Optimization of the ARC Waste Collection Process

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Abstract

The Amager Resource Center is a public nonprofit waste management company that performs incineration of household waste in their waste-to-energy plant, the Amager Bakke. In a team of four, we designed a series of recommendations centered around E-truck fleet optimization as the company will begin collecting household waste, from the entire Municipality of Copenhagen, effective in 2022. These recommendations included a Capacity Calculator created by the team that acted as an algorithm to output the number of trucks needed for any given input of waste. This algorithm determined the E-truck quota for any given area to then create waste truck routes and assign collection days based on given frequencies for residual waste collection in the districts of Amager East/Vesterbro. Standard work instructions were created to aid these processes. This resulted in finding that residual waste collection could be conducted with two less trucks than the current number used thereby, saving two waste trucks for the regions.

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WPI

Copenhagen Has Ambitious Environmental Visions

The city of Copenhagen is committed to the implementation of their CPH 2025 Climate Plan. This plan strives to "combine growth, development and increased quality of life with the reduction of CO_2 emissions"[1]. The city prides itself on making Copenhagen the world's first carbon neutral capital, focusing specifically on energy consumption, production, green mobility and City Administration[1]. In addition, it is intended that Copenhagen will serve as a model for other cities as Copenhagen demonstrates that carbon neutrality is feasible.

As shown in Figure 1, the transportation industry accounts for 14% of greenhouse gas emissions globally[2]. Currently, it is common practice for heavy load-carrying vehicles to run on diesel fuel. Diesel combustion emits carbon dioxide, smog, and other pollutants. In addition to the pollutants these vehicles produce, extracting the fuel from the ground can damage ecosystems and requires significant amounts of energy. Transportation of the fuel further contributes to the cycle of pollution and can even lead to environmental disasters such as oil spills[3]. One common way of addressing this problem is through electric vehicles. Electric vehicles offer a significant decrease in the amount of greenhouse gas emissions released and minimize the number of pollutants produced by moving and idling vehicles, provided the source of electricity is clean.

Recently, Copenhagen has decided that the waste collection process in the city will be taken over by the Amager Resource Center (ARC) starting in 2022. In order to better meet the city's goal of carbon neutrality, ARC will use E-trucks as their waste collection vehicles. This change represents an opportunity to restructure certain aspects of waste disposal and collection. In order for this challenging transition from diesel to electric to be successfully carried out, ARC must assemble data about variables such as routes, amount of waste collected, and specifics of waste collection practices. In addition, information on E-trucks and their limits in terms of range and charging ability must be collected.

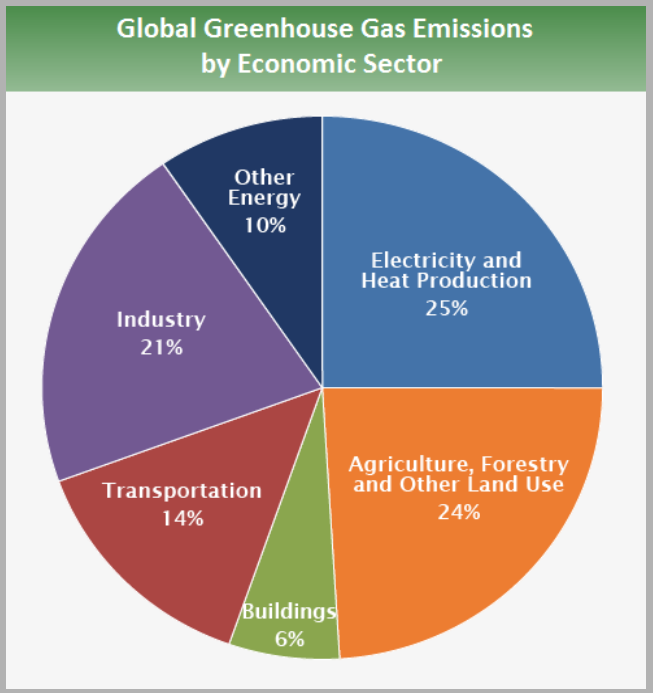


Figure 1: Greenhouse Gas Emissions by Sector[2]

This project explored the challenges of this transfer and presented recommendations as ARC assumes the responsibility for collecting household waste in the Copenhagen Municipality beginning in 2022. The group specifically looked into E-truck capabilities, improving route efficiency, and methods to determine the E-truck fleet size. The local waste management system in the Copenhagen Municipality was observed through hands-on waste collection, as well as meetings and interviews with representatives from local waste companies and lobbyist groups. From analysis of these findings, a series of recommendations were presented for ARC's waste collection in the Copenhagen Municipality.

Denmark Plans to Become Environmentally Sustainable

Denmark has been recognized globally for its efforts in producing an environmentally sustainable nation centered around its culture. The 2016 Energy Index from the World Energy Council ranks Denmark #1 when it comes to the sustainability of national energy systems[1]. The capital, Copenhagen, attempts to take this one step further by declaring that it will go carbon neutral by 2025. Overall, the view of environmental sustainability in Denmark is an ideal that thrives politically and culturally within the country.

Following the Oil Crisis of the 1970s, Denmark as a country took the threat of limited energy seriously. Not only did the cost of oil and overall energy shock Denmark economically, but this resource deprivation sent a message that something had to be done for the future well-being of the country. This crisis made the country look for a 'greener' approach to achieve independence from the Middle East's oil supply. Beginning with a slow implementation of wind

power into energy production, Denmark focused primarily on research to make their country more environmentally sustainable. Identification and implementation of alternative energy sources assisted in Denmark's growth as a nation. Now, Denmark plans to modernize all their energy consumption by addressing each of the economic sectors, including public transportation, city utilities, and now waste collection. For Copenhagen to become environmentally sustainable, it must consider all sectors contributing to the problem of environmentally unsustainable practices.

Copenhagen's Waste Industry will Undergo Significant Changes

Currently, three private companies operate the waste collection process for the city of Copenhagen. These companies are Urbaser, City Container, and City Renovation. These companies were selected through the government via public procurement, a process whereby public authorities purchase goods or services from companies[4]. Waste collection is currently executed with hybrid vehicles that run on both certified biogas and electric power. Beginning in 2022, all waste collection in Copenhagen will be handled by ARC. The transition from the currently operated hybrid vehicles to E-trucks will be implemented as the Amager Resource Center acquires the responsibility of waste collection. Residential waste produced by Copenhagen's 600,000 residents is typically collected from large apartment blocks and transported to the proper waste/recycling facility such as a landfill, plant, or recycling zone. In the case of ARC, this waste will be sent to various destinations such as recycling facilities, processing plants, or the Amager Bakke. The Amager Bakke is a publicly owned incineration plant located in Copenhagen.

During the transition, ARC must consider Copenhagen's ambitious goals, such as carbon neutrality. Another ambitious goal is to raise the percentage of recycled household waste from 45%, as of 2018, to 70% in 2024[5]. Ideally, Copenhagen could adopt a circular economy in which the use of materials is prioritized. Materials can be reused, refurbished, recovered, or thrown to waste. Reusing and refurbishing are the most efficient processes. Next, recovering collection, but also various services such as energy by means of incineration results in energy produced in the forms of heat and electricity. However, this process still pollutes via carbon dioxide, ash, and many other harmful chemicals. Lastly, throwing material away is the most wasteful process as the material sits in a landfill, serving no function. Incineration and landfill are not sustainable practices and do not align with Denmark's CPH 2025 Plan.

As shown in Figure 2, ARC has substantial business operating around the Copenhagen Municipality. ARC's business in Copenhagen does not only involve driven waste recycling and sorting centers. ARC also owns half of Denmark's landfills and hazardous waste receiving plants. As of March 2019, ARC began managing waste in the municipalities of Tårnby and Dragør. Currently, ARC handles 25,000 households in these two municipalities with twelve waste trucks. Their trucks operate using battery as well as either biogas or biodiesel, with 25 employees. Collecting waste in the municipalities of Tårnby and Dragør act as the beginning of their waste collection upscale plan into the Copenhagen municipality. Eventually, ARC will collect waste from roughly 300,000 households and will have an estimated fleet size of 125 E-trucks and 330 employees[6] .

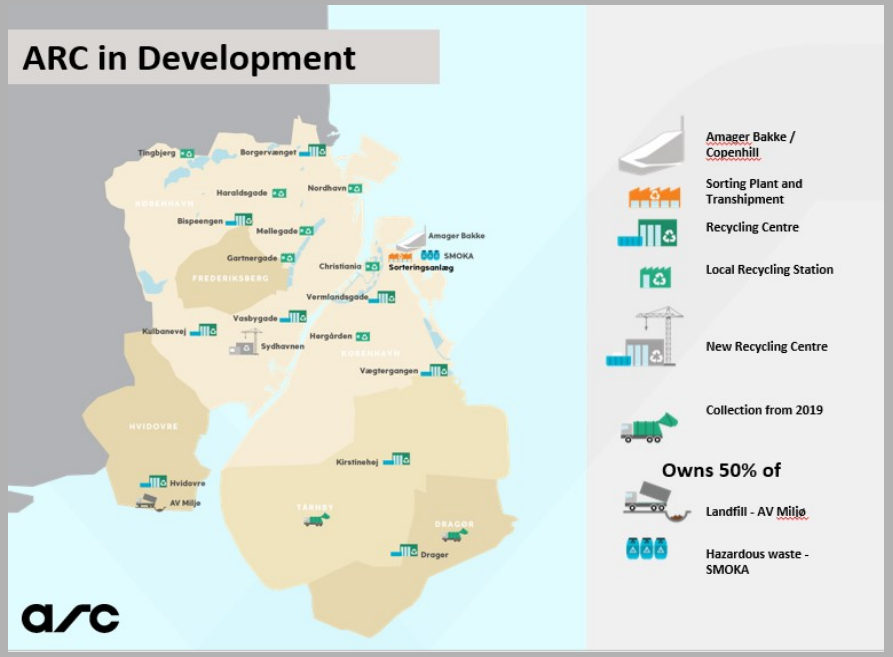


Figure 2: ARC Business Map[6]

The Municipality of Copenhagen's choice to have ARC handle household waste beginning in 2022 is politically motivated. Specifically, ARC had already been handling almost all aspects of waste management except collection. Amager Bakke, ARC's innovative incineration plant, operates as the world's cleanest and safest incineration plant[6]. Additionally, ARC had expanded its business model to handling recyclables at their local recycling centers across the Copenhagen metro area. ARC is selling this waste to their recycling subcontractors as well as handling residual waste at Amager Bakke. The Municipality felt that ARC would be able to handle waste collection due to their size, and ability to absorb workforce. ARC intends to absorb the laborers and management from the three currently operating waste collection companies (Urbaser, City Container, and City Renovation). The plan is to transfer efficient collection practices from the currently operating companies to ARC in 2022, while identifying and eliminating inefficient practices.

Copenhagen's Household Waste Collection Industry Can Be Improved

This project allowed the group to present recommendations to ARC as they prepare to take over household waste collection using E-trucks for the Copenhagen Municipality in 2022. In order to achieve this goal, WPI's 2019 Waste Collection Team created the following objectives:

- **Objective 1:** Understand the process and procedures of the European waste industry (particularly within the Copenhagen Municipality) and identify opportunities to improve the waste collection processes.
- **Objective 2:** Develop a method to optimize route planning for household waste collection in Copenhagen and conduct a pilot study using the districts of Vesterbro and Amager East, taking into account the current waste collection practices and areas of improvement that were identified in objective 1.
- **Objective 3:** Formulate recommendations on how to replicate the optimization process created in objective 2.

Objective 1: Understanding Waste Collection in Copenhagen and Other European Cities

The first step of the project was focused on obtaining information about the waste collection industry in the Municipality of Copenhagen as well as throughout select cities in Europe. This comparison was done through a series of interviews, presentations, and observations with several different representatives from lobbyist groups, municipalities, and multiple companies that work within the Copenhagen municipality.

The first meeting was with the Danish Waste Association (DWA) to learn about their lobbying efforts and statistics on the waste management issues in Denmark. Next, the team visited the Vermlandsgade Recycling Center, which is run by ARC, to understand how our sponsor functions as a business and the services they provide to the public. Additionally, the team met with a city planning representative who provided the Municipality of Copenhagen's perspective on how goals for waste management in the city are established. This meeting focused on the history of waste collection and how environmental goals are established and enforced by the municipality. More importantly, we discussed how the municipality plans to reach its ultimate goal of recycling 70% of all waste by 2024. This is important to the project because, as these goals progress, waste collection systems will have to adapt to help the city achieve its goals.

Figure 3: Waste Collection Runs

We also observed and participated in collection runs of residual waste, underground residual waste, bio waste, paper recycling, and bulky waste. Each member physically participated in two shifts of waste collection to

gain an understanding of current waste collection procedures in Copenhagen, as illustrated in Figure 3. The goal from this experience was to understand how the system ran from a ground level and to provide a "hands on" approach to explore what areas of the industry have room for improvement. Next, the team interviewed logistics managers of the three currently operating waste collection companies - City Container, Urbaser, and City Renovation - to understand the processes and procedures currently used in route planning, any issues the companies face, and how management organizes shifts. To further understand management practices as well as to enrich the team's analysis, Urbaser provided the team with data from the Municipality's software. These data included the location, collection day, and waste fraction for each bin. Using these data, multiple capacity and statistical analyses were conducted.

Objective 2: Optimize waste collection in Vesterbro and Amager East

Based on the analysis of current practices in the waste industry, the next part of the project involved developing a method to optimize collection capacity. Considering current practices such as pivot tables and union agreements, a practical workload was selected in order to achieve a reasonable decrease in the number of required E-trucks. These calculations along with criteria such as proximity and street limitations were then used to group addresses into recommended routes with the aid of computer software.

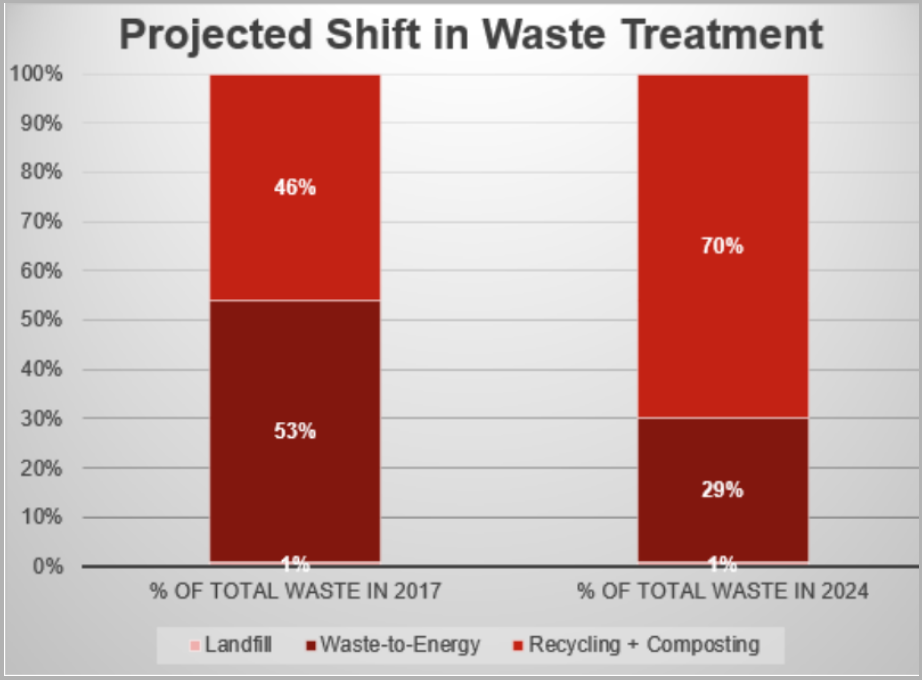


Figure 4: Projected Shift in Waste Treatment for the Copenhagen Municipality[7]

Objective 3: Formulate recommendations on how to upscale the optimization process

Analysis of the local and global systems and route grouping provided the information to formulate and present a series of recommendations to ARC. In doing so, the team created standard work instructions to present to the ARC's waste project team. These instructions contained detailed steps to aid in the upscaling of the created process for the entire Municipality of Copenhagen. The process includes both how to optimize the fleet size of the E-trucks and how to group collection addresses. From these objectives, the team was able to develop a deeper understanding of ARC's situation and present a series of findings from the research.

The waste collection industry is changing and adapting to develop a more sustainable model.

With Copenhagen's ambitious goal of recycling 70% of all waste by 2024, more citizens will begin to recycle each fraction in larger volumes. The industry will undergo a massive change from primarily incinerating waste, which is currently the city's major practice, as shown in Figure 4, to primarily recycling waste, requiring a great need for flexibility in the truck fleets and routes.

Achieving Copenhagen's goal will require changes in how frequently each fraction is collected as well as adjustments in the number of trucks allocated to collect different fractions. The frequency of cardboard collection is already in the process of transitioning from every two weeks to every week.

As shown in Figure 5, the number of cardboard bins collected each year has more than doubled since 2014. It is speculated by ARC employees that the growth and popularity of E-Commerce, such as Amazon, has increased the amount of cardboard households handle in a year.

Due to the projected increase in percentage of recyclables and decrease in residual waste, Copenhagen will decrease the amount of waste that is incinerated. This process will lead to Copenhagen operating more in the recycling tier of the waste hierarchy, shown in Figure 6. This tier is much more environmentally efficient and less wasteful.

Additionally, some technology has not been developed to meet the standards that the Copenhagen Municipality has set for the waste industry. The collection of residual waste from basements using Mobilsug is a growing option for waste collection, shown in Figure 7. Mobilsug is a form of waste collection where waste is collected from storage bins in the buildings basement and sucked through a pipe into the truck using a vacuum, as shown in Figure 8. This trend is speculated to correlate with the increasing number of large apartment buildings being built around the city. The Mobilsug vehicle consumes too much energy to be able to run on an electric battery, conflicting with the hybrid to electric truck transition ARC is implementing. As E-trucks become standard and waste collection using Mobilsug vehicles becomes more popular, there must be change in collection practices as the use of E-trucks and the increase in Mobilsug collections are not compatible.

Similarly, the crane system used to collect waste from underground bins in Copenhagen is currently not compatible with E-trucks. However, it is projected that improved battery technology will enable the crane system to be compatible with E-trucks within two years.[5] Regardless, the upcoming change with these useful and popular forms of waste collection must be accounted for in our recommendations, once again requiring significant flexibility.

Lastly, Copenhagen has been experimenting with the prospect of operating a fully automated waste sorting plant. This future technology will change many aspects about the waste collection industry by eliminating the need to ship recyclables to Germany for sorting.

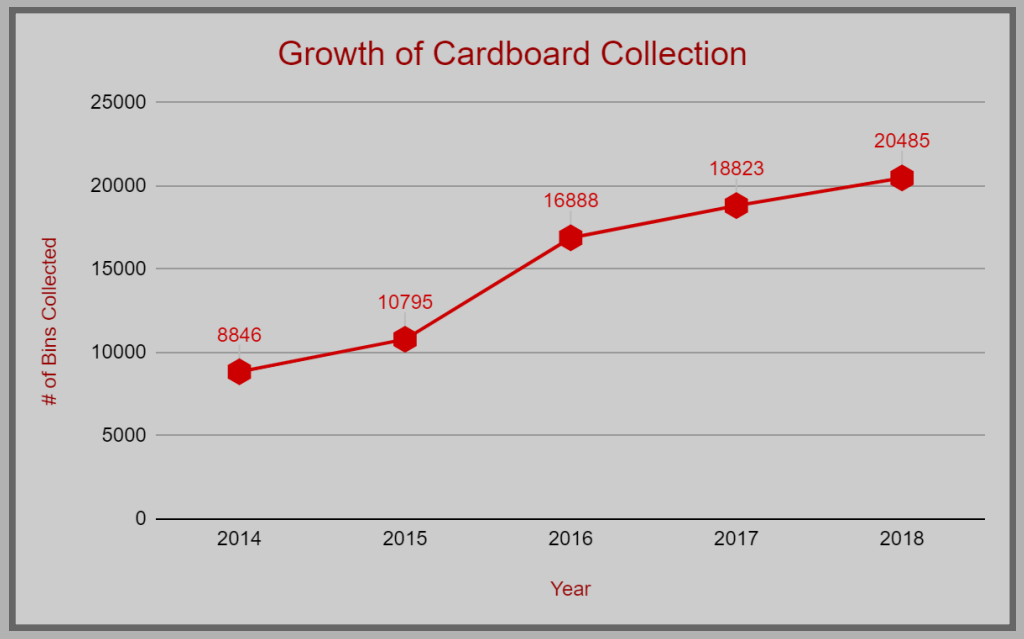


Figure 5: Growth in Cardboard Collected from 2014-2018[7]

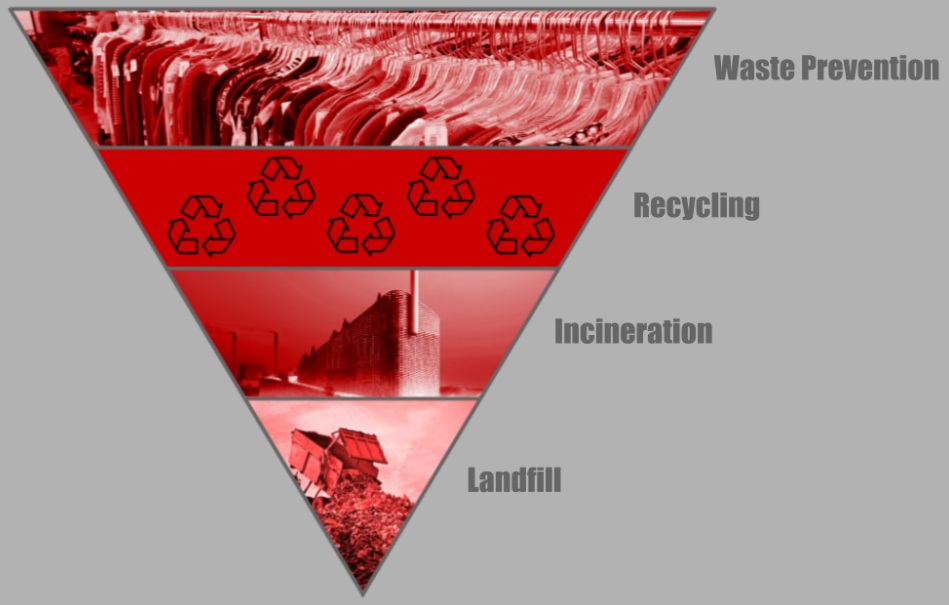
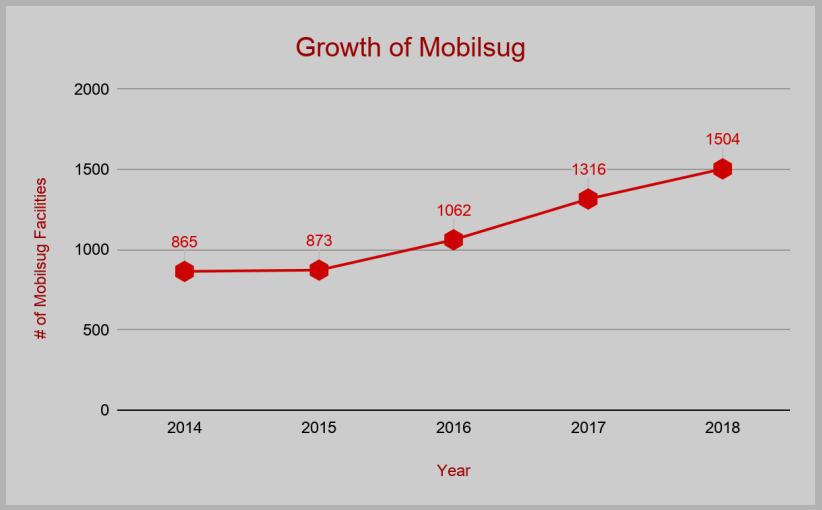


Figure 6: The Waste Hierarchy[6]



Figures 7: Increasing popularity of the Mobilsug waste collection vehicle[7]

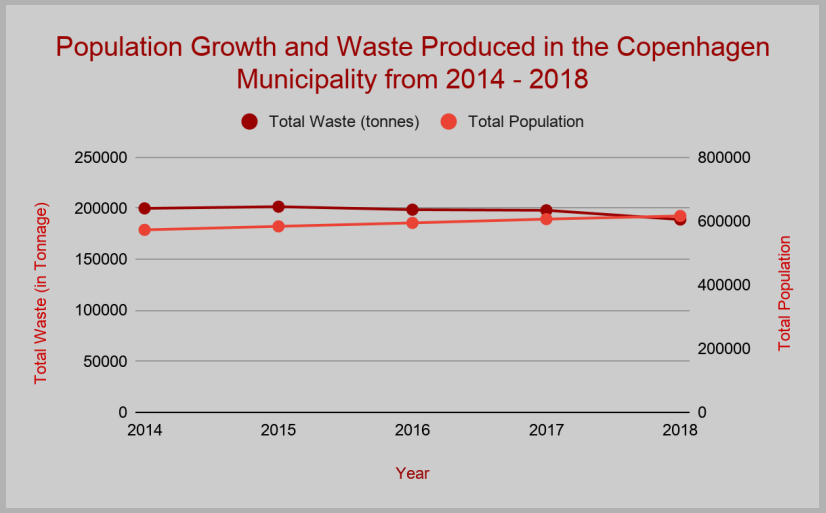


Figure 9: Total waste in Copenhagen from 2014 to 2018[7,9]

Figure 8: The Mobilsug waste collection practice

Sorting centers will be able to sort out multiple fractions from one another, meaning that the drop off locations for waste will change as time progresses. Additionally, there is a possibility that the industry may see a decrease in the number of fractions that must be collected. Should automated sorting facilities prove to be reliable and able to separate multiple fractions, the need for garbage collectors to individually pick up each fraction type diminishes. The Municipality of Copenhagen has been considering increasing the number of fractions to try to ensure more accuracy of sorting[8] however, this technology could ultimately ease the need for increased number of fractions as well as sorting by the public.

Although the industry is facing large shifts and changes, according to the Copenhagen Municipality, the total amount of waste produced in Copenhagen in previous years has remained relatively constant despite the population slowly increasing, as shown in Figure 9. Because of this, there is no reason to project that the total amount of waste produced in this area will increase dramatically in the future.

The City of Copenhagen and ARC prioritize the health and safety of citizens and workers.

ARC is taking safety features of E-trucks into account when deciding which manufacturer to partner with. More specifically, the director of waste collection at ARC has decided that a requirement for the E-truck that the city will purchase has sliding bus doors. The reasoning for this is that ARC does not want a waste collection employee to injure a cyclist or damage any property by opening a large door in traffic. Another safety precaution ARC is taking, is to encourage their employees to operate slowly so as to not injure themselves. Furthermore, ARC has expressed that they want to change the garbage collectors' unsafe practices, such as backing down one way streets in order to reach a pickup location.

E-truck manufacturers have followed suit in prioritizing safety. Scania, an E-truck manufacturer, is starting to incorporate major safety features in their latest vehicle.

Features, such as that shown in Figure 10, include an aerial view of the environment outside the truck, a low riding cabin, as well as an alarm that sounds when a pedestrian is passing the truck on the right. These features also serve to keep pedestrians and cyclists safe by making the driver aware of their location. A low riding cabin is a feature that allows the truck cabin floor to be closer towards the ground. This eases the workers' burden of constantly getting in and out of the waste truck.

Figure 10: Scania's Aerial View Feature

The manufacturer of the PVI C-Less E-truck, has also expressed a focus on safety. In the winter, the temperature of the cabins can become so low that electricity is not powerful enough to heat the cabin without reducing the travel range. This not only leads to discomfort of the drivers, but also poses a major safety risk as the truck cannot defrost the windshield, resulting in decreased visibility. As a result, PVI C-Less has placed a small diesel heating system in each of the operator cabins to combat this issue.

Performance of E-trucks is similar to that of diesel and biogas trucks.

According to Mathias Thuborg from Fredericksburg Renovation, which has been using the PVI C-Less E-truck since 2013, the performance of diesel and E-trucks are for the most part similar. Regarding maintenance, these E-trucks can be brought to the same location as diesel trucks for repairs and upkeep. The frequency of required maintenance on the E-truck battery is similar to the frequency of that on a diesel engine. Additionally, the tires on both vehicles wear at approximately the same rate.[10]

In Frederiksberg, the E-trucks have similar performance to the hybrid trucks currently operating in the Copenhagen districts in terms of the amount of time each truck can run under one refuel, even on the longest days. Figure 11 shows the longest time either truck would spend during waste collection, as defined by the waste collection hours for each municipality. Regardless of the 15 minute difference between Fredericksberg and Copenhagen, E-truck expert Mathias Thuborg describes from experience that the E-trucks are still able to complete their two shifts within 11 hours and 15 minutes without using more than 80% of their capacity.[10] E-trucks take longer to recharge, approximately six hours for the PVI C-Less truck to recharge from 20 percent battery, when compared to a diesel truck refuel time of approximately ten minutes. However, Frederiksberg utilizes overnight charging which does not affect waste collection

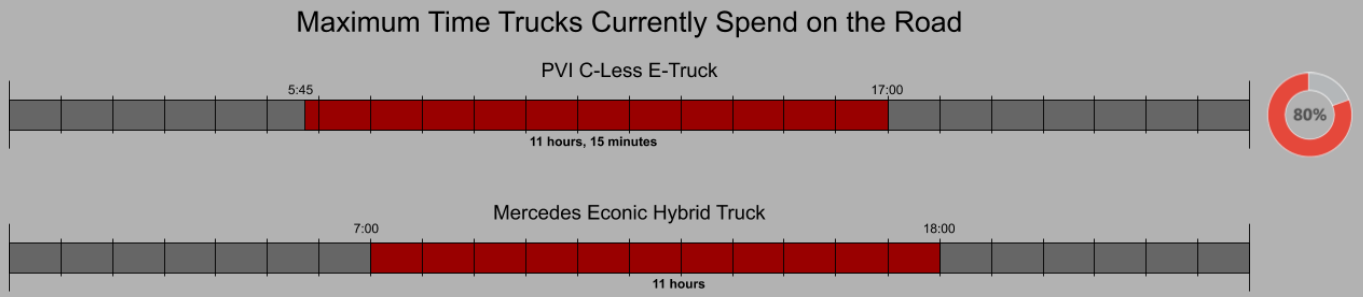


Figure 11: Longest observed time the PVI C-Less truck will spend driving in two shifts compared to the Mercedes Econic Hybrid truck[10]

or any daytime activities. Therefore when planned appropriately, charging time is not a problem.

Figure 12 compares the capacity of the Mercedes Hybrid and Volvo E-truck assuming an equivalent Gross Vehicle Weight (GVW) for both trucks. Trucks with higher GVW were not considered as they would most likely be larger and more difficult to maneuver on city streets, and could cause more damage to the infrastructure due to the higher weight and size than the current vehicles. Payload between the two vehicles is also comparable, since Volvo sits at about 9.9 tonnes and the capacity of the Mercedes Hybrid can range from 10-11 tonnes depending on the fraction collected, resulting in the small difference of 0.1-1.1 tonnes[13] due to the extra weight needed for the battery on the E-truck.

In favor of E-trucks, they are much quieter than diesel, shown in Figure 13. Noise studies were conducted by Frederiksberg Renovation in cooperation with a truck repair shop and concluded that E-trucks are quieter when driving and operating the lift/compactor.

When workers collect with these trucks, they are much closer to the vehicles than the 7 meter distance from which the study was conducted. This ultimately means truck noise levels are slightly louder to a garbage collector than they are in the study. Generally, over a prolonged period of time 70 decibels will cause annoyance in most people, and 80-85 decibel sounds can cause long term hearing damage.[14] Therefore, E-trucks are better for worker health and hearing since they do not approach unsafe noise levels as do diesel trucks.

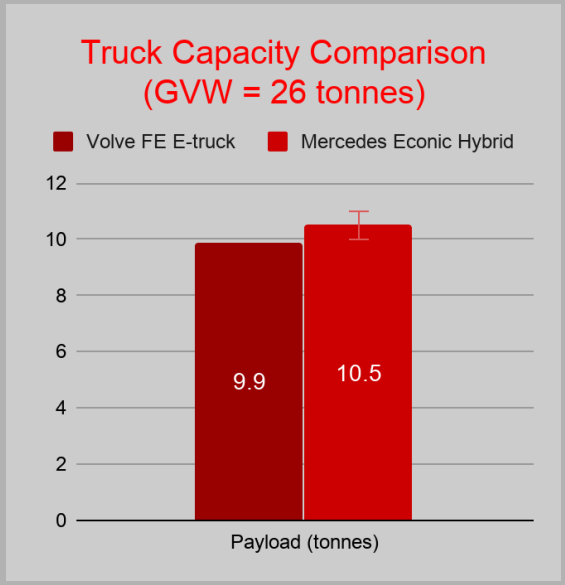


Figure 12: Comparison of the Volvo E-truck and Mercedes Hybrid Capacity Capabilities[11,12]

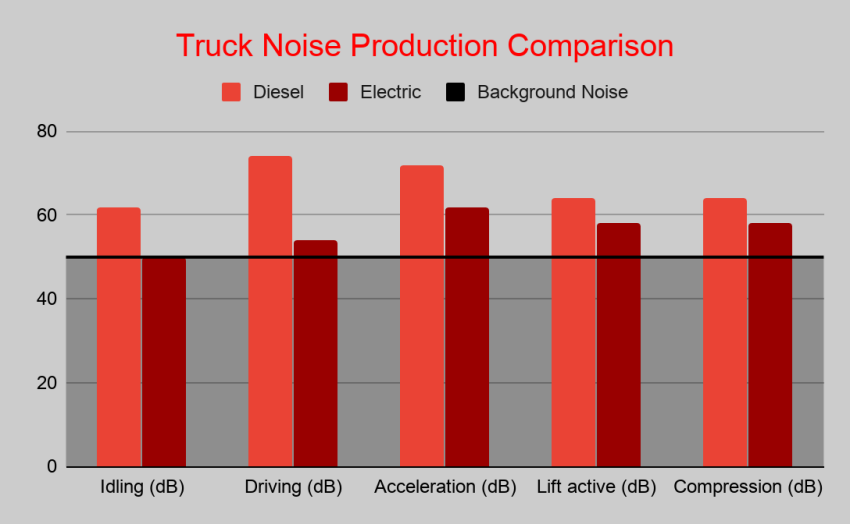


Figure 13: Noise study of PVI C-Less E-trucks compared to diesel trucks[10]

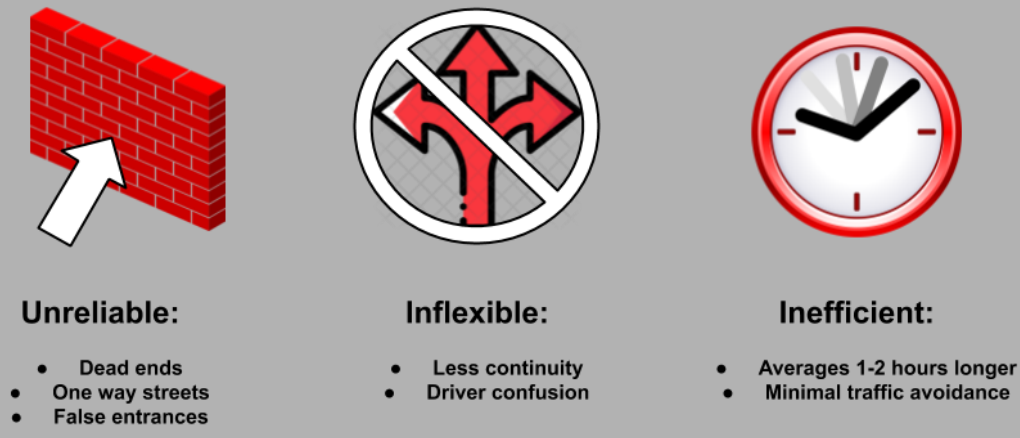


Figure 14: Reasons route planning software is inefficient

Automated route planning software has not been effective.

City Container and Urbaser had previously attempted to design routes purely with software, however, it was found to be unreliable, inflexible, and inefficient, shown in Figure 14. Route planners stated that software will often not accurately reflect Copenhagen's street layout. The software may design routes which lead trucks down dead end streets, down a one way road, or to the wrong side of a building, thus leaving the driver in a location far from a courtyard where they must retrieve waste. Additionally, route planning programs are designed to find the exact path which is most efficient. This means that when an address is added, all routes are recalculated to account for the change. With frequently changing routes, drivers do not learn the information essential to correctly collect waste, such as where bins are located in a courtyard. This leads to an increased number of missed bins.[15] With a predetermined order of addresses from which to collect waste, the job will take about 1-2 hours longer since software can not accurately predict Copenhagen's sporadic traffic.[16]

Waste collection can be conducted with fewer trucks than are currently utilized.

Currently, twelve trucks operate in the regions of Vesterbro and Amager East to collect residual waste. The labor-management agreement, specifies the maximum number of bins each collector is allowed to collect per week is 900 without having to offer shift premium pay. This agreement weighs larger sized bins more than others; the weights of these different sized bins contribute to the labor capacity agreement. Workers can collect past the weighted 900 bins, however they are expected to be paid more depending on the number of bins by which they surpass the baseline. In fact, many collectors are in favor of surpassing this 900 bin baseline as to be paid extra.[16] Figure 15 shows the various brackets at which waste collectors can operate, as well as the premium pay they receive for operating in each interval of bin collection.

Level	Weighted Bins	Index of Shift Premium
3	900	100%
4	950	106%
5	1000	112%
6	1050	118%
7	1100	124%
8	1150	130%
9	1200	136%
10	1250	152%

Figure 15: Copenhagen's Union Agreement[12]

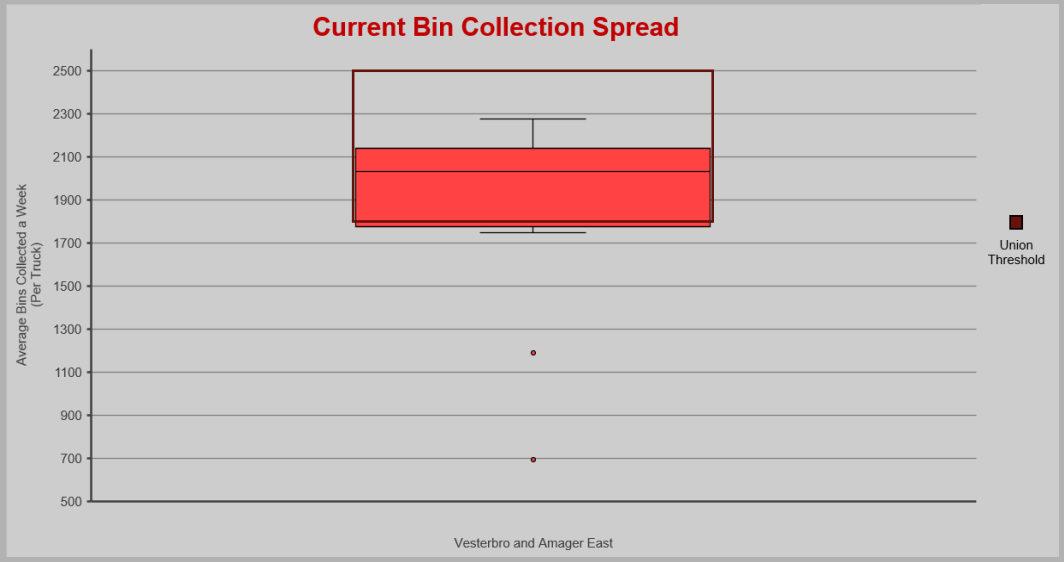
Each truck is operated by two waste collectors for residual waste collection; therefore, the number of bins collected per truck per week corresponds to double what the level of union agreement states. Currently, trucks operating in Amager East and Vesterbro range from collecting between approximately 700 and 2275 weighted bins per week (excluding outliers such as microcollectors).[12]

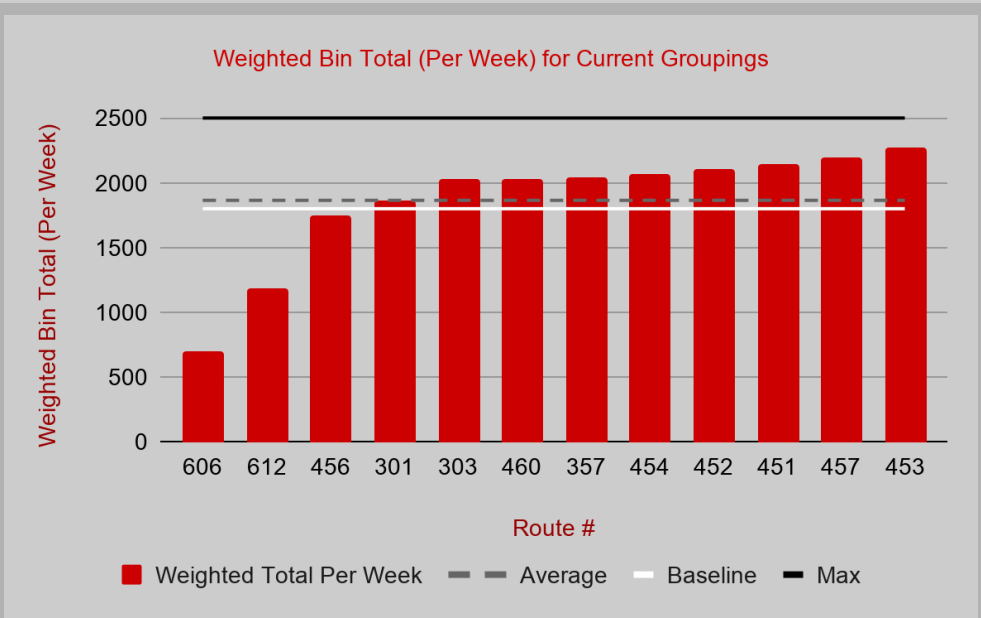
Inefficiencies in the current waste collection practices can be optimized

This process used to optimize the collection inefficiencies consists of increasing the average workload and distributing it more evenly, while paying employees a higher shift premium. Optimizing collection for waste vehicles in this region involves a combination of analysis from ASK data (database run by the Municipality of

Copenhagen including information about each bin, its size, and location), union analysis, and statistical analysis to see which options would best fill capacity for the given regions. The calculations which coincide with this analysis can be found in the supplementary material. Increasing the number of bins per truck would also increase the amount of waste collected per shift. Both waste collectors and route planners of the operating waste companies stated that they are not concerned about the vehicles filling up during a shift. For the majority of days, Tuesday through Saturday, it is common to end a shift with extra space in the garbage truck for more waste. Although waste trucks can frequently fill up during shifts on Mondays, waste collectors from the regions Amager East and Vesterbro have made it clear that ARC is close in proximity, so emptying a truck mid-shift is not a major hindrance. Since trucks are not utilizing all the space they have, and waste collectors are not collecting as many bins as the union states is manageable, there are more trucks on the road than necessary.

Trucks operate substantially under the labor contract's maximum limitations relating to number of bins being collected. This is an inefficient practice since the number of trucks on the road could be reduced should all trucks increase the number of bins collected while remaining within the contractual guidelines. Data from Vesterbro and Amager East show that the spread of the number of bins collected in one week is mainly operating in the lower half of the contract's acceptable range, as shown in Figures 16 and 17. The mean of the number of bins collected per route is 1865 with a min/max of 693/2276, however it is important to note that Routes 606 and 612 are outliers which bring the mean of this data down. The contract allows a maximum of 1250 bins per worker per week. Thus, a truck with two workers can collect a maximum of 2500 bins per week.





Figures 16 and 17: Vesterbro and Amager East bin collection for residual waste in relation to the union threshold

An important note is that these groupings were determined based on current scheduled shifts of 7 hour work days. However, most collectors do not need this allotted time and typically complete their routes in 4-4.5 hours.

It has also been observed that multiple trucks may operate on the same street at the same time, leading to delays in waste collection. When two waste collection trucks are operating on the same road, it is not uncommon for one truck to wait for the other to finish and leave the area before they continue. Since it can be difficult for two large trucks to move past each other on the streets of Copenhagen, this leads to an increase in the length of time trucks spend on the road.

A combination of mapping software and manual routing is an effective option for route planning.

Although previous efforts have proven route designing software to be ineffective in the city of Copenhagen, all route planners currently working at Urbaser, City Container, and City Renovation have expressed that grouping software is an extremely effective first step to designing these routes. All companies currently collecting waste throughout the city have found that it is more useful to produce groupings of collection addresses for the drivers. It is important to note that driver knowledge and opinions must also be taken into account with route groupings.[17] A waste collector will be able to provide the route planners with invaluable information about the city. In addition, when the opinions of the waste collectors are taken into consideration in these groupings, the collectors will be much more receptive to a new route. With the flexibility to plan the path themselves, drivers are able to master their routes and know the locations from which they collect waste. Urbaser, City Container, and City Renovation have found that this flexibility reduces, and in some cases solves, the unreliability, lack of versatility, and time issues that occur when automated route planning software is used.

The optimized process for creating waste collection groupings creates less geographically dispersed groupings and uses fewer trucks than the current practice.

As shown in Figure 18, many current route groupings for Amager East have a large spread across the region. This can lead to waste collectors unnecessarily driving across a district. To improve this aspect of the routing process, new groupings for this region were made focusing on geographic location to start. To do this, ASK data was loaded into BatchGeo, which pinpoints and sorts every address while allowing the user to isolate a section, and groupings were made based on location, number and size of bins in that location, and surrounding characteristics of the region such as train tracks, one way streets, etc. In terms of proximity of bins collected in one route, the created groupings for Vesterbro and Amager East are more compact when compared to the current groupings, as shown in Figure 19. This leads to increased optimization since drivers are not going far out of their way for a small number of bins.

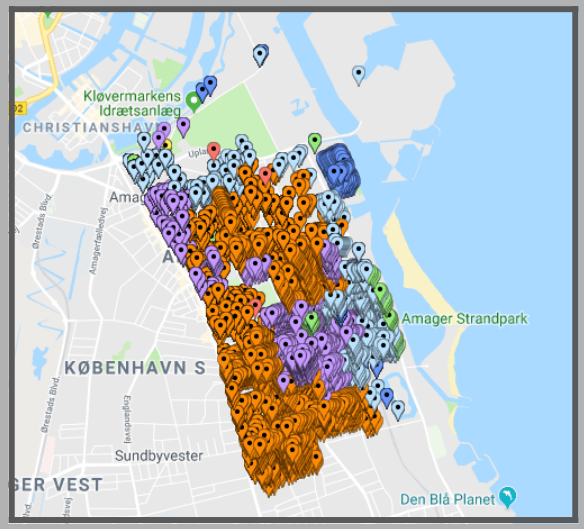
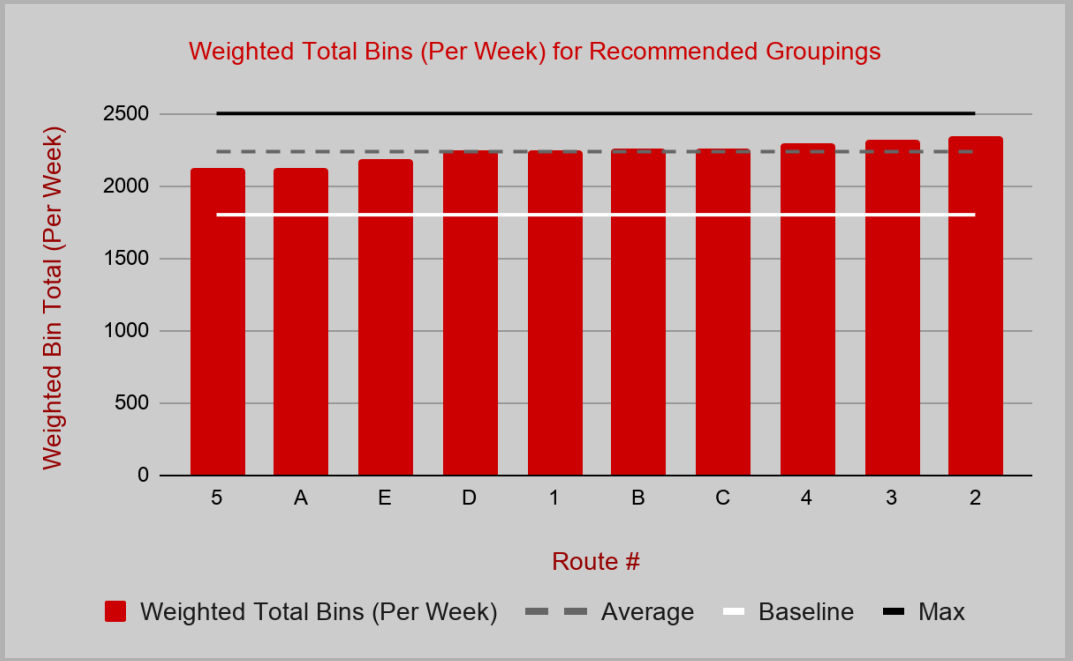


Figure 18: Current Collection Groupings in Amager East

Figure 19: Recommended Collection Groupings in Amager East

Additionally, as shown previously in Figures 16 and 17, the spread of collection of bins in current routes can be widely spread and mainly operates in the lower half of the labor contractual threshold. This process allowed for a more even distribution of the number of bins collected on each route, which mainly operates within the upper middle half of the union threshold, shown in Figure 20. By adjusting the number of bins collected per truck, from an average of 1865 with a min/max of 693/2276 to an average of 2236 with a min/max of 2120/2338, collection can be handled between Amager East and Vesterbro with 10 trucks rather than 12 trucks, shown in Figure 21. The optimized combination consists of ten trucks in which two workers collect at a rate of 2300 bins per week, five trucks at 2200 bins, and three trucks at 2100. These ranges fall within the current approximate labor contract's operating range of 1750-2275 bins.

With a more equal distribution and increased number of bins collected per workers, the number of routes was reduced from 12 to 10 between the two areas of Vesterbro and Amager East. Reducing this segment of the fleet by two E-trucks presents overall capital savings of 8.000.000 DKK to ARC. However, ARC will need to increase the amount of shift premium paid to collectors due to the increased number of bins per worker. The incremental shift premium, minus the current cost of shift premium, amounts to a net salary difference of approximately 2.000.000 DKK over 15 years. The 15 year cutoff is used as a general rule of thumb for most financial analysts. This is due to the expectation that there will be changes in the industry, such as technological advancements or changes in demand, after that time span to give reason for change in the investment. The difference in cost



Figures 20 and 21: Vesterbro and Amager East bin collection in relation to the union threshold for the newly designed groupings

amounts to approximately 6.000.000 DKK, as shown in Figure 22.

It is important to note that these calculations do not take into account externalities such as E-truck maintenance, cost of capital finance (loans), or inflation in the calculation. Labor savings were also not considered in the calculation due to the current standing that ARC will be absorbing all laborers in the future. The overall savings are based only on the change in shift premium after the capital savings were considered in this calculation. However, these preliminary calculations show that substantial savings will come from reducing the number of E-trucks required by utilizing shift premium pay in the labor agreement.

It is evident that the advancements in technology for E-trucks as well as the rapidly changing industry will likely require ARC to invest in new E-trucks or upgrades and adjust waste collection practices within this 15 year period. Right now, ARC seeks to optimize collection with a smaller E-truck fleet because many E-trucks are currently functioning as prototypes, and have many unknown variables associated with them.

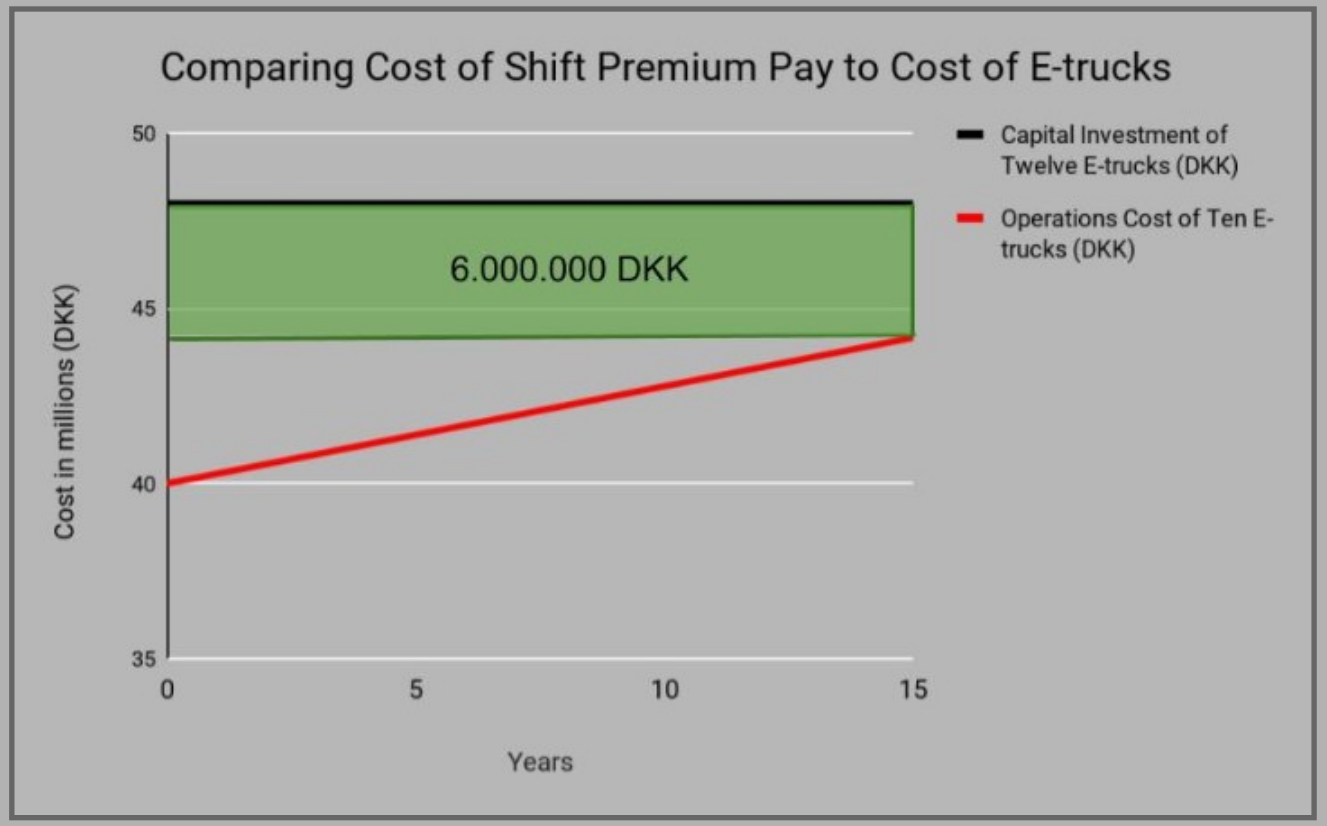
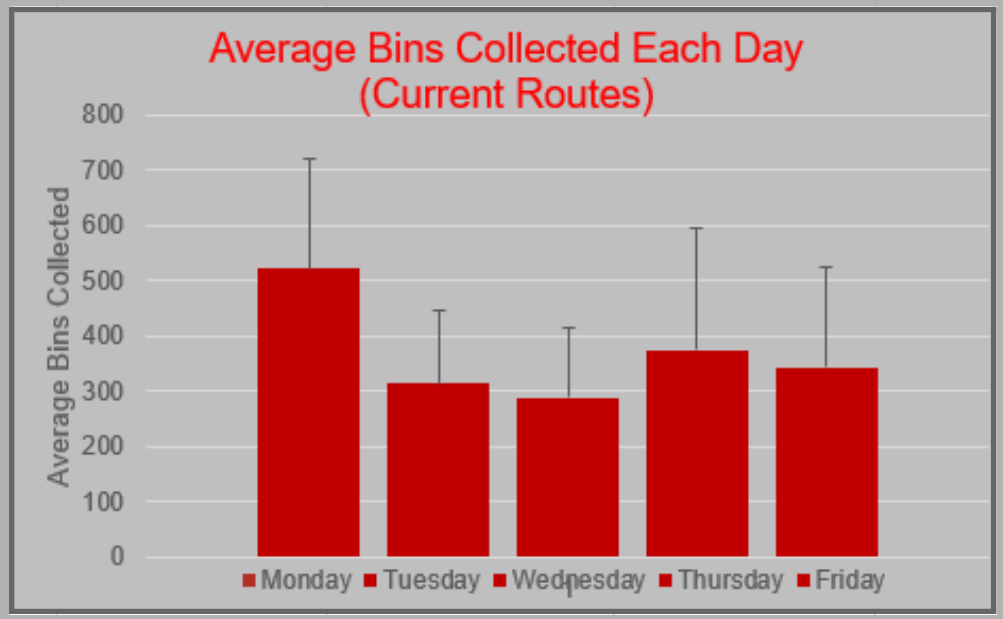
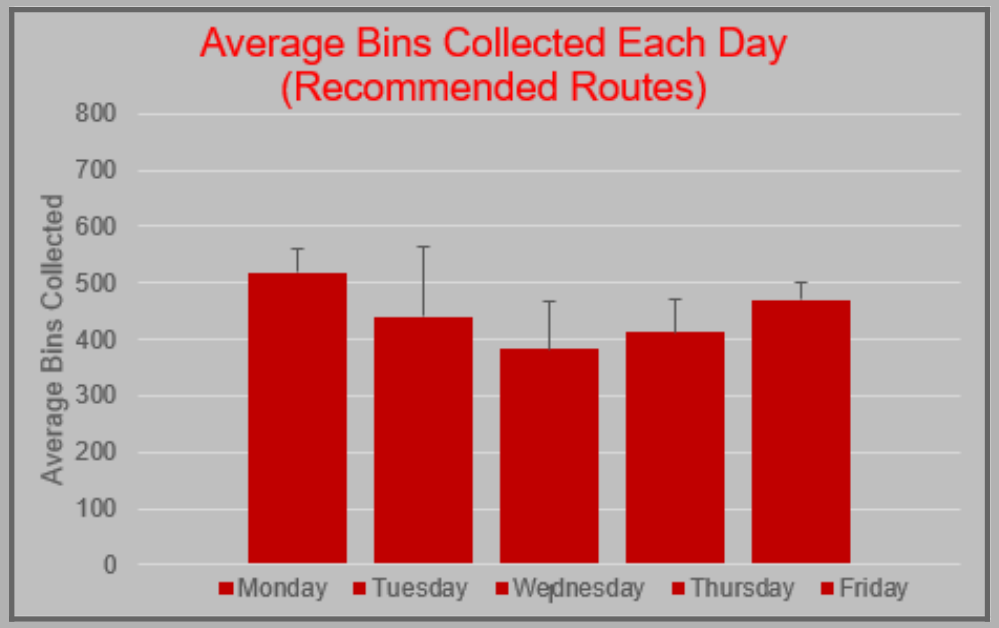


Figure 22: Cost of 12 E-trucks vs. Cost of 10 E-trucks plus Incremental Shift Premium

Additionally the allocated collection day for each route was distributed with a more even spread by determining days of high and low collection. Some frequencies already had set days, like the bins which must be emptied 6 times per week being collected every day but Sunday or 3 times per week being collected Monday - Wednesday - Friday. Then the bins that need to be collected once or twice a week were redistributed among the days with lower volumes. This can be seen from differences in the distribution of each day of the current route groupings in Figure 23 to the spread of recommended route groupings in Figure 24.

Main outcomes from the research and analysis are the tools and processes that were created. The team used data from Amager East and Vesterbro to display the reliability of these processes as well as to show how they work. The created procedure was able to reduce the number of projected routes (and therefore E-trucks) from 12 to 10 in Amager East and Vesterbro, which equates to about 6 M DKK in overall savings. The current shift premium bracket pay values were taken and used to calculate savings based on Urbaser's current agreement with 3F.[12] The created groupings were not only able to reduce the number of trucks on the road, but to increase the geographic proximity of bins within each grouping, thus reducing the travel distance for each route. Additionally, the group was able to identify points of change within the waste industry that will likely affect ARC in the future. Based on these points of change, the developed processes were made flexible to account for adjustments that might occur in the future.





Figures 23 and 24: Average and Maximum Bins Collected in Amager East and Vesterbro for Current Routes and Recommended Routes, Respectively

ARC route planners should utilize the team's Capacity Calculator tool to determine the capital investment and shift premium needed to collect waste in a specific region.

The team's Capacity Calculator tool can be extremely useful as route planners look to create route groupings for the entire city of Copenhagen. Specifically, this tool allows the user to input the number and type of bins in a region and presents various truck requirement outputs based on labor agreement brackets. Additionally, there is an option to input a combination of trucks coinciding with multiple union bracket levels to determine the most cost effective way to collect waste while minimizing shift premium pay. Lastly, if a smaller fleet size can be used in a specific area, the tool will calculate the incremental shift premium resulting from the reduction in the number of required E-trucks. These values will help justify offering shift premium pay as the E-truck market is undergoing substantial changes, and will continue to, as models become more efficient and continue to advance. Route planners should utilize this calculator's adaptability to experiment with different ways to minimize the number of E-trucks in an area before they start grouping.

ARC route planners should implement effective route grouping throughout the city to present an opportunity for savings in the E-truck fleet requirements for Copenhagen.

Based on the values calculated in the capacity calculator, these truck requirements can be used when creating and assigning route groupings for vehicles. The research team found that the geocoding software, BatchGeo, was a valuable tool in creating route groupings for areas all around Copenhagen. Allowing the drivers freedom to go to and from collection points without any navigation has been found, in current practice, to yield the fastest waste collection times. Using the work instructions created by the team, ARC can save time and money when they organize grouping for the next 8 districts around Copenhagen. These work instructions offer a set of intuitive, straightforward guidelines for designing routes in a specific area.

The ARC waste collection team must take into account considerations for the changing and adapting waste model in Copenhagen.

The Municipality of Copenhagen has set their goal to recycle 70% of all household waste by 2024. Furthermore, encouraging citizens to move towards a more circular economy may minimize both recycling and residual waste. While this ambitious goal is desirable in terms of environmental sustainability, appropriate adjustments will have to be determined in household waste collection. Moves towards these goals are already evident. The population in the Copenhagen Municipality has been growing at an estimated 40,000 people per year,[7] however the volume of residual waste has not increased, whereas the volume of recyclables has been increasing each year. As ARC plans to organize collection routes, there needs to be a fundamental understanding that most of the collection routes organized should stay the same, however the frequencies of collection during the week will ultimately change and eventually lead to more trucks needed for recycling than for residual waste, given the Municipality's goal to encourage greater use of recycling.

The use of E-trucks for Copenhagen aligns well with the Municipality's agenda/goals, however it is important to note the E-truck market is currently undergoing significant changes. Most of the E-trucks on the market are only prototypes. In fact, the only E-truck on the market that is no longer listed as a prototype is the PVI C-Less truck.[10] This truck, however, is not available in mass production yet. Currently, the E-truck that best fits ARC's waste collection model is the Volvo prototype E-truck.[5] It is important to understand the changes and advancements that will be made in the coming years within the E-truck market. ARC should plan to build their fleet keeping in mind the ever changing E-truck market.

Additionally, Copenhagen also has set goals to be the first city to go carbon neutral by 2025. While the use of E-trucks for household waste collection will coincide with this goal, the growing expansion of apartment buildings with basement waste collection facilities will work against this goal as it will require diesel/LNG Mobilsug vehicles to operate. ARC must keep this in mind when working with the Municipality about waste collection. Many new apartment housing developments in Copenhagen have their waste collected by Mobilsug.[5] Carbon neutrality is possible with using E-trucks for collection, however more Mobilsug locations will require either more diesel/LNG trucks as these vehicles are currently the only vehicles on the market capable of producing the amount of power Mobilsug demands. Technology must advance to be able to make this form of collection compatible with the carbon neutrality goal. Alternative fueling vehicles or other collection process should be investigated further to adapt Mobilsug technology to fit the Municipality's goals.

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