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A triple-bottom-line evaluation of municipal solid waste collection

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ABSTRACT

Municipal Solid Waste (MSW) collection systems can contribute to a sustainable society by transforming waste to valuable resources. However, if not properly designed, the MSW collection systems can become a liability in terms of high cost, high emissions and reduced service. There is still a lack of knowledge on how MSW collection system designs trade off the elements in the triple bottom line. The purpose of this study is to contribute to such understanding. A service-mix framework is proposed, demonstrating trade-offs among the decision areas of bin types, vehicle types, pick-up frequency, delivery distance, co-collection, and sorting in MSW collection systems. The triple bottom line performance is evaluated on cost, service, and emission levels. Two MSW collection systems are analysed and compared, using an Excel-based spreadsheet model. The findings show a potential to improve sustainability in MSW collection systems by trading off service-mix components. Specifically, the findings show that if five households share bins (accept reduced convenience, and the data indicate that they do) the reduction potential is 46 % for cost and 27 % for the CO_2 emissions. Similarly, reducing the pick-up frequency service reduces cost and CO_2 emissions. Finally, a sensitivity analysis of fill rates shows that using dual chamber trucks gives a high risk of increased cost and CO_2 emissions, due to the difficulty of matching waste volumes and chamber sizes. Thus, the paper demonstrates that significant reduction of cost and emission levels are possible without a significant sacrifice of service levels in MSW collection systems.

1. Introduction

Municipal solid waste (MSW) collection systems are becoming more complex when more sorting at source is implemented [1]. The development is transforming what was once one product flow of residual waste with all types of waste mixed in one category, into multiple product flows with separated waste categories like food, plastic, glass, metal, paper, and residual waste. Sorting waste at source has become standard in MSW collection systems [22,35], and new waste categories for sorting at source are being added to the municipalities' assignment [3], further increasing the number of product flows.

Sorting of waste at source is implemented as a sustainability measure to reduce emissions and secure better use of valuable resources. With reference to the waste hierarchy [14], emissions levels are lower and resources better taken care of when waste is used for material recycling and reuse compared to alternatives like energy recovery and landfilling (see e.g. [23]).

Introducing separate and several product flows in the MSW collection systems, increase the scope of logistics activities within such systems, and new demands for systems design. Setting up a sustainable MSW collection system becomes a complex and challenging task [1]. Well-adapted system design is necessary to prevent the value in waste resources to get lost in the process of collection and to prevent the collection operation itself becoming a sustainable liability. Sustainable MSW collection system design and performance are still not sufficiently addressed [26].

MSW collection systems performing at sustainable standards refers to the triple bottom line (TBL) [30]. TBL refers to performance levels which improve economic results, reduce carbon footprint and enhance customer service and satisfaction [13]. Thus, it is necessary to understand, discuss and evaluate TBL performance trade-offs when establishing MSW collection systems. There is still, however, limited insights into trade-offs for the triple bottom line performance elements for MSW collection systems [3]. One explanation can come from the lack of standardization in indicators [7], but also from the tensions between functions in the collection systems [18].

One area that is characterized with tensions is the role of the household [18]. The households can be viewed as the most important function in the MSW collection system as they are the starting point for the waste flows [19], also referred to as the first-mile logistics [18].

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Studies show that if the system design makes it easy and advantageous (high service, low cost and reduced environmental impact) for households to sort waste, they will most likely perform well [9,10,15]. Thus, the service level that a MSW collection systems are delivering to households will have a direct impact on system performance. How to structure a service however, depends on multiple interdependent activities and functions within the MSW collection systems [27].

To delineate and evaluate such trade-offs a service-mix framework is proposed, and evaluate cost, emission, and service level outputs from various set-ups for MSW collection systems. Our research question is 1) How are the triple bottom line trade-offs between the cost, environmental, and service effects for waste collection services in MSW collection systems?

Data is collected from two municipalities. The case data is used to highlight three service areas, including sorting and bin service, the pick-up service, and the vehicle service [3]. The paper demonstrates that there is a positive net effect in trading off a reduction in the waste collection service set-up on the sustainable TBL performance.

The paper is continued with a materials and methods section, where the service-mix framework areas and the TBL effects are presented and discussed. Further, research design and methodology are presented, before the case data is described and analysed. The paper is closed with a discussion, limitations, and suggestions for further research.

2. Framework

Any given design of a MSW collection system will manifest itself through a performance level, combining service, cost, and emission levels. Evaluating trade-offs between these performance dimensions is crucial for well-informed decision-making in establishing sustainable waste collection services [13]. On the contrary, failure to consider relevant performance factors can lead to system collapse [17]. Ability to be specific in the evaluation of the waste collection services is necessary. Ansari and Kant [2] state that this is a research field at a preliminary stage, dominated by qualitative research and the quantitative methodologies have great potential (p. 2537).

2.1. Social perspective

The service that are offered to households from MSW collection systems are determined by many interdependent decision areas, like type of bins and vehicles, emptying frequency, walking distance, degree of co-collection and sorting (e.g. [27,36]). Thus, design of such systems depends on careful consideration both within and across these decision areas (M. K [20]).

The bin and the vehicle are two decision areas, also viewed in a dichotomy [27,28]. Bins represent what and where households deliver their sorted waste and come in many shapes and sizes. Decision about which to use is often a function of household type (e.g. the number of people in a household) and housing structure (e.g. single houses or apartment buildings). Different types of waste can be delivered in the same bin or sorted separately into individual bins. The waste types may also be subject to a bring or kerbside system structure, which implies that there may be a delivery distance for the households.

2.2. Cost calculations

Many factors drive collection costs, and collection costs are reported to contribute to over 40 % of the total cost in a MSW collection system [8]. From a country like Greece, there are even reports of cost levels tied to collection and transport as high as 70–100 % [8]. Cost drivers in waste collection services come from population features, household structures and operational characteristics like geography, distances, and quantities [17]. Similarly, Greco et al. [16] ascertain that the economies of scale and cost drivers vary across different waste types collected, in their study of MSW collection system costs.

Thus, the operational transport setup has a decisive impact on costs for waste collection services [4]. Such costs are not easily calculated given the multi-criteria characteristics of MSW collection system design [1]. To calculate cost for a waste collection services, it is suggested to work with the three main factors of fixed, variable costs and salary costs [5], and the model has proved valid in a sensitivity analysis for transportation of household waste [4].

The fixed costs are independent of the yearly driving distance and consist of depreciation, interest rate, insurance, administration, and taxes.

The annual fixed costs are calculated as follows:

$$C_{fixed} = (\mathrm{P} - \mathrm{RV} - T)/L + ((P + \mathrm{RV})\,/\,2) * r + I + A + T$$

Where C_{fixed} is the annual fixed cost, P the purchase price of the vehicle, RV is the residual value of the vehicle and T one set of tires (tires are modelled through the variable cost). L is the lifetime of the vehicle. r is the annual rate of capital. I is insurance cost, A administration and T annual taxes.

The variable cost and distance dependent are calculated as follows:

$$C_{variable} = (F + M + T)$$

Where F is fuel cost, M is maintenance cost and T tire cost.

For salary calculations, all time processes must be documented and measured, such as loading and unloading time, speed and distance. The formula for salary is as follows:

$$C_{salary} = D/s + \mathrm{Nb} * B + \mathrm{LT}$$

Where D is distance and s is speed, Nb number of bins and B is loading time per bin, and LT loading time. These time processes identify the hours of idling and the number of stops.

2.3. Calculating emissions

The transportation sector is a major contributor to greenhouse gas emissions, with diesel-powered trucks playing a significant role. Diesel is still the dominant fuel type for trucks [29]. Alternative fuels like biodiesel and biogas derived from food waste is also used in transport for waste collection services. Such fuel gives reduced emissions compared to fossil-based diesel, but its availability is still too limited to support fleets of trucks. In addition, electric trucks are available, but prices are as much as twice that of a diesel truck, and the charging infrastructure still insufficient. Thus, emission levels are directly linked to the type of fuel and vehicles used in the collection systems [24].

In addition, fuel consumption is also largely influenced by driving behavior, topography, vehicle type, and the weight of the load [25]. The more frequent the stops and the smaller the volume per stop, the higher the fuel consumption. Time processes also influence CO_2-emissions. At the same time, efficient loading processes will reduce idling and thereby lower fuel consumption (Megan K [21]). The calculation of CO_2 emissions from transport is therefore based on fuel consumption from the two main factors of driving and idling when stopping. The diesel use elements are multiplied with an average rate of CO2 emission per liter of fuel consumption, which is 2.69 kg per liter of diesel (EN, 2013). The formula can read as follows:

$$CO_2 emissionsfromtransport = \big(Diesel_{use-driving} * D + Diesel_{use-ideling*} (Nb * B + LT)\big) * CO_2 - rate$$

For transport in waste collection services the total operational time consists of the three components of driving time, time spent emptying the bins and time spent emptying the truck at depot [4]. Fuel consumption is higher for idling when stopping compared to driving, and therefore idle time is more prominent from transport in waste collection services due to frequent stops.

To fully evaluate emissions from waste collection services, it would also be relevant to take production of the trucks themselves into account, and the effect of bin manufacturing and use. The discussion of how to evaluate emissions need therefore to take a life cycle assessment perspective [32]. This would be a relevant analysis if the goal were to assess the total footprint of waste collection [4].

Research confirms that levels of CO_2-emissions it is linked to fill-rates, driving distance and type of vehicle. Usón et al. [32] has addressed and quantified CO_2 equivalents impacts associated with different ways of collecting waste and find that environmental performance depends on fill rates when comparing two different MSW system set-ups. Gilardino et al. (2017) found that bin systems reduce emission compared to door-to-door collection systems, mainly due to reduction in distance travelled. In addition, the number of waste types sorted at source will drive emission, and Edwards et al. [12] demonstrate the magnitude of increase when a waste type is added for separation at source.

2.4. Trade-offs in waste collection services

There are trade-offs in design of waste collection services. Teixeira et al. [31] evaluate a MSW collection system by assessing the triple bottom line and find that mixed collection is better compared to separate collection, dependent on the waste generation rate and population density. They find that the collection systems are sensitive to source separation and recycling collection rates, and that collection distances, fuel consumption and reduced crew productivity are the main threats to collection route efficiency. Vučijak et al. [[33], p. 23] also evaluate different MSW collection systems from a triple bottom line perspective. They demonstrate that a decision-making tool that takes multiple criteria into consideration can guide selection of MSW collection systems. Of particular interest in such decision making, is for municipalities to evaluate to what extent the households themselves can be included as part of the evaluation and trade-offs in the waste collection system [18].

Thus, a service-mix framework is proposed for this study to capture the decision areas and their interdependency considerations in structuring waste collection services in the MSW collection system, and the trade-offs necessary in performance evaluation (Fig. 1). The service-mix framework shows how waste collection services may serve households through different set-ups, and how trade-offs between decision areas are evaluated according to the triple bottom line. The framework responds to Bing et al. [3]'s call for more detailed knowledge about the multi-disciplinary problems MSW waste collection systems have on different decision levels simultaneously.

3. Research design and results

The section starts with a discussion of research design, where the framework for this study is operationalized into specific waste collection services discussed in this paper. Secondly, a description of two cases is provided, before an analysis is presented.

3.1. Research design

The service-mix framework shows service dimensions necessary to design and structure waste collection services in a MSW collection system. To further analyze the performance of these waste collection services, a structure in three steps is provided in an analytical framework (Fig. 2), showing the sequence in the actual execution of the waste collection services.

The first step is referred to as the sorting and bin service, including the number of fractions households sort, and how convenient it is to place the waste in the bins. The second step is the pick-up service, including how frequent the bins are emptied and the type of vehicles. The third step includes the deliveries at depots.

Data is collected from two municipalities, referred to as MUN-A and MUN-B, where waste collection services are compared across the sequences shown in Fig. 2. The description for each case is described below, and input data is further documented in the appendix.

The two municipalities that is included in the study are chosen because the households sort the same types of waste fractions, but with different collection system designs. One has optical sorting (MUN-B), and one has separate bins for each fraction (MUN-A). MUN-A is a medium sized system serving approximately 21 000 households, while

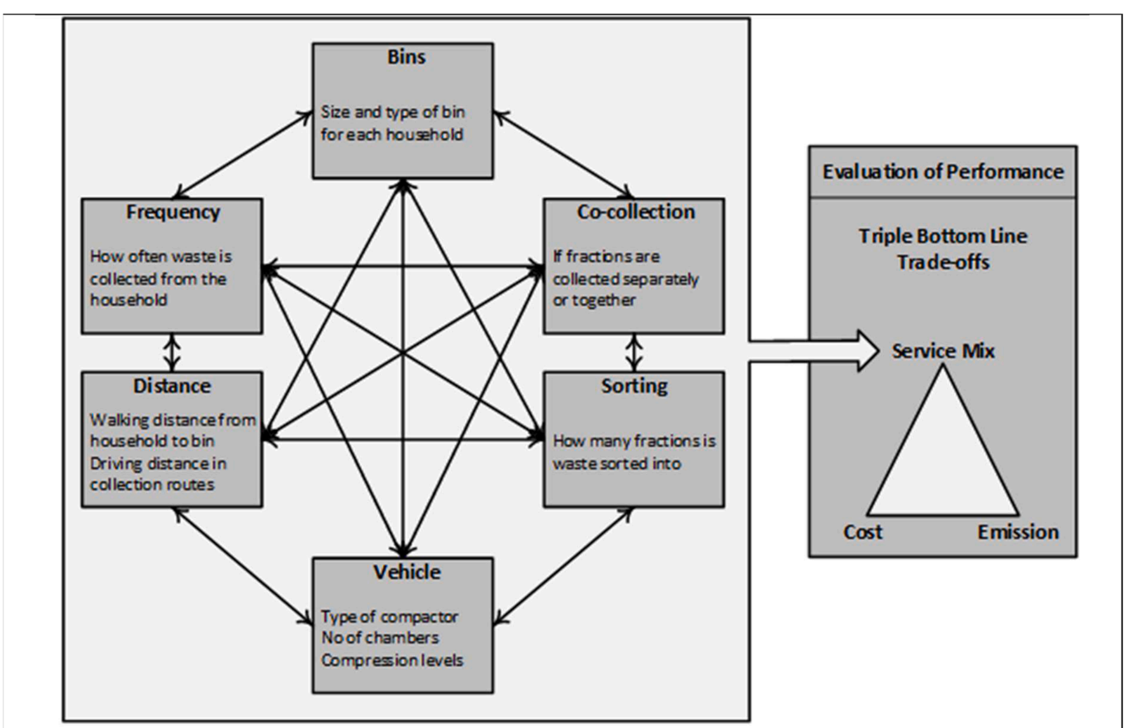

Fig. 1. The service-mix framework for waste collection.

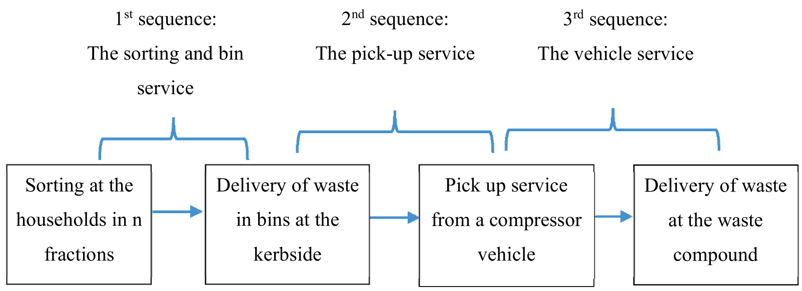

Fig. 2. An analytical framework for the research design.

MUN-B is a large system serving approximately 300 000 households. Data were obtained through both primary and secondary data collection, using interviews, field observations and company reports.

3.2. Case descriptions

3.2.1. Description of MUN-A

In MUN-A, the municipality has decided that households should sort in four fractions, namely food, paper, plastic, and residual waste. Their collection method is based on separate sorting into individual bins, so there are four bins for four fractions of waste. The collection vehicles have two-chambers divided into one chamber for food or plastic waste (30 %) and one for residual or paper waste (70 %). Residual and food waste is collected every second week, while paper and plastic waste is collected every third week; the same vehicles are used for both collections, with an expected 30/70 % share. The routes are planned according to capacity, which is calculated to 550 households (stops) and 1100 bins. The waste is delivered to four depot locations, one for each type. The average route is approximately 80 km. Thus, the vehicles have two destinations each time the waste is delivered to waste depots. MUN-A is a typical suburban municipality with a high level of single house structures.

In terms of the number of bins, the majority of households in MUN-A have four each. This results in waste from approximately 1100 bins to be collected on each transport route. The fill rate depends on the extent to which the collected waste actually divides according to the 70/30 ratio (70 % residual and paper waste, 30 % food and plastic waste). The vehicles continue collecting waste until one chamber is full, and experience shows that the number of actual compared to planned stops often varies. Collection frequency in MUN-A is every second week for food and residual waste and every third week for paper and plastic. The number of inhabitants per household is 2,33.

The compression level in a dual-chamber vehicle, has a 450 kg/m^3 limit. Experience has shown that food waste is difficult to compress due to its high level of water content. In these collection set-ups, vehicles drive until they reach full capacity and, therefore, their distance per trip will vary according to the volume of collected waste and compression levels. Lower compression levels decrease the distance per trip.

3.2.2. Description of MUN-B

In MUN B, the municipality have decided to sort out three fractions from the residual waste, namely paper, plastic, and food. The collection system is based on a dual bin system. The fractions of food, plastic and residual waste are sorted into colour-coded waste bags. The three coloured waste bags are sorted into one bin, while the second bin is for paper waste. In MUN-B, the collection vehicles have one chamber, and they operate with a reduced compression level in order to avoid breaking the waste bags. Paper waste is collected separately. At delivery, the colour-coded waste bags are subject to optical sorting at a central facility. The vehicles have one delivery location for emptying and the collection system has two optical sorting facilities in two separate locations for waste delivery.

The collection system in MUN-B is located in a city with urban areas. Its housing structure is a mixture of all housing types, from single households to large apartment buildings. Hence, the bin structure varies with household structure, both in terms of size and number, but is nearly identical within the same housing structure segments. In most cases, the routes serve homogenous housing structures. Collection frequency is also fixed per route but varies across routes. Depending on the space available for bins and on the capacities per household, the collection frequency varies from three times a week to once a week for the waste bags. For paper, the frequency varies between once a week to once every fourth week. The number of inhabitants per household is 1,95.

In MUN-B, the compression level is set at 350 kg/m^3 in order to avoid destroying the bags and making them suitable for sorting. To control for the right compression level, the vehicles are weighed and compared to a norm when delivering waste at the sorting facility. Experience shows that the vehicles in MUN-B drive until they reach full capacity and that their distance per trip varies with the volume of waste and the compression level.

A challenge posed by urban areas with a high population density and large apartment buildings is a need for high bin capacity. At some locations there may be many large-sized bins alongside one another. This is considered negative for several reasons (aesthetic, hygiene, use of space).

The bin volume varies from household to household in both municipalities. Its up to each household to decide the bin volume. The sizes are from 140 liters to 660 liters. However, both municipalities argued that the time to empty one bin was independent of bin volume.

3.3. Analysis

First, in this paragraph, the effect of merging bins and the effect of different collection frequencies is analysed to answer research question one; (1) What are the triple bottom line trade-offs between the cost, environmental, and service effects for the household collection function? Secondly, the pick-up service in the two municipalities is analysed to answer research question two; (2) What is the cost and environmental difference comparing given design set-ups?

3.3.1. The sorting and bin service (the effect of merging bins)

The case studies show that the default option for the municipalities has been to offer each household a full set of bins. This implies a high service with a short walking distance, and convenient sorting availability. At the same time, however, the case evidence also show that households voluntarily have started to merge bins, which is explained by discounts, space and aesthetic reasons. Thus, an implication from this observation is that households accept a reduced service level, in terms of increased walking distance, to achieve a lower cost, better utilization of space and fewer bins in their views. The insight from this observation is that the municipalities could explore trade-offs between the service of offering each household a full set of bins, and the cost and emission level from driving distance and bin emptying time. Pick-up service at the kerbside implies less transport for the households but trades off for more municipality transport. Fig. 3 demonstrates an analysis of such a trade-off.

The analysis simulates a range from no sharing to five households sharing bins,[1] and shows that when households share bins it reduces the time spent on collection. For example, when two households share bins, it is possible to reduce the collection time from 8.12 h to 5.37 h on one route per day servicing the same number of households. The cost effect is significant, as Table 1 demonstrates, and if five households merge bins, the estimated cost reduction is as much as 46 % and 27 % for the CO_2 emission.

3.3.2. The pick-up service (the effect of frequencies)

Findings from the case studies show that when sorting of waste is implemented, municipalities adapt collection frequencies. The change follows from the adaptation of capacities. Separate sorting of waste types in individual bins reduces the volume per bin per pick-up and provides the rationale for the municipalities to reduce pick-up frequency per bin. In comparison, when there is co-collection, as in MUN-B, the case study demonstrate that pick-up frequency is not reduced. High pick-up frequency is a valued service by households because it has positive hygienic and aesthetic consequences. This insight from the case study convey that it is relevant for the municipalities to explore the trade-off effects of adapting the pick-up frequency when implementing sorting at source in a collection system.

Thus, Tables 2 and 3 summarize a trade-off analysis for different pick-up frequencies in MUN-A and MUN-B.

In MUN-A, alternative 1 represent the as-is situation in which the pick-up frequency is every second week (26 times per year) for food and residual waste, and every third week (17 times per year) for paper and plastic. The trade-off analysis shows three alternative frequencies for the food and residual waste collection, from once a week (52 times per year), once every three weeks (17 times per year) or once every four weeks (13 times per year), and the number of bins is adjusted accordingly. The paper and plastic frequency is already at a minimum and is therefore analysed with only one alternative. The cost and CO_2-emissions effects are calculated using the values per unit obtained from the as-is alternative.

MUN-B is an urban area with different categories of housing structures that have adapted pick-up services, and pick-up frequencies vary from one to two or three times a week. Thus, the alternatives 1, 2 and 3 are the as-is situations, and the collection of waste types are divided between one route for food, plastic and residual and one for paper. The trade-off analysis show the same alternative frequencies as MUN-A, adding an alternative for every second week (26 times per year), every third week (17 times per year) or every fourth week (13 times per year). As for MUN-A, the number of bins is adjusted accordingly, and the costs and emissions effects are calculated using the values per unit obtained from the as-is alternative.

The analysis shows how trading off between frequencies have a significant effect on costs and CO_2–emissions. For example, in MUN-A, by choosing alternative 4 instead of alternative 2, the CO_2-emissions are reduced by 46 % per year (from 15.58 to 8.44 kg CO_2 per household per year). The cost effect has a similar reduction of 52 % (from 798 to 382 NOK). In MUN-B, a major difference of 40 % exists between alternatives 3 and 6, with 15.21 kg CO_2 per household per year for the former in comparison to 9.13 kg CO_2 per household per year for the latter. The cost effect follows the same pattern, with a 63 % reduction.

However, it could be expected that the households would be less willing to accept reduced pick-up frequencies in high density populated areas, where the risk of littering is present if bins become filled before pick-up. To mitigate this effect, the trade-off depends on a potential in the system to utilize added storing capacity. Sorting waste in individual bins often increases storing capacity, plainly because the standard minimum bin size is 140 l Co-collection of sorted waste in the bin does not add storing capacity, unless of course bin size is increased. However, one argument for co-collection in MUN-B was lack of urban space to add bins. Therefore, collection frequency is more difficult to adjust in MUN-B. An alternative is that households co-operate and share common bins. This could allow them to increase storing capacity and adapt collection frequency.

Thus, the findings demonstrate that separate sorting gives a higher potential for adapting collection frequency, and the potential for increased performance in accordance with the triple bottom line is higher for MUN-A as compared to MUN-B because of the storing capacity.

3.3.3. The vehicle service (the effect of fill-rates)

The case study demonstrates that municipalities choose different designs for their collection systems set-ups. Given that MUN-A and MUN-B sort waste into four fractions, separate sorting or co-collection is a differentiated service offered to the households. The decision for type of vehicle follows from the system set-up. MUN-A has chosen a 70/30 dual chambers vehicle and collect two separate sorted waste types in parallel. MUN-B has chosen single chamber vehicles and co-collects colour-coded waste bags. The compression level for these single chamber vehicles is lowered in order not to break the bags and mix waste types, reducing the maximum loading capacity of the vehicle. Separate chamber vehicles on the other hand allow for maximum compression of waste since there is no risk of mixing waste fractions. The capacity of the vehicles in MUN-A can therefore be utilised in full, while this is not the case in MUN-B. Thus, the insight from the case study shows that the municipalities accept trade-offs between the type of sorting and type of vehicle, where capacities in vehicles is traded off against the service of co-collection (fewer bins).

Such a trade-off is analysed by comparing the vehicle service of MUN-A and MUN-B. The analysis is based on the total number of bins and identical pick-up frequencies for all waste types. The total capacity of the bins depends on the compression level and the time required for emptying them. Fig. 4 shows the results for CO_2-emissions.

MUN-A has lower CO_2-emissions compared to MUN-B, ceteris paribus. The comparison assumes full vehicle loads in MUN-A, which means that the split of waste is exactly 70/30. High efficiency (fill-rate) reduces CO_2-emissions. Thus, the trade-off between co-collection and reduced vehicle compression level, gives a higher level of CO_2-emissions compared to separate sorting and maximum compression levels.

A challenge with this service, however, is to identify a chamber split (size) that matches the volume of sorted waste. If one chamber is filled up before the other, the vehicle must deliver its waste even if the vehicle load is not full. The results in Fig. 4 shows that the difference between MUN-A and MUN-B would soon level out if the fill-rate in MUN-A is reduced. Hence, a sensitivity analysis of fill-rates is shown in Fig. 5. For example, with a pick-up frequency of 13 times per year, the emissions in the two cases are equal if MUN-A has a fill rate of 92 % and the fill rate is 100 % in MUN-B. Similarly, with a pick-up frequency of 17 times per year, a fill rate of 98 % in MUN-A will cause the same emissions as will a 100 % fill rate in MUN-B. Achieving a high fill-rate is hence crucial for the emission efficiency in MUN-A. Fig. 5 shows that if the fill-rate is as low as 60 %, then the CO_2-emissions increase 67 %.

Analysing the cost trade-offs for the fill rates (still using the frequency of 13 and 17), the case data demonstrates (see Tables 2 and 3) that the cost per household per year are 382 and 433 in MUN-A, and 348 and 381 for MUN-B. Thus, the costs are lower for MUN-B compared to MUN-A and giving the opposite result as compared with the CO_2 calculations, where MUN-A is performing better. The cost differences are explained with the time it takes to empty bins. It is more cost efficient to empty fewer bins per household. Emptying time is a key cost driver for the vehicle efficiency when collecting waste and the data from this study

[1] The largest bin available is 660 ltr., and the bin size offered per households is usually 140 ltr. It is therefore assumed that 660 ltr., would be sufficient for five households.

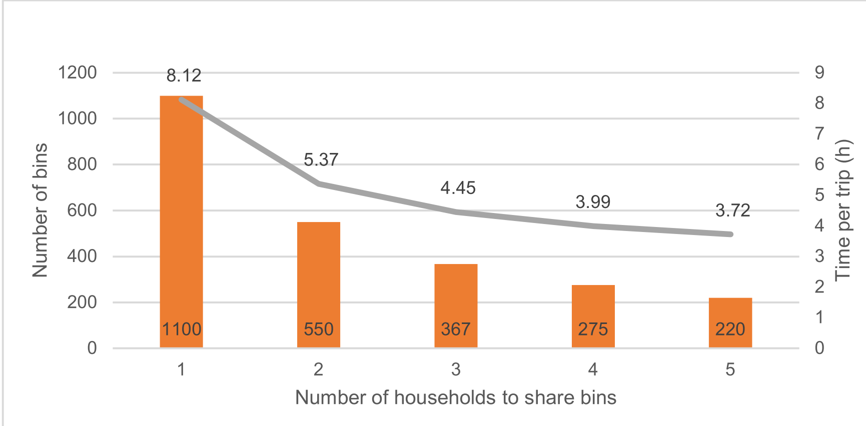

Fig. 3. Effect on the trip time by merging bins for up to five households (using MUN-A data).

Table 1
The effect of merging bins (using MUN-A data).

Number of households that merge bins	1	2	3	4	5	1 vs 5 In %
Cost per bin per pick up	5.78	7.72	10.3	12.9	15.5	167
Cost per household per pick up	5.78	3.86	3.43	3.22	3.09	46
Cost per year per household	497	332	295	277	266	46
Kilo CO_2 emission per household per year	9.7	8	7.5	7,2	7,1	27

Table 2
Analysis of pick-up frequencies in MUN-A.

MUN-A	As-is: Alt.1	Alt.2	Alt.3	Alt.4
Pick-up service parameters (Annual basis)				
Frequency				
Food and residual	26	52	17	13
Paper and plastic	17	17	17	13
Number of bins				
Food and residual	1.100	1.100	733	550
Paper and plastic	1.100	1.100	1.100	825
Cost calculations				
Cost per household per year	497	798	433	382
Emissions per year				
Food and residual	5.87	11.74	5.1	4.86
Plastic and paper	3.84	3.84	3.84	3.58
Per household	9.71	15.58	8.94	8.44

(comparing MUN-A and MUN-B) shows that it is more significant than compression level.

Additionally for the vehicle service, the fill rate trade-off also has a significant impact on cost, and the sensitivity analysis in Table 4 show the effect for MUN-A.

The analysis demonstrates that the vehicle efficiency is vulnerable if it is difficult to utilize the capacity of the vehicle. Even though the vehicles in MUN-A can utilize max compression levels, the challenge is matching capacities in fill rates across the split chambers. The data reveal that it is difficult to utilize the capacities in the MUN-A vehicles, and one explanation is found in the difficulty to compress food waste. An additional explanation comes from the dependency of the households to sort waste according to the expected 70/30 levels, while there is variability in the actual volumes sorted. The case study also revealed that the choice of a split chamber set up of 70/30 in MUN-A was made because this was the only vehicle with dual chambers available on the market. Thus, the case study shows that there are several challenges in achieving vehicle efficiency for MUN-A.

In sum, the analysis of the vehicle service demonstrates that a split

Table 3
Analysis of pick-up frequencies in MUN-B.

	As-is alternatives					
MUN-B	Alt.1	Alt.2	Alt.3	Alt.4	Alt.5	Alt.6
Pick-up service parameters (annual basis)						
Frequency						
Food, residual and plastic	52	104	156	26	17	13
Paper	26	52	26	17	17	13
Number of bins						
Food, residual and plastic	619	1.238	1.857	310	206	155
Paper	1.650	825	1.650	1.100	1.100	825
Cost calculations						
Cost per household	525	686	927	435	381	348
Emissions per year						
Food, residual and plastic	8.86	10.89	12.91	7.85	7.37	7.34
Paper	2.29	7.15	2.29	1.92	1.92	1.79
Per household	11.15	18.04	15.21	9.77	9.28	9.13

chamber set-up is more challenging for predictable performance levels compared to vehicles with single chambers, and that the trade-offs between the vehicle service mix, cost and emission are not a straightforward analysis.

4. Discussion

Each of the decision areas in the service-mix framework contribute to the service experienced by the households, and the analysis demonstrate different trade-offs. Evaluating the triple bottom line parameters, the study finds that it is possible to trade off service elements and get significant reductions in cost and emission levels. The insights from this study suggest that households are willing to accept such trade-offs.

The first argument pointed out is an empirical observation that some households in both municipalities have decided to merge bins, without this being asked of them from the municipalities. Thus, it can be inferred that these households have chosen a reduced service level in the collection function, because the average walking distance is bound to increase to a common collection pick up point. The analysis shows that the TBL trade-off is a positive effect for cost and emission. An explanation for such behaviour could come from the households wanting to have a green image [9], and that households after years of sorting waste and achieving new habits in this direction realize that they are part of the value creation for waste management [18,19]. However, the findings also indicate that households most probably differentiate between service elements, which can be explained with different perceptions of

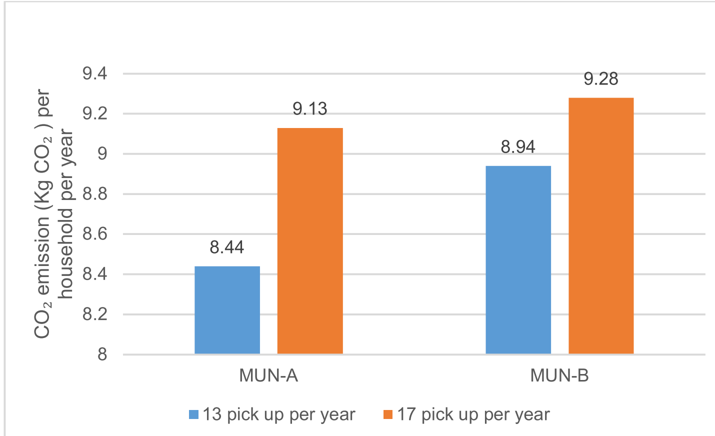

Fig. 4. CO_2 emission (Kg CO_2) per year per household, MUN-A and MUN-B compared.

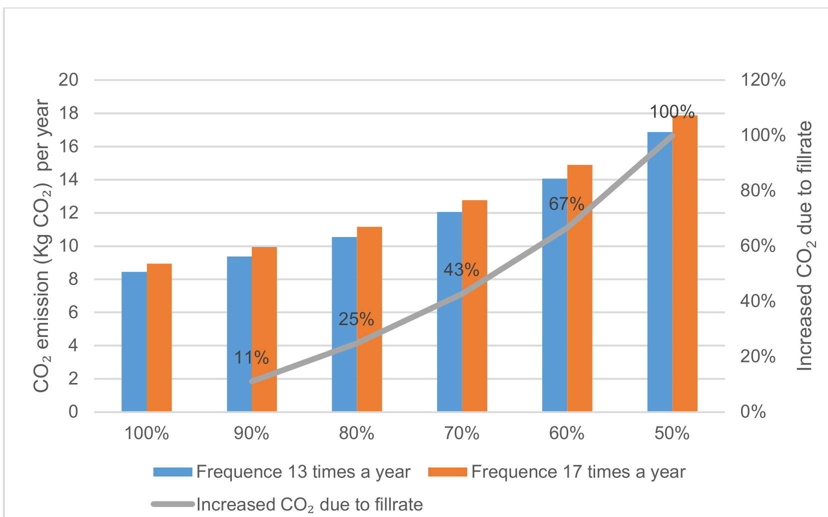

Fig. 5. Sensitivity analysis based on different fill rates for MUN-A in CO_2 kg/y.

Table 4
Sensitivity analysis based on different fill rates for MUN-A (cost/household per year).

Fill rate	100 %	90 %	80 %	70 %	60 %	50 %
Cost NOK	497	528	567	616	682	774
Cost index	1.00	1.06	1.14	1.24	1.37	1.56

what is convenient [34], especially since customer and household features have a high impact on collection efficiency [17].

Realizing that cost- and emission performance can be significantly improved by reducing the service level somewhat for key components is a valuable insight. In fact, the findings in this study suggest that there could be a limit to service and that households could contribute substantially to sustainability by trading off some service elements in waste collection systems. However, the study shows that the issue of fill-rates and recycling behaviour needs to be considered, which is also confirmed in previous research [36].

The goal of the MSW collection system is to collect as high volumes as possible, or as referred to in this study, to improve sustainability and strive for high fill-rates. If the households do not comply with the system, and sort waste according to the municipalities aspirations, fill-rates may suffer. This study demonstrates the significant impact that the fill-rates have on efficiency and how difficult it is to match the operations across waste volume, bin size and vehicle capacity. Service levels is a tool that incite households to conform to the system, and it may be high risk to modify the service levels.

However, the municipalities (MUN-A and MUN-B) did not always make decisions on the basis of detailed knowledge of the service-mix components. Confronting the decision-makers in the municipality with respect to the insights from this analysis, interviews revealed that selected decisions are taken qualitatively and not based on calculations. One explanation may be the complexity of the MSW collection system (M. K [20,33]). Decision makers may feel that it is too difficult to find an optimum, with too many components, and may just as well decide on a qualitative evaluation. Typically, then decision makers continue with existing systems, and make smaller adjustments to the going concern. A second explanation may come from system adaptations, when something new (e.g. more fractions for sorting) is included, previous data and experience are not available. A third explanation can be the feeling of uniqueness. The decision makers experience that the collection system is not similar to anything else, because of the location specific characteristics, and therefore believe that trial-and-error is equally efficient as modelling.

5. Conclusions and future research

The triple bottom line is the new standard of performance evaluation. A business' sustainability is evaluated by its implications for profit, the planet, and people. Municipal solid waste collection systems are facing these demands in the same way as any other business, but in a double sense since they are set up to ensure resource recovery.

The study findings demonstrate how the municipalities can improve their MSW collection systems, evaluated in terms of the triple bottom line. The analysis shows that several trade-offs need to be considered. The service-mix framework points to essential trade-offs that need to be considered when designing MSW collection systems. Different service levels can be traded off against costs and CO_2-emissions. Hence, arguably, the service-mix framework, combined with performance evaluation, is a promising tool for improving sustainability Table A1, Table A2, Table A3, Table A4.

The findings from this paper can be summarised in five main points:

1. It is possible to reduce costs and emissions at the expense of service to residents
2. Fill rate is essential to reduce cost and emissions
3. It is complicated to find an optimal solution with so many components involved
4. Much of the system is new, and there is a lack of empirical data
5. Municipalities do not possess the detailed expertise required to conduct a proper triple bottom line analysis

Future research should develop quantitative models incorporating the decision areas from the service-mix framework and attempt to simultaneously optimize sustainability in MSW collection systems. A necessary and interesting continuation of this research is to investigate how the different service elements affect the sorting rate. A question is whether good service and convenient solutions are essential for residents to sort their waste correctly.

CRediT authorship contribution statement

Eirill Bø: Project administration, Conceptualization, Writing – original draft, Formal analysis, Methodology, Writing – review & editing, Investigation. **Bente Flygansvær:** Writing – original draft, Formal analysis, Writing – review & editing, Investigation, Project administration, Conceptualization, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A1
Characteristics of the two systems.

Household-fixed parameters	System description MUN-A	System description MUN-B	Parameter measure MUN-A	Parameter measure MUN-B
bins	Kerbside system: Four bin bins	Kerbside system: two bins	4 bins (individual sorting)	2 bins
Vehicle	Compactor vehicle with two chambers and an adapted compression level.	Compactor vehicle with a single chamber	2 waste fractions in vehicle. 70/30 divide chamber 450 kg/m^3 compression	Single chamber 350 kg/m^3 compression
Frequency	Every second week for food and residual waste. Every third week for plastic and paper waste.	Once, twice or three times a week for food, plastic and residual waste. Once or twice a month for paper.	26 times per year 17 times per year	52/104/156 times per year 26/13 times per year
Distance	Single house structures with individual bins. Separate destinations for each waste fraction type.	Single housing structures with individual bin bins. Apartment buildings. One destination for food/plastic/residual waste and one for paper waste.	Max 50 m to bin 550 bins 4 depots 80 km to waste depot	Max 50 m from household to bin 619/1238/1857 bins 2 depots
Co-collection	Co-collected: Food and residual Co-Collected: Plastic and paper.	Three waste fractions are co-collected: food, plastic and residual.	Single fractions per bin	3 waste fractions in one bin
Sorting	Sort for food, plastic, paper and residual waste.	Sort for food, plastics, paper and residual waste.	4 fractions	4 fractions

Table A2
Cost* calculation and model.

FIXED COSTS	MUN-A	MUN-B	*Detailing the model:*
Input data			
Number of chambers	2	1	
Investment chassis	1550,000	1449,351	*Interview transport company*
Write off period	6	6	*Interview transport company*
Rest value chassis in %	40 %	40 %	*Interview transport company*
Rest value chassis in NOK	620,000	579,740	
One set of tires	30,000	30,000	*Interview transport company*
Bank rate	4 %	4 %	*Industry norm*
Insurance	50,000	50,000	*Interview transport company*
Administration	100,000	100,000	*Interview transport company*

(*continued on next page*)

Table A2 (*continued*)

FIXED COSTS	MUN-A	MUN-B	*Detailing the model:*
Fee based on the weight of the vehicle	2949	2949	*Actual tax for the vehicles*
Calculated data - to find yearly cost per vehicle			
Write off chassis	150,000	139,935	*Formula:(investment - rest value chassis - one set of tires)/lifetime*
Rate chassis	43,400	40,582	*Formula:(Investment + rest value)/2) * bank rate*
Insurance	50,000	50,000	*Interview transport company*
Administration	100,000	100,000	*Interview transport company*
Toll fee	0	0	
Fee based on the weight of the vehicle	2949	2949	*Actual tax for the vehicles*
Total fixed costs per year per vehicle	346,400	333,517	*As calculated, cost independent of distance*
VARIABLE COSTS	MUN-A	MUN-B	
Input data			
Repair and maintenance per month	4500	4500	*Interview transport company*
Repair and maintenance per km	2.60	1.83	
Diesel cost per year	120,000	120,000	*Interview transport company*
Diesel cost per km	5.77	5.77	*Formula: cost per year/number of km per year*
Tire-cost per km	1	1	
Variable cost per km			
Diesel per km	5.77	6.67	
Repair and maintenance per km	2,60	2,13	
Tire-cost per km	1	1	
Total variable costs per km	9.37	9.8	
SALARY COST	MUN-A	MUN-B	
Wage cost per hour	245	245	*Average in the industry in Norway*
Number of operators per vehicle	2	2	*One driver and one helper*
Input data for average trip - routesystem	MUN-A	MUN-B	
Distance per trip	80	80	*Average - input from MUN-A interview*
Number of weeks per year	52	52	*Work weeks*
Frequence per week	5	5	*Working days per week*
Speed km/hour	35	35	*Average - input from MUN-A interview*
Load time per vehicle in minutes	20	20	*Interview transport company*
Load time per bin in minutes	0.3	0.3	*By observation*
Number of bins per trip	1100	619	*Estimated number of bins to fill one vehicle*
Number of fractions per trip		1858	*Three fractions per bin * number of bins*
Increased distance due to lower time used		42 %	*Transport time in MUN-B is faster than MUN-A, because of fewer bins to empty. Assume therefore an added driving distance per day in MUN-B according to time used. (8,12/5,72=1,42)*
Yearly distance - km	20,800	29,546	

[*] Costs are reported in Norwegian currency (NOK).

Table A3
Summary of key input data.

Summary of key input data	MUN-A	MUN-B	*Detailing the model:*
Fixed costs per km	16.65	11.29	*Fixed vehicle cost divided by yearly distance*
Total variable costs per km	9.37	9.8	*Variable vehicle cost divided by yearly distance*
Wage cost per hour per vehicle	490	490	*Wage per hour * the number of personnel*
Time per trip	8.12	5.72	*80 km*35 km/t + 20min+ 0,3 × 1100 or 619*
Cost per trip	6060	4488	*Formula: (Fixed cost/km + Variable cost/km) * distance + time per trip * wage per hour)*
Cost per hour	746	785	*Formula: Cost per trip/ time per trip*
Cost per bin	5.51	7.25	
Cost per fraction		2,42	
Expected profit	5 %	5 %	*Industry norm*
Trip price incl profit	6363	4712	
Cost per hour incl profit	784	824	
Cost per bin incl profit	5.78	7.61	
Cost per fraction incl profit	5.78	2.54	

Table A4
CO_2 calculations.

CO_2 calculations	MUN-A	*Detailing the model:*
Litre diesel per km	0.366	Measured by vehicle company
Litre diesel per hour idling	2.90	Interview vehicle supplier
CO_2 emission (Kg CO_2) per l diesel	2.69	Interview vehicle supplier
Time per trip	8.12	
Idling time	5.83	*Formula: Total time - driving time*
Diesel use in l one trip	46.16	*Formula: (Litre diesel per km * km per trip) + (Litre diesel per hour idling * Idling time)*
Kg CO_2 per trip	124.2	*Formula: Diesel use in litres one trip * Kg CO_2 emissions per litre diesel*
Kg CO_2 per bin	0.113	*Formula: Kg CO_2 per trip/Number of bin per trip*
Kg CO_2 per year for food and residual	5.87	*Formula: Kg CO_2 per bin * Frequency * 2 bins per pick up*
Kg CO_2 per year for plastic and paper	3.84	*Formula: Kg CO_2 per bin * Frequency * 2 bins per pick up*
Total kg CO_2 per year per household	9.71	

The vehicle company input data are obtained from the Scania company and their vehicles black box information, in addition to the information provided by the University of Exeter regarding the kg CO_2 per litre [11] and the average numbers identified from the cases. The calculation of the CO_2-emission is based on the use of diesel, which is, by far, the dominant vehicle fuel in Norway [6].

Data availability

Data will be made available on request.

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