Environmental & Economical Optimization for Municipal Solid Waste Collection Problems, A Modeling and Algorithmic Approach Case Study

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Abstract: - Increasing environmental concerns and interests in material and energy conservation have lead to increasing advancement in the management of solid waste over the past two decades. The field of modeling of waste management system, as opposed to the modeling of a particular component of the system, has been active since the late 1980s. Many modeling approaches are being utilized; including optimization, statistics, and simulation in recent years. The cost of managing residential solid waste in the United States in 1990 has been estimated to be on the order of U.S. $19.5 billion annually, with collection accounting for approximately 50% of this total (Tchobanoglous et al. 1993).

In this paper, using data from one of the populated cities in Germany, MSW logistic mathematical model is presented, capable of estimating the collection and transportation costs as well as the environmental impact for Municipal solid waste.

Key-Words: - network design, MSW costs analysis, CO2 emission, MSW collection and routing.

1 Introduction

The solid waste management process can be commonly classified into generation, collection, storage, processing, transportation and disposal (Tchobanoglous et al 1993). In the solid waste collection process, trucks with diesel engine are generally used, which release to environment several emissions from its exhausts. Emissions resulting from solid waste collection vehicles, of course, are proportional both to route time and route distance. Today it’s already a well known fact, that all over the world and here in Germany and especially in NRW where our case study located that personal and freight traffic volumes are continually growing year to year, among them the volume of the solid waste transportation. The logistic provider network has many participants; these are connected to each other dynamically. In this supply chain there are many logistic activities like collection and transportation using vehicles for that task. Most of them are converting fossils to mechanical energy and during this conversion at least 40 % of the fossil energy is converted to heat that is useless, thereby heating our environment.

Literatures contain very few specific references to complete cost logistic models with environmental considerations. Thuy T.T, Wilson 2009 presented a model to estimate the fuel consumption for curbside MSW collection activities. They evaluated the potential effectiveness of some possible methods for reducing fuel consumption during waste collection. Gaines et al. 2006 reported that waste collection vehicles are classified as one of the five least fuel-efficient single-unit body trucks. He also reported that garbage trucks burn a great deal of fuel while idling and advised that it is better to turn off a truck’s engine while waiting for collector to empty the container. In literatures, there are several models dealing with transport of waste in a broad sense. One group of models (Bodner et al, 1970; Clark & helms 1972; Kirca & Erkip 1988; Gelders & Cattrysse 1991; Vasanthakumar 1996;) has an operations research approach. They minimize cost or total driving distance by using different methods like linear Programming & Mixed Integer Programming. Other examples of optimization models for integrated waste management systems with objective costs minimization can be found in work by Vigil & Zevely 1986; Lund 1990;Jacob & Everett 1992; Pugh 1993; Lea & Kowalewski 1994. Agar et al. 2007 estimated fuel consumption rates for co-collection trucks while they were on duty, but this study did not separate fuel consumption rates while driving inside and outside the collection area.
Between 1990 and 2003, total emissions of greenhouse gases in Germany were reduced by 18% (to 1,017.5 million t CO2 equivalent). In the National Inventory Report (NIR), some 20 million tons of CO2 equivalents are attributed to the waste sector as a result of the landfill ban alone. Thus, the waste industry has achieved the contribution expected to make the reduction target of the National Climate Protection Program 2000. The next table presents the major activities in waste management system and the reduction of CO2 emission in 1990, 2005 and the expected reduction in 2020. The contribution of the collection and transportation of solid waste is expected to remain unchanged during the next years.

<table>
<thead>
<tr>
<th>Emission Disposal path</th>
<th>1990</th>
<th>2005</th>
<th>2020 **</th>
<th>reduce*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste Incineration</td>
<td>-1.00</td>
<td>-2.47</td>
<td>-5.42</td>
<td>-2.95</td>
</tr>
<tr>
<td>Co-Incineration</td>
<td>-0.05</td>
<td>-2.16</td>
<td>-3.55</td>
<td>-1.39</td>
</tr>
<tr>
<td>Biowaste</td>
<td>0.10</td>
<td>0.19</td>
<td>-0.06</td>
<td>-0.25</td>
</tr>
<tr>
<td>L-packaging</td>
<td>0</td>
<td>-0.54</td>
<td>-0.63</td>
<td>-0.09</td>
</tr>
<tr>
<td>Waste paper</td>
<td>-0.31</td>
<td>-1.71</td>
<td>-1.65</td>
<td>0.06</td>
</tr>
<tr>
<td>Waste glass</td>
<td>-0.39</td>
<td>-0.61</td>
<td>-0.61</td>
<td>0</td>
</tr>
<tr>
<td>Bulky /wood</td>
<td>-0.005</td>
<td>-0.27</td>
<td>-0.3</td>
<td>-0.03</td>
</tr>
<tr>
<td>Metals</td>
<td>-0.28</td>
<td>-0.78</td>
<td>-1.55</td>
<td>-0.77</td>
</tr>
<tr>
<td>Collection</td>
<td>0.48</td>
<td>0.36</td>
<td>0.36</td>
<td>0</td>
</tr>
<tr>
<td>MBT</td>
<td>0</td>
<td>0.21</td>
<td>0.19</td>
<td>-0.02</td>
</tr>
<tr>
<td>Landfill</td>
<td>39.23</td>
<td>0.09</td>
<td>0.02</td>
<td>-0.07</td>
</tr>
</tbody>
</table>

Table 1 Greenhouse gas emission and reduction option 2005 to 2020
* Reduction potential 2005 to 2020 optimized
** 2020-optimised

The market volume according to the process chain of waste treatment is structured as follows:

- Approx. 50% of total revenues come from collection services (= 27.5 bill. EUR)
- Approx. 50% of total revenues come from handling, recycling and landfill site services (= 27.5 bill. EUR).
- Finally, the market volume is segmented according to geographical markets. The major market for waste management services in the European Union is Germany with a market share of 35% (= 19.2 bill. EUR), followed by France, the United Kingdom and Italy.

The main focus of this article is derived from the demand of research regarding the need to develop a new method for the quick and accurate calculation of the logistics costs in the municipal waste disposal with environmental impact considerations during solid waste collection. Furthermore, according to the global warming problem from the data in Table 1, the waste management plays an important role in CO2 emission. Therefore self-developed calculation methodology is being introduced. Only with the aid of this model, a fundamental analysis of the influencing variables regarding its importance for the cost calculation can be accomplished. The data presented in table1 and figure 2 show the importance and the role of the MSW collection problem from economical and environmental prospective. The reasons which related directly and indirectly to the logistic activities encourage us as logistics researchers to contribute to optimize this problem. The goal of this paper is to present a MSW logistic model to estimating the total costs per ton, to examine the effect of different scenarios, like different service option and different type of vehicle.
1.1 Case City Duisburg Background

The city of Duisburg comprises an area of 232.81 km² in Nord-Rhine Westphalia, the most densely populated state in the Federal Republic. This is the Ruhr region, Germany’s industrial heartland. With its 31 power stations, this area is also Germany’s major source of energy.

In 2008, there were 500914 residents in Duisburg, making it the eleventh largest city in Germany. Aside from its total population, Duisburg is also one of the country’s most densely populated cities. With the total number of residental in the City Duisburg were 78775. While the Federal Republic’s average population density is 222 inhabitants/km² and Nord-Rhine Westphalia’s is 489/km², Duisburg stands at 2,299 inhabitants/km², the main residential area are distributed along the west side of Rhine river [1].

The regional municipality of City Duisburg includes seven main areas, which were further divided into 46 districts shown in figure 1. The municipality of Duisburg generated 132000 ton/a residual waste, 38500 ton/a waste paper, 11200 ton/a packing, 38600 ton/a compost waste and 222 ton/a waste of glasses. As municipal service WBD Wirtschaftsbetriebe Duisburg-AoR [WBR] are responsible to collected the entire waste daily using different collection vehicle located in two different depot where the starting in the morning and turn back in the end of the working day and or the working task, the target of WBR is to provide high quality of customers service at reasonable prices.

The central vehicle depot is located in the southern part of the city with more than 40 collection vehicle with different capacity and task, the second depot is located in the northern part of the city with 25 collection vehicle to service the neighbourhood part of the city. All the necessary data for the model calculation like facilities location, waste generation quantities, data for vehicles, labors data and costs data we obtained from city Duisburg and the WBD [Wirtschaftsbetriebe Duisburg] the company which is responsible for waste collection and disposal in city Duisburg.

This study does not consider a detail of the waste collection routing problem, for transportation purposes the waste generated in each of the 46 districts is considered to exist at a single point within the center’ Centroid of the district which is determined manually. The vehicle/Ship transportation distances were determined between each district, transfer station, and Incineration plant using MapPoint as real distance.

For minimizing the total CO2 emission and the total logistic costs we create new scenario using Ship to transport the MSW form tow ports one in the north area and one in the south area of the City used as transfer station.

2 Disposals Logistic Mathematical Model

2.1 Total logistic cost

\[ C_{\text{log,ton}} = C_{\text{veh,ton}} + C_{\text{con,ton}} + C_{\text{per,ton}} + C_{\text{ship,ton}} \] (1)

- \( C_{\text{log,ton}} \): Total logistic costs of waste collection per tonne
- \( C_{\text{veh,ton}} \): The cost of the vehicle per tonne waste
- \( C_{\text{con,ton}} \): The cost of the container per tonne waste
- \( C_{\text{per,ton}} \): The cost of the person per tonne waste
- \( C_{\text{ship,ton}} \): transport cost by ship per tonne waste

Vehicle cost:

\[ C_{\text{veh,ton}} = \sum_{i=1}^{\text{veh}} \left( \frac{C_{\text{veh,fix}} + C_{\text{veh,var}}}{Q_{\text{year}}} \right) \] (2)

- \( C_{\text{veh,fix}} \): Total fixed costs / year.
- \( C_{\text{veh,var}} \): Total variable costs / year
- \( Q_{\text{year}} \): Quantity of the waste / year

\[ C_{\text{veh,fix}} = C_{\text{veh,cap}} + C_{\text{veh,insu}} + C_{\text{veh,tax}} + C_{\text{veh,svzo}} \]
\( C_{\text{veh\_cap}} = \text{Capital cost / year} \)
\( C_{\text{veh\_insu}} = \text{Insurance cost / year} \)
\( C_{\text{veh\_tax}} = \text{Tax cost / year} \)
\( C_{\text{veh\_stvzo}} = \text{Investigation cost by stvzo / year} \)

\[ n_{\text{veh}} = \frac{\left[(C_{\text{veh\_inv}} - C_{\text{veh\_sal}})/\text{Dep} + 0.5(C_{\text{veh\_inv}} - C_{\text{veh\_sal}})\right] \times \text{Rainterest}}{} \]  

\( n_{\text{veh}} \): the number of the vehicle
\( C_{\text{veh\_inv}} \): the investment cost of the vehicle
\( C_{\text{veh\_sal}} \): the salvage value of the vehicle
\( \text{Dep} \): Depreciation period of Vehicle (5 years)
\( \text{Rainterest} \): Interest rate of the investment vehicle

\( C_{\text{veh\_var}} = C_{\text{veh\_fuel}} + C_{\text{veh\_main}} \)  

\( C_{\text{veh\_fuel}} = \frac{\text{CS\_fuel} \times \text{Dist\_veh} \times \text{Pfuel}}{} \)  

\( \text{CS\_fuel} \): Fuel consumption for vehicle / km
\( \text{Dist\_veh} \): The Total travel distance of vehicle / year
\( \text{Pfuel} \): Fuel price / liter

\( \text{Personnel cost:} \) 
\( C_{\text{per\_ton}} = \frac{(C_{\text{per\_dri}} + C_{\text{per\_loa}})}{Q_{\text{year}}} \)  

\( C_{\text{per\_dri}} = \text{The personnel cost for the driver / year} \)
\( C_{\text{per\_loa}} = \text{The personnel cost for the loader / year} \)

\[ C_{\text{per\_dri}} = \sum_{i=1}^{\text{veh}} (W_{\text{dri\_h}} \times n_{\text{dri\_h}} + W_{\text{dri\_ov\_h}} \times n_{\text{dri\_ov\_h}}) \times n_{\text{dri\_i}} \times n_{\text{work\_day}} \]  

\( W_{\text{dri\_h}} \): The driver wage per regular working hour
\( n_{\text{dri\_h}} \): The regular working hours of driver / day
\( W_{\text{dri\_ov\_h}} \): The driver wage per overtime working hours
\( n_{\text{dri\_ov\_h}} \): The overtime working hours of driver / day
\( n_{\text{dri\_i}} \): The number of driver for type \( i \) vehicle
\( n_{\text{work\_day}} \): The working days / year (251)

\[ W_{\text{dri\_year}} = W_{\text{dri\_year}} \times (n_{\text{work\_day}} \times n_{\text{dri\_h}}) \]  

\( W_{\text{dri\_year}} \): The driver salaries / year

\[ W_{\text{dri\_ov\_year}} = W_{\text{dri\_ov\_year}} \times (1 + W_{\text{sur\_ov\_dri}}) \]  

\( W_{\text{sur\_ov\_dri}} \): The surcharge of the overtime for the driver

\[ C_{\text{per\_loa}} = \sum_{i=1}^{\text{veh}} (W_{\text{loa\_h}} \times n_{\text{loa\_h}} + W_{\text{loa\_ov\_h}} \times n_{\text{loa\_ov\_h}}) \times n_{\text{loa\_i}} \times n_{\text{work\_day}} \]  

\( W_{\text{loa\_h}} \): The loader wage per regular working hour
\( n_{\text{loa\_h}} \): The regular working hours of loader / day
\( W_{\text{loa\_ov\_h}} \): The loader wage per overtime working hours
\( n_{\text{loa\_ov\_h}} \): The overtime working hours of loader / day
\( n_{\text{work\_day}} \): The working days / year = 251days

\( n_{\text{loa\_i}} \): The number of the loader for type \( i \) vehicle

\[ W_{\text{loa\_year}} = W_{\text{loa\_year}} \times (n_{\text{work\_day}} \times n_{\text{loa\_h}}) \]  

\( W_{\text{loa\_year}} \): The loader salaries / year

\[ W_{\text{sur\_ov\_loa}} \]: The surcharge of the overtime for the loader

\( \text{Container cost:} \)
\( C_{\text{con\_ton}} = \frac{(C_{\text{con\_cap}} + C_{\text{con\_main}})}{Q_{\text{year}}} \)  

\( C_{\text{con\_cap}} \): The total cost of container / year
\( C_{\text{con\_main}} \): The total cost of container maintenance / year
\( Q_{\text{year}} \): Quantity of the waste / year

\[ C_{\text{con\_cap}} = \sum_{i=1}^{\text{con\_i}} n_{\text{con\_i}} \times (C_{\text{con\_i\_inv}} / \text{Depcon}) \]  

\( n_{\text{con\_i}} \): The number of the container for type \( i \)
\( C_{\text{con\_i\_inv}} \): The investment cost of the container
\( \text{Depcon} \): Depreciation Period of container

### 2.2 CO₂ Emission

An ineligible problem related to the waste collection or waste transfer is waste gas emissions. As normal the solid waste collected by diesel vehicle which cause of CO₂ emission from the flowing activities:

- Emission when vehicle is running \((E_\text{t})\).
- Emission when vehicle stops at each collection point \((E_\text{o})\).

For the calculation of the CO₂ emissions it is needed the following parameters: The mileage per year and the vehicle’s CO₂ emissions per Km.

For the mileage calculation we can use the following formula:
\[
FL = n \times (S_{\text{last}} + S_{\text{heer}}) \ [\text{Km/a}] \tag{12}
\]

\(FL\) = Mileage per year [Km/a]
\(n\) = Number of tours per year [tours/a]

Where:
\(S_{\text{last}}\) = Kilometers from the depot to the destination (incineration plant)
\(S_{\text{heer}}\) = Kilometers from the destination (incineration plant) to the depot.

\[
E_{\text{co2}} = \text{ave}_{\text{co2}} \times FL \tag{13}
\]

\(E_{\text{co2}}\) = total CO₂ emission / year g / a
\(\text{ave}_{\text{co2}}\) = average CO₂ emission / km

The previous equations from 1 to 12 shows in detail the analytical natural of the model allows it to be easily and directly implemented on a spreadsheet.
3. Model implementation

In this section we present the data need as input for the model and result from implement our model using real data collected from our City case study including the vehicle, personal, and container data as follow:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment cost of the vehicle</td>
<td>200,000 €</td>
</tr>
<tr>
<td>Investment cost of the big vehicle</td>
<td>160,000€</td>
</tr>
<tr>
<td>Vehicle capacity for collection waste</td>
<td>8 tonne</td>
</tr>
<tr>
<td>Big vehicle capacity for transport</td>
<td>40 tonne</td>
</tr>
<tr>
<td>Insurance cost / year</td>
<td>2,800 €</td>
</tr>
<tr>
<td>Tax + Investigation cost by stvzo / year</td>
<td>5,000 €</td>
</tr>
<tr>
<td>Fuel consumption for vehicle (i)</td>
<td>55 L/100km</td>
</tr>
<tr>
<td>Fuel Price /L</td>
<td>1.20 €</td>
</tr>
<tr>
<td>Depreciation Period of Vehicle</td>
<td>5 years</td>
</tr>
<tr>
<td>Vehicle scrap</td>
<td>15%</td>
</tr>
<tr>
<td>Interest rate of the investment vehicle</td>
<td>15%</td>
</tr>
<tr>
<td>Preventative maintenance cost / year</td>
<td>5000 €</td>
</tr>
</tbody>
</table>

Table 2 Parameters used to calculate vehicle costs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment cost of the container 1100 L</td>
<td>300 €</td>
</tr>
<tr>
<td>Investment cost of the container 240 L</td>
<td>65 €</td>
</tr>
<tr>
<td>Investment cost of the container 120 L</td>
<td>45 €</td>
</tr>
<tr>
<td>Investment cost of the container 80L</td>
<td>30€</td>
</tr>
<tr>
<td>Investment cost of the container 60 L</td>
<td>25 €</td>
</tr>
<tr>
<td>Container bulk density</td>
<td>0.12 t / m³</td>
</tr>
<tr>
<td>Container life time</td>
<td>10 year</td>
</tr>
<tr>
<td>Filling rate of the container Rfill</td>
<td>70 %</td>
</tr>
<tr>
<td>Maintenance cost as % investment cost</td>
<td>4.3%</td>
</tr>
</tbody>
</table>

Table 3. Container parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working days / year</td>
<td>251 day</td>
</tr>
<tr>
<td>Loader salaries / year</td>
<td>50,000 €</td>
</tr>
<tr>
<td>Driver salaries / year</td>
<td>50,000 €</td>
</tr>
<tr>
<td>Normal Service 1 vehicle with</td>
<td>1 driver</td>
</tr>
<tr>
<td>Normal Service 1 vehicle with</td>
<td>2 loader</td>
</tr>
<tr>
<td>Full Service 1 vehicle with</td>
<td>4 loader</td>
</tr>
<tr>
<td>1 big vehicle with</td>
<td>1 driver</td>
</tr>
<tr>
<td>1 big vehicle with</td>
<td>0 loader</td>
</tr>
</tbody>
</table>

Table 4 Parameters for personal costs

<table>
<thead>
<tr>
<th>Container type</th>
<th>total Number</th>
<th>weekly empty</th>
<th>2 weeks empty</th>
<th>Total /week</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 L</td>
<td>509</td>
<td>125</td>
<td>384</td>
<td>317</td>
</tr>
<tr>
<td>80 L</td>
<td>34,790</td>
<td>20,296</td>
<td>14,494</td>
<td>27,543</td>
</tr>
<tr>
<td>120 L</td>
<td>50,439</td>
<td>27,679</td>
<td>22,760</td>
<td>39,059</td>
</tr>
<tr>
<td>240 L</td>
<td>10,429</td>
<td>9514</td>
<td>915</td>
<td>9,971</td>
</tr>
<tr>
<td>1100 L</td>
<td>9,919</td>
<td>8719</td>
<td>1,200</td>
<td>9,319</td>
</tr>
<tr>
<td>sum</td>
<td>106,086</td>
<td>66,333</td>
<td>39,753</td>
<td>86,209</td>
</tr>
</tbody>
</table>

Table 5 Container number empty/week, 2 week

Using those input data to our model the total logistic costs for solid waste is calculated in three scenarios as follow:

First scenario
In this scenario we investigate exists situation ‘real situation’ without transfer station.

Second scenario
In this situation including tow transfer station one the north and one in the south of the city with direct to the incineration plant option after we run the network design model which give the optimization of the waste flow allocation.

Scenario three
In this scenario as we have the Rhine river link between the City and the Incineration plant therefore using the location and network model we find tow port along Rhine as to transfer station using the barrage to transfer the waste form this port to the Incineration plant show in Fig 5.

Fig 5: ship concept for residual waste
A- schwig port
B- logar port
C- Oberhausen Incineration Plant

First scenario normal service
\[ C_{\text{log ton}} = C_{\text{veh ton}} + C_{\text{con ton}} + C_{\text{per ton}} = 26.4 + 5.48 + 56.50 = 88.3 \text{ €/ton} \]

First scenario full service
\[ C_{\text{log ton}} = C_{\text{veh ton}} + C_{\text{con ton}} + C_{\text{per ton}} = 26.4 + 5.48 + 94.17 = 126.0 \text{ €/ton} \]

Co2 emission = 856617463.7 g

Second scenario normal service
\[ C_{\text{log, ton}} = C_{\text{veh, ton}} + C_{\text{con, ton}} + C_{\text{per, ton}} \]
\[ = 17.455 + 5.48 + 35.79 \]
\[ = 58.37 \text{ €/ton} \]

**Second scenario full service**
\[ C_{\text{log, ton}} = C_{\text{veh, ton}} + C_{\text{con, ton}} + C_{\text{per, ton}} \]
\[ = 17.455 + 5.48 + 58.39 \]
\[ = 81.325 \text{ €/ton} \]

\[ \text{Co2 emission} = 472907748.6 \text{ g} \]

**Third scenario normal service**
\[ C_{\text{log, ton}} = C_{\text{veh, ton}} + C_{\text{con, ton}} + C_{\text{per, ton}} + C_{\text{ship, ton}} \]
\[ = 13.4 + 5.48 + 30.13 + 3.09 \]
\[ = 52.1 \text{ €/ton} \]

**Third scenario full service**
\[ C_{\text{log, ton}} = C_{\text{veh, ton}} + C_{\text{con, ton}} + C_{\text{per, ton}} + C_{\text{ship, ton}} \]
\[ = 13.4 + 5.48 + 47.1 + 3.09 \]
\[ = 69.1 \text{ €/t} \]

\[ \text{Co2 emission} = 362234835.7 \text{ g} \]

Comparing those calculation results with costs calculated by the city we find that our model give more detail and more realistic.

### 4. Conclusion

Nowadays Waste industrial in Germany start to be profitable, independent sector and contributing in the economic growth. This industrial employs more than 250000 people and generates an annual turnover in excess of 50 billion Euros.

The solid waste collection logistic costs play a major role in the total solid waste and disposal costs, which approval by many researches.

Therefore, solid waste logistic costs model which consider most logistic activities as costs and environmental impact, help to improve the solid waste supply chain and minimize the city budget for waste management activities. The model presents a reasonably effective way to predict the fuel consumption; distance traveled for waste collection in different area with different collection intervals within alternative network option.

The results from those different models give a different investigation but all the result show that the vehicles and man power play a big role in the waste logistic costs.

Moreover, using this model give the municipal authority the possibility to control all the waste management activities in advance. Collection and transport is the field of waste management where effective measures aiming at cost reduction can be taken. For example, the reduction of the waste generation may reduce the collection costs if fewer trucks, workers and routes are needed.

Future research should including the collection distance and different collection vehicle using GIS.

### References:

[1] City Duisburg department of waste management [Amt fur Wasser-und Kreislaufwirtschaft]


