \in I} y_{ij} = (1 - RR1)(1 - RR2) \quad j \in J \quad (10)
\]

\[
\sum_{j \in J} x_{ij} \leq \sum_{k \in K} x_{ij}^k \quad i \in I \quad (11)
\]

\[
x_{ij} \leq y_{ij}^k \quad i \in I, j \in J \quad (12)
\]

\[
\sum_{k \in K} y_{ij}^k \leq 1 \quad i \in I \quad (13)
\]

\[
y_{ij}^k \in \{0, 1\} \quad i \in I, k \in K \quad (14)
\]

\[
y_{ij}^k \in \{0, 1\} \quad i \in I, k \in K \quad (15)
\]

The objective function minimizes the total costs: the setup...
costs of opened remanufacturing sites, transportation cost between service points and the opened remanufacturing center, and the reprocessing costs at the opened remanufacturing center. In order to obtain environmental impact, the cost function is reconstructed by the amount of carbon emissions instead of monetary expense. Constraints (10) ensure that the demand of each customer is satisfied. Constraints (11) ensure that all demand is met, while constraints (12) force a remanufacturing center to be open if any demand is supplied by reproduction at that remanufacturing center. Among different capacities, only one capacity will be chosen which is guaranteed by constraints (13). Constraints (14) means that demand fractions will be positive. Finally, constraints (15) impose the requirement that a remanufacturing center either be opened or not.

4.3. Results

The mathematical model is written by using Java-Cplex® and the results are obtained by Eclipse®. The optimal location and the number of remanufacturing centers are obtained as a result of different capacity essays. Different cases are created considering required capacities of machines. Case 1 has an oven for creating 900 products per year. In other cases, the capacity of each remanufacturing center is augmented as to be appropriated to multiple of 900 products until case 5. After case 5, augmentation of annual production amounts is 4500 products between each case.

Optimal case is the case 4 with minimum total cost value both environmental and economical impact. The capacity of remanufacturing center is 3600 products/year. Each remanufacturing center requires 4 ovens, one cleaning machine and one cleaning machine to satisfy annual product demand.

The geographical locations remain the same for both euro and carbon results in Fig. 3. In the optimal solution mathematical model propose opening 12 remanufacturing centers from 307 possibilities. The round symbols show the available service points in France and the squares symbols represent the possible positions of remanufacturing centers.

Table 1 shows that the transportation cost increase with capacity augmentation. Indeed, when the individual capacity of each remanufacturing becomes higher, the required number of remanufacturing becomes smaller. On the other hand, transportation cost increases when the number of remanufacturing center decreases.

Reprocessing cost of a product is 537 Euros. This amount is cheaper than creating a new product. So, installation of a reverse logistics network is advantageous when it is compared with the current situation. This also reduces the raw material consumption. Advantage of using less amount of raw material is the decrease in the corresponding impact on the environment. Thus company takes place in green line. Costumers also obtain profit through the reverse logistics system.

Finally, the results show that reprocessing cost has the
major affect on total cost. It could be better to work on the amelioration of the remanufacturing process itself before optimizing the logistics.

Table 1: Experimental Results

| Case No | Capacity (thousand) | Total cost | Opening cost | Transportation cost | Amount of new facility |
|---------|---------------------|------------|--------------|---------------------|-----------------------|
| 1       | 0.9                 | 21,272.137 | 690.900      | 66.630              | 47                    |
| 2       | 1.8                 | 21,061.418 | 446.400      | 100.411             | 24                    |
| 3       | 2.7                 | 21,002.077 | 360.000      | 127.470             | 16                    |
| 4       | 3.6                 | 20,985.792 | 316.800      | 154.385             | 12                    |
| 5       | 4.5                 | 20,992.001 | 303.000      | 174.394             | 10                    |
| 6       | 9                   | 21,013.903 | 249.000      | 250.296             | 5                     |
| 7       | 13.5                | 21,028.495 | 227.200      | 286.688             | 4                     |
| 8       | 18                  | 21,158.167 | 288.900      | 354.660             | 3                     |
| 9       | 22.5                | 21,216.667 | 347.400      | 354.660             | 3                     |
| 10      | 27                  | 21,266.628 | 270.600      | 481.422             | 2                     |
| 11      | 32                  | 21,327.228 | 331.200      | 481.422             | 2                     |
| 12      | 36                  | 21,366.228 | 370.200      | 481.422             | 2                     |
| 13      | 41                  | 21,405.228 | 409.200      | 481.422             | 2                     |
| 14      | 45                  | 21,402.182 | 231.600      | 655.976             | 1                     |
| 15      | 49.5                | 21,421.682 | 251.100      | 655.976             | 1                     |
| 16      | 54                  | 21,441.182 | 270.600      | 655.976             | 1                     |

5. Conclusion

We have proposed a model that is able to choose an optimal location of remanufacturing centers. CFLP is convenient to solve one-echelon localization. Mathematical model wants to minimize all expense during the reverse logistics network construction. Model can also choose the optimum capacity among different possibilities.

The model works with both economical and environmental cost function than the available mathematical models in literature can also be used for calculation of environmental impacts. The more suitable location for reverse logistics process is chosen in consideration of machine request, environmental impacts and easiness. The solutions show that economic cost and environmental cost seems correlated. The correlation is explained by the ratio between unit transportation cost per km and the opening cost per m² which has a same value for both cases.

Disassembly and testing process at the service point are not considered by CFLP model because these operations do not occurs in the remanufacturing center. In order to overcome this limitation, the idea could be setting up 2 echelons CFLP model which enables site selection for service points for disassembly and testing operation. Total demand was considered as constant value. For future studies, increasing factor in estimates of future demand should also be considered and the model can be handled as a multi-period problem. In this study, the optimal solution of facility location is handled as a strategic decision. However, optimality can only be guaranteed with full integration of tactical and operational decisions. Facility location problem can also be combined with inventory and production decisions.

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