The Impact of Different Waste Collection Systems on Carbon Footprint

Eirill Bø and Bente M. Flygansvær
BI Norwegian Business School

Trond Hammervoll
The Arctic University of Norway

Abstract

Climate change can be mitigated by reducing energy consumption, pollution and the emissions of greenhouse gases to the atmosphere. There are novel opportunities for research into how supply networks can contribute to a more sustainable society. Little research has addressed how different ways of collecting waste from private households affect the carbon footprint of the waste collection network, and the purpose of this research is to fill some of the knowledge gap. In the reverse supply chain, there are several decisions to be made concerning the system, sources of variability and uncertainty. Starting with the end-user, the "waste" as a category may be sorted for several purposes according to the waste hierarchy. In addition to the decision of how to handle the various types of waste, there is also a question of how many fractions the waste is sorted into. We have compared CO_2 emissions in two waste collection networks, both using diesel trucks. An extensive Excel-based spreadsheet model include information on truck systems, fill rates, loading times, number of waste bins, frequency, waste compression levels, fuel consumption, empty driving and driving distances are used to calculate CO_2 emissions. The findings indicate that collective waste solutions result in significant reductions in CO_2 emissions. Individuals can contribute to reduce the carbon footprint by accepting solutions less convenient.

Introduction

Climate change can be mitigated by reducing energy consumption, pollution and the emissions of greenhouse gases to the atmosphere (Ali et al., 2013). There are novel opportunities for research into how supply networks can contribute to a more sustainable society (Gonzales et al., 2015). Little research has addressed how different ways of collecting waste from private households affect the carbon footprint of the waste collection network. One exception is Mühle, Balsam, and Cheeseman (2010), but their research focused on solid waste, and compared recycling and recovery to landfill waste handling strategies. The purpose of this research is to fill some of the knowledge gap.

Reverse supply chains structured to collect waste from end-users can be detailed into the functions of sorting, collection, transport, reprocessing and trading in secondary markets (Guide Jr & Van Wassenhove, 2009). In the reverse supply chain, there are several decisions to be made concerning the system, sources of variability and uncertainty. Starting with the end-user, the "waste" as a category may be sorted for several purposes according to the waste hierarchy. In addition to the decision of how to handle the various types of waste, there is also a question of how many fractions the waste is sorted into.

The attractiveness of different waste collection alternatives to society depend on how willing individuals are to accept inconvenience for disposing their waste so that it may be collected. No research has addressed how different waste collection solutions can reduce CO_2 emissions. Individuals are supposed to sort their waste into many fractions, such as for example residual, food, paper, plastic, glass and all types of WEEE. All municipalities in Norway are forced by the government to collect sorted waste. Therefore they must design a transport system; type of trucks and bin system by the household. The question is whether the waste should be picked up at the household or if the individual should bring the waste to a certain place. For the two municipalities as cases in this paper, they decided different ways to pick up the waste by the households. One municipality decided to use a two-chamber truck and pick up two fractions at the same time. With this system, it is possible to compress the waste and the households will need four bins. The other municipality decided on a one-chamber truck. Here the households need to sort the waste into color-coded bags. In this system, it is not possible to put compress in danger of destroying the bags. This municipality needed an optical sorting system at the landfill. Both municipalities based their decision on a qualitative consideration. In this paper, both systems are considered and their carbon footprint is evaluated. To collect and sort the waste for reprocessing, it is important to design an environment friendly transport system.

Hence, the purpose of this paper is to investigate the effects of different ways of collecting waste from private households. Different systems will affect CO_2 emissions variously and the required levels of effort will differ from individuals disposing their waste. Data from two waste collection networks in two municipalities are used to calculate CO_2 emissions. An extensive Excel-based spreadsheet model include information on truck systems, fill rates, loading times, number of waste bins, frequency, waste compression levels, fuel consumption, empty driving and driving distances are used to calculate CO_2 emissions.

Case description

Both cases are limited to the kerb-side systems.

Case A

In case A the municipality have decided to sort out three types of waste from the residual, namely food, paper and plastics. They have implemented separate sorting in individual bins for these fractions. The collection is therefore based on a system of four bins for the four fractions of waste, where the waste is sorted in one bin for food waste, one bin for residual waste, one bin for paper waste, and one bin for plastic waste. The trucks are two-chamber, and divided in one chamber for food waste or plastic (30%) and one for residual or paper waste (70%). Residual and food waste are collected every week, while paper and plastic waste is collected every third week, using the same trucks, with an expected 70% - 30% share. The routes are planned according to capacity, and the trucks continue the route until one chamber is full. The waste is delivered to four locations, one for each type. The table below summarizes the key characteristics of the case, and further description follows below the table.

Table 1: Characteristics of case A

	Sorting at households	Collection - accumulation	Collection - transportation	Delivery for recycling
Reverse supply chain:	Sort four types of waste at kerb side; food, plastics, paper and residual waste.	Sorts in four bins	Trucks with two chambers Adapted compression levels for each waste type A high number of trucks and routes	Four locations one for each type

In terms of *number of bins*, the majority of households in case A have four each. This results in approximately 1100 bins to be collected on each transport route if the waste harmonizes with 30/70 % share. The fill rate depends on to what extend they will match the share 70/30 %. They have to empty the whole truck when one chamber is full.

The *compression level* in case A with a dual-chamber truck has a 450 kg/m^3 limit. Experience showed, that food waste was difficult to compress due to its high level of water consistency. Trucks in case A drive until they reach full capacity, and therefore *distance per trip* will vary with volume of waste and compression levels. Lower compression levels decrease the distance per trip, because the truck fills up sooner than planned. Collection *frequency* is fixed in case A, with every week for food and residual waste, and every third week for paper.

Case B

In case B the municipality have also decided to sort out three fractions of waste from the residual, and this includes the same as in case A, namely paper, plastics and food. However, the collection system is based on a dual bin system, and is a mix of the systems of separate and co-collection. The fractions of food, plastics and residual waste are sorted in color coded waste bags, and are subject to optical sorting at a central facility. The three colored waste bags are sorted in one bin, and the second bin is for paper waste. The trucks have one chamber, and are the color coded waste bags in one bin is collected on one route. The trucks operate with a reduced compression level in order to not break the waste bags. The paper is collected separately on its own route. The waste is delivered to a sorting facility where the waste bags are separated before they are transported to treatment. Therefore, the waste is delivered at two locations. However, in case B the housing structure is different with a mix of all types, from single households to large apartment buildings. The bin structure is therefore also very different across households. Depending on the type of households, and type of bins, each route has individual data. The *number of bins* is therefore also highly variable across households, and size varies considerably as well. There may be many large size bins alongside each other. This takes up space and is not viewed as nice aesthetically, among other things. A development taking place, is therefore that many apartment building complexes have started to replace these types of bins with underground solutions. This is a decision they make privately, and get approval and register it with the municipality. The municipality does not interfere in these decisions unless there is a technical issue. However, the underground solutions have impact on transportation, because they need to be emptied by a different type of truck. Therefore, the routes are influenced in terms of the driving distance when number of stops are changed.

Collection frequency is also fixed in case B, but varying across different routes. Depending on the space for bins and capacities per households it varies from three times a week to once a week for the waste bags. Paper is collected from once a week to every fourth week.

In case B, *the compression level* is set at 350 kg/m^3 in order not to destroys the bags and make them unsortable. In order to control for the right compression level, the vehicles are weighed and compared to a norm when delivering waste at the sorting facility. By separate sorting in bins a higher compression level is possible. In a one-chamber truck, it is possible to compress 750 kg/m^3. Trucks in case B drive until they reach full capacity, and therefore *distance per trip* will vary with volume of waste and compression level.

The table below summarizes the key characteristics of the case, and further description follows below the table.

Table 2: Characteristics of case B

	Sorting at households	Collection - accumulation	Collection - transportation	Delivery for recycling
Reverse supply chain:	Sort four types of waste at kerb side; food, plastics, paper and residual waste.	Sorts in two bins. One bin for paper, and on bin for color coded waste bags to separate out three types of waste	Trucks with one chamber Adapted compression levels A high number of trucks and routes	Two locations. One sorting facility for color-coded bags and one location for paper.

There are several similar features for case A and B, but some quite different. As for case A, the fraction of each waste type is crucial to the efficiency, in case B the truck will always be full since they use only one chamber. In case A it is possible to compress the waste highly but in case B compression is reduced because it can destroy the bags. Higher transport efficiency will give the lowest CO2 footprint, and the question is whether case A or B is most efficient.

Calculations

The calculation of CO2 footprint is based on the use of diesel. The diesel use is calculated based on hours with the engine on without driving, empty driving, and the use of diesel per kilometer driving. The diesel use for empty driving is 2,9 liter per hour and the use of diesel per kilometer is 0,366 liter. (Source; truck supplier Scania). The CO2 emission is 2,69 kilos per liter diesel. (source; energilink.tu.no) Based on a transport trip of 80 kilometer we have calculated the footprint in both case A and B. We have collected input numbers for calculations by interviewing the two municipalities, the transport companies and by own observation. We have developed an excel worksheet to calculate the diesel use in the two different transport solutions; municipality (case) A and B, and tested different scenarios on pick up frequencies and collecting systems that will affect the CO2 footprint.

The calculations is based on following numbers;

One round trip:	
Distance per trip	80
Number of weeks per year	52
Number of days per week	5
Speed Km/hour	35
Loading time in minutes	20
Unloading time in minutes per bin	0,3

Table 3. Calculated CO2 emissions from one trip based on case A

Input variables: Time used on the trip	**Value:**
Driving time:	80 km/ 35km/h = 2,29 hours
Loading time:	(1100 bins * 0,3 min/ bin) /60 min./hour = 5,5 hours
Unloading time	20 minutes = 0,33 hours
Trip time:	2,29 + 5,5 + 0,33 = 8,12 hours
Empty driving;	total time 8,12 minus driving time 2,29 = 5,8 hours
Further CO2 calculations:	
Calculation of CO2 on one trip;	Diesel use: 80 km * 0,366 liter/ km = 29,28 liter Empty driving: 5,8 timer * 2,9 liter per hour = 16,82 liter CO2 emission on the trip: (29,28+16,82)*2,69= **124 kg CO2**
Calculation of CO2 per bin:	124 kg CO2: 1100 bins = **0,113 kg** CO2 per bin per pick up
CO2 per year for food and residual CO2 per year for plastic and paper	0,113*2*26 = 5,88 CO2 per year 0,113*2*17 = 3,84 CO2 per year **Total: 9,71 Kg CO2 per year per household**

Analysis and results

The effect of different pick up frequencies

The decision to sort waste in four fractions resulted in added number of bins for each households. This led to a reduction in frequencies, because each fraction then had a lower volume. From the customers perspective, they want to get rid of the waste as often as possible, especially food waste, because of unwanted smell.

Evaluating this decision using the DST model we show that the CO2 emission of different frequencies vary quite substantially, see Table 4 and 5 below. The evaluation is based on four different frequencies in case A, and six different frequencies in case B (choice of alternatives is based on a realistic choice of frequency in the cases).

Table 4: CO2 emission in case A, collection system; sorts in four bins

Case A	Alt.1	Alt.2	Alt.3	Alt.4
Frequency per year				
Food- residual	26	52	17	13
Paper-plastic	17	17	17	13
Capacity in number of bins				
Food- residual	1100	1100	733	550
Paper-plastic	1100	1100	1100	825
Co2 emission food and residual	5,87	11,74	5,1	4,86
Co2 emission plastic and paper	3,84	3,84	3,84	3,58
Co2 emission per household per year	9,71	15,58	8,94	8,44

Table 5: CO2 emission in case B, collection system; sorts in two bins

Case B	Alt.1	Alt.2	Alt.3	Alt.4	Alt.5	Alt.6
Frequency per year						
Food-residual-plastic	52	104	156	26	17	13
Paper	26	52	26	17	17	13
Capacity in number of bins						
Food- residual –plastic	619	1238	1857	310	206	155
Paper	1650	825	1650	1100	1100	825
Co2 emission food, residual and plastic	8,86	10,89	12,91	7,85	7,37	7,34
Co2 emission paper	2,29	7,15	2,29	1,92	1,92	1,79
Co2 emission per household per year	11,15	18,04	15,21	9,77	9,28	9,13

In case A, by choosing different frequencies, like alternative 2 compared to alternative 4, it is possible to reduce the Co2 emission by 75% per year (from 15,58 CO2 to 8,94 CO2 per household per year). In case B we can see a major difference between alternative 3 and 6, from 15,21 CO2 per household per year compared to 9,13 CO2.

The effect of bin capacity

Type and size of bins has a direct effect on the transport efficiency. However, there are several interests tied to the bins, and therefore a decision concerning bins is not easily decided. From the household perspective, they want their bins as close to their home as possible, but from transport perspective is better to merge the households in common bins to reduce the number of stops and total time. Larger bins will have higher capacity in serving several households. However, the decision is that all households have their own bins, but the households may themselves decide to merge if they want to. If households choose to merge in common bins, the municipalities have offered a discount.

From the discussion above we see that number of bins is essential for the efficiency and the CO2 footprint. It is therefore interesting to test the effect on the CO2 footprint if the households merge in common bins. We tested this effect in case A, to the maximum of five households sharing the bins for each waste fraction. We assume that each household have 140 liters, and 660 liters is the largest bin size (660/140 = 4.7). The loading time per bin is independent of size. The table below shows how the number of bins influences the total trip time:

Table 6: Effect of time on a trip by merging households in common bins

Number of households	1	2	3	4	5
Number of bins	1100	550	367	275	220
Time per trip	8,12	5,37	4,45	3,99	3,72

The simulation shows that merging households in common bins have a major impact on time spent. If two and two households share one bin, the total time per day will be reduced from 8.12 hours to 5.37 hours. This makes it possible to run two trips each day, which have a major effect on the transport arrangement. The table below shows the CO2 effect of merging households (the calculation is based on a frequency of 26 per year on residual and food, and a frequency of 13 per year on paper and plastic).

Table 7: CO2 calculator: effect of merging households in common bins

No of households per bin	1	2	3	4	5
Kilo CO2: food and residual	5,9	4,9	4,5	4,4	4,3
Kilo CO2: plastic and paper	3,8	3,1	3,0	2,8	2,8
Kilo CO2/household per year based on todays frequency	9,7	8,0	7,5	7,2	7,1

The table shows that it will be possible to reduce CO2 per household per year with 9,9-7,1 = 2.6 kg CO2 by forcing five and five neighbors share their bin. The inconvenience for the households by sharing bins can totally reduce the CO2 footprint by 37%. It is quite surprising that this decision is voluntary for each household. On the contrary, the municipality could have had a more active strategy on this issue, and they should have forced the households to share bins.

Another technical solution, instead of bins, is to use underground containers with a capacity of 5000 liters. These solutions are common in urban areas but could also be used on the countryside. In the further calculations, we based the capacity on a maximum of 20 household for food, residual and plastic and a capacity of 36 households for paper. With a pick up frequency of 26 per year on residual, food and plastic and a frequency of 13 per year on paper an underground solution gives a carbon footprint of 3,3 kilos per year per household. Comparing the underground solution with a solution where all household has their own bin, which is practically convenient, you can reduce the carbon footprint by 292%.

How will different transport equipment and bin systems influence the CO2 footprint?

In case A they chose a truck system with a duel chamber so they could pick up two types of waste at the same time. The truck had one chamber with 70% capacity and one with 30%. With this system they were able to compress the waste heavily since each chamber had only one fraction of waste. The challenge with this type of systems is to know the right split between the chambers. In case A they presupposed that residual waste and food waste had a spilt 70/30 and that paper and plastic had the same 70/30 split. They had no experience or data to build this decision on. At the kerbside system each household had to deliver the waste in four separate bins.

In case B they chose a truck system with a single chamber. At the kerbside system the households had to sort the waste in different color coded bags, and they had one bin for residual, food and plastic and one for paper waste. In case B with color coded bags the total number of bins were lower than in case A.

To compare the two systems, the difference is the total capacity due to different compression levels and the different time consumptions due to the fact that there are more bins to empty in case A.
To compare the systems equally we choose to calculate the CO2 emission based on two different frequencies; 17 and 13 times a year in both systems. By using the DTS model we got the following results;

Table 8:

	Frequence:13 times a year	Frequence:17 times a year
Case A, total CO2 emission per year per household	8,44 kg/year	8,94 kg/year
Case B, total transport cost per year per household	9,28 kg/year	9,13 kg/year

From the figures above, we can compare the transport system in case A with case B. We can see that from an overall perspective, alternative A has lower CO2 emission, averagely 6%. On the other hand, the comparison is based on a 100 % fully loaded truck in case A. This means that the split of waste is exactly 70/30.

Discussion

The amount of CO2 emissions from manufacturing and construction industries has steadily decreased the last 20-30 years, but emissions from the residential sector have continued to increase. Approaches to shift consumers' behavior are needed to reduce resource consumption and pollution associated with their daily activities, and consumers` active involvement in solutions for environmental issues is required to build sustainable societies. (Kikuchi-Uehara, Nakatani, and Hirao, 2016).

In this paper we have shown that consumers can contribute to reduce the CO2 emission within their choice of waste system. Each consumer can accept lower pick up frequencies and they can accept a longer distance to deliver their waste. The municipalities have used a democratic model when deciding the waste system for private households. In case A the solution they use gives a CO2 footprint of 9,71 kilo per household per year and an underground solution gives a footprint of 3,3 kilo. The municipality in case A have 23 864 households. If they had changes their system to underground solutions for all inhabitants, which would lead to a longer distance for each consumer to deliver the waste, they could reduce the CO 2 footprint by 152 968 kilo CO2 per year (23 864*(9,71-3,3). Number of households totally in Norway in 2016 is 2 316 600. It is not relevant to calculate the same reduction for the whole country, but this is an indication of how consumers can contribute to a more environmental friendly society.

Conclusions

It is necessary to do detailed calculations to be able to choose the right system for how to handle waste in a municipality. Decisions are complicated and need to be based on a proper calculation. Based on the results of these calculations the municipality has to decide on how much the single consumer can decide themselves. A consumer will often decide the solution which is most convenient. In this case this is not the most environmental friendly solution and the municipality should consider what to decide by whom.

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