Masters thesis

A feasibility study of setting up a pre-sorting system for recyclable textiles and textile waste in Denmark

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Preface

Acknowledgements

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Reading guide

When referring to appendixes A.1 and A.2 it means the appendixes that are within this report, and when referring to attached appendixes B.1 through B.4 it describes the ones that are attached to the report in the system where it was turned in.
When a number in square brackets is used, e.g. [1], it indicates a citation of a source. The respective information on the source can be found in the Bibliography in the end of the report. When the citation includes a 'p.' followed by a number within the brackets, e.g. [1,p.1], it refers to a specific PDF-page in the source where the referenced information can be found.
In this report the following abbreviations are used; DKK (Danish kroner), kg (kilogram), km (kilometer), NGO (Non-governmental organization).
When a term is followed by a parenthesis, e.g. waste management company (WMC), the parenthesis informs the reader of the abbreviation of said name. This abbreviation is hereafter used for the remainder of the report.
When the title of a table or figure contains the reference 'S1', 'S2' or 'S3' it means that the table or figure displays data or information regarding the corresponding scenario. For example, figure 4.1 has the title 'Decision variables for MILP S1', meaning that it displays the decision variables for the MILP in scenario 1.
When the terms facilities and locations are used throughout the report in regards of determining possible facilities and locations through the MILP, it is important to note that this can also be one single facility or location.

Mads Bjerregaard Møller-Madsen | Nina Dobler | Stephanie Sandager

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Summary

Målet med dette projekt er at evaluere om det giver mening fra et økonomisk perspektiv at opstille et system der for-sortere genanvendelige- og affalds-tekstiler i Danmark. Samtidig vil der blive undersøgt hvor stor den miljømæssige påvirkning af dette system vil være. Dette bliver gjort gennem brug af metoderne Mixed Integer Linear Programming (MILP) og Analytical Hierachy Process (AHP).
Grundlaget for dette projekt er lovændringer i Danmark der kræver at der indføres separat indsamling af brugte tekstiler fra den 1. januar 2022, for at skabe bæredygtighed i denne sektor. Denne indsamling bliver udført af de kommunalt ejede affaldshåndteringsfirmaer i Danmark, og det bliver antaget at denne indsamling sker gennem brug af specielle poser der kun skal indeholde genanvendelige- og affalds-tekstiler. Disse poser bliver smidt ud sammen med pap og papir på husstandsniveau. For-sorterings niveauet er bestemt ved at undersøge hvilke krav den efterfølgende sorterings proces har. Derefter bliver de 6 største aktører på det danske marked identificeret for at sammenligne deres sorterings niveau med for-sorterings kravet, hvilket konkluderer at disse aktører skal foretage nogle justeringer for at kunne for-sortere. Herefter bliver inputtene til MILPerne bestemt, heraf bliver nuværende og fremtidige mængder af genanvendelige- og affalds-tekstiler i Danmark fundet, og det bliver bestemt hvordan disse er fordelt i landet. Dernæst bliver kapacitetsniveauerne for de mulige for-sorterings faciliteter, og størrelsen på disse udregnet, samt metoden brugt til transport af disse tekstiler bestemt. Det sidste input er omkostninger af systemet som er yderligere inddelt i variable- og faste-omkostninger. De variable omkostninger er bestemt gennem transport og lønninger for de ansatte, og de faste omkostninger er bestemt gennem leje af faciliteterne, og omkostninger ved åbning af nye eller udvidelse af eksisterende faciliteter.
Tre scenarier bliver herefter analyseret ved brug af MILP, det første scenarie konkluderer at tre eksisterende faciliteter skal åbnes, og resulterer i en total omkostning på 58.970.141,75 DKK og 507.269,2 $kgCO_2$ udledt. Scenarie 2 konkluderer at fire nye faciliteter skal åbnes, hvilket resulterer i en total omkostning på 57.347.348,29 DKK og 378.589 $kgCO_2$ udledt. Scenarie 3 konkludere at tre nye faciliteter og to eksisternede skal åbnes, hvilket giver en total omkostning på 56.671.842,11 DKK og 369.579,12 $kgCO_2$ udledt.
Til slut bliver AHP brugt til at evaluere de tre scenarier ved brug af flere kriterier end blot omkostning, disse kriterier er CO_2 udslip, total omkostning, risiko, og overskydende kapacitet. Kriterierne bliver tilskrevet en score baseret på deres vigtighed når en løsning bliver evalueret, her er total omkostning det vigtigste, efterfulgt af CO_2 udledning, derefter overskydende kapacitet, og til sidst risiko. Dette resulterer i at scenarie 3 er den mest optimale løsning af de tre scenarier. Herefter bliver muligheder for indkomst gennem salg af genanvendelige tekstiler bestemt, og sammenlignet med omkostningerne ved at drive for-sorterings faciliteterne. Gennem sammenligningen af dette bliver det konkluderet, at det ikke giver mening fra et økonomisk perspektiv at oprette et for-sorterings system i Danmark men det optimale system ville have en miljømæssig påvirkning på 369.579,12 $kgCO_2$.

1 Introduction

This chapter will give an introduction to the planned law changes regarding the waste fraction of used textiles, in the EU and in Denmark. Hereafter, a brief overview of the current used textile system in Denmark will be presented, to gain an overview of the flows herein. From this, it will be described how the new used textile system is assumed to function after the implementation of the law changes on January 1st 2022. Next a problem statement is proposed based on the collected information, lastly literature relevant to the problem that was proposed is reviewed.

1.1 Used textile system in Denmark

In May of 2018 there was an amendment to the EU directive regarding waste prevention, management legislation and policy, which has a focus on circular economy within the EU. It states that 10 waste fractions, including used textiles, should be separately collected from households, and thereby eliminate mixed collection. These separately collected fractions should be reused and/or recycled instead of being incinerated or landfilled. All used textiles from countries that are a member of the EU should be separately collected and sorted at the latest by January 1st 2025. [5,p.21] From these used textiles, reusable textiles must still be donated directly to NGOs or other private collection companies, however, who handles the remaining fractions of the used textiles, which are recyclables and textile waste is yet to be determined. Therefore, the focus of this project is on recyclables and textile waste.
The definitions of reuse and recycling used throughout this report are the same as the definitions from the EU directive from the article 'Guidance on the interpretation of key provisions of Directive 2008/98/EC on waste' [6]. Reuse is defined as 'any operation by which products or components that are not waste are used again for the same purpose for which they were conceived' [6,p.30]. And recycling is defined as 'any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or backfilling operations' [6,p.32]. No definition of textile waste has been found through literature research and therefore it will be defined through the definitions of reuse and recycling as 'any textile that can not be reused and/or recycled and therefore ends up being burned or landfilled'.
Following the EU directive the Danish government proposed a climate plan for Denmark, which states that the separate collection of recyclables and textile waste has to be carried out by the municipalities from January 1st 2022. The sorting process of these must be put up for bidding where only private companies are allowed to place a bid. Therefore the municipalities will not be allowed to perform the sorting unless no adequate bid has

been made throughout multiple bidding rounds. This also excludes most NGOs, as they do not pay VAT and they are therefore excluded from being able to place a bid. It is the responsibility of the individual municipality that the regulations for treatment of used textiles are complied with by the winner of the bid, this also includes complying with the waste hierarchy [7,p.7-8]. The waste hierarchy, as seen in figure 1.1, states what type of process is the most preferable to the least preferable in regards to the overall environmental impact the process will have that it has to go through [8,p.6].
Prevention is reduction of textile resource usage, and will therefore decrease the general textile demand and lead to less textiles being manufactured. The previous definition of reuse and recycling is still applicable to the waste hierarchy. Recovery and Disposal are both handling textile waste, however, recovery means recovering energy through incineration and disposal is either incineration without any energy recovery or it is landfilled. [9]

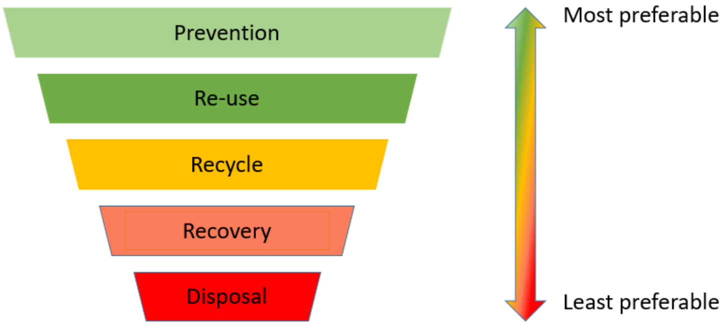

Figure 1.1: Waste hierarchy

The flows of used textiles in Denmark were mapped by Miljøstyrelsen (the environmental department) in 2016 in the article 'Kortlægning af tekstilflow I Danmark' [1,p.30]. It estimated that approximately 36,000 tons of used textiles were separately collected from households, and approximately 41,000 tons of textiles were directly incinerated in 2016 in Denmark. These incinerated textiles were collected as a part of mixed collection from small combustibles, bulky waste or household mixed waste, instead of being separately collected. Mixed collection is when a number of different waste fractions are collected through the same collection method, and then incinerated.
Currently, separate collection of used textiles in Denmark occurs through either bags, bins, or store collection. The collection of used textiles in bags is done in a few locations in Denmark, for municipalities by waste management companies (WMC), these being ARWOS and AffaldPlus. The bags are disposed of as part of paper and cardboard bins on a household level. These bags are then transported to the WMCs and sorted out of the other waste fractions. Some of the bags are being opened by the WMCs in order to pick the best quality reusable textile items for sale in their second hand shops, henceforth referred to as cherry picking. The remaining textiles are exported unsorted or partially sorted, while the sorted out waste is incinerated. The majority of NGOs have donation points, in form of bins, for used textiles at WMCs and in different cities throughout the country, and some have their own thrift stores where they also collect and sort used textiles. All

textiles that are not sold in stores, are exported, incinerated or landfilled. Trasborg is currently the only private actor in Denmark, who separately collects and partially sorts their used textiles, for either export, incineration or landfill. This collection happens through bins located throughout Denmark. Currently NGOs and private collectors in Denmark, solely wish to receive reusable textiles as this is currently the only textile type that is economically feasible to handle, as informed by multiple actors in the used textile industry in Denmark. Economic feasibility is defined by Cambridge as 'the degree to which the economic advantages of something to be made, done, or achieved are greater than the economic costs' [10], in this case it means, only the sale of reusable textile generate more income than handling costs required.
The flows of mixed- and separate-collection can be seen in figure 1.2 below.

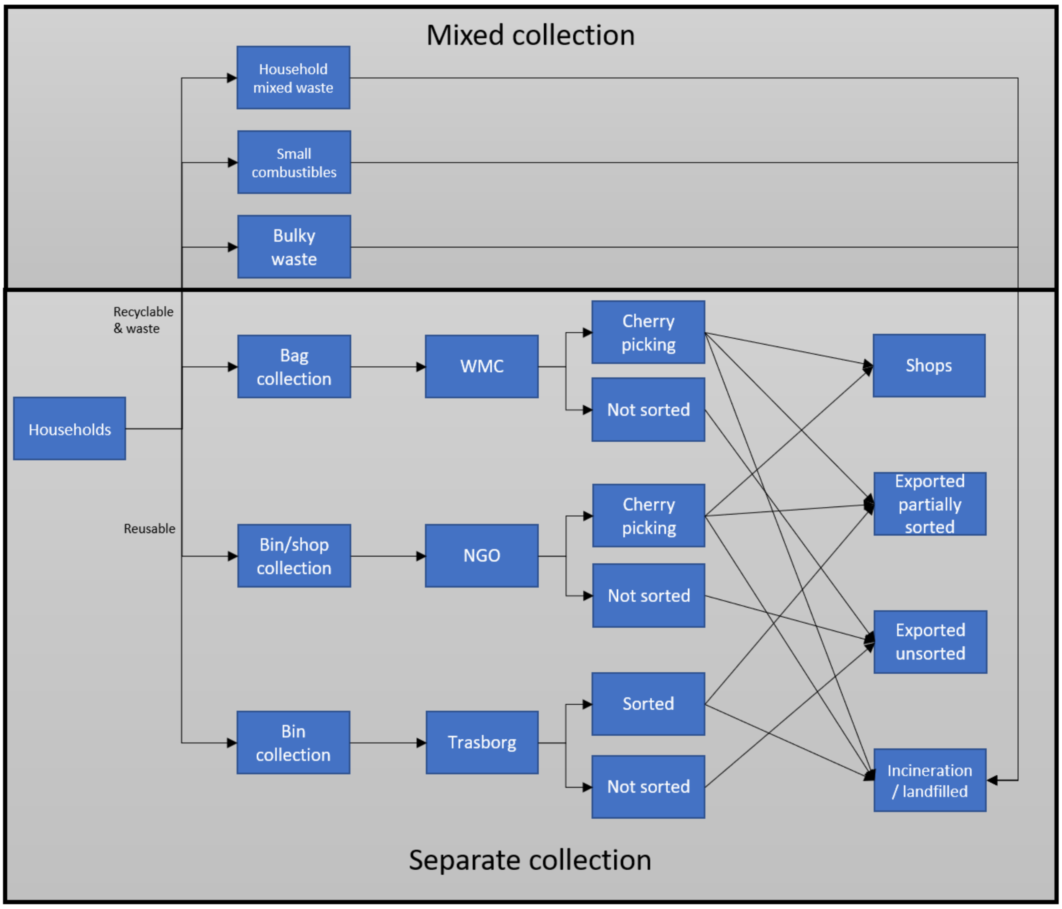

Figure 1.2: Current used textile flows in Denmark

From January 1st 2022, used textiles should no longer be found in the mixed collection. Therefore, this project will be based on the assumption that all used textiles are collected through a separate collection system, and that reusable textile are collected by NGOs or Trasborg. For the separate collection method for recyclables and textiles waste it was informed by Nikola Kiørboe, a used textile, circular economy and waste expert, that the bag collection was proposed to the Environmental Department to be implemented nation wide. The proposal is currently being reviewed, and a final decision on changes is expected sometime in 2021. This report will work with the assumption that this separate collection method for recyclables and textile waste is approved and implemented. Both of these assumptions are made as this project aims to aid the decision making regarding the options of handling recyclables and textile waste after the separate collection.

The following figure 1.3 shows the steps connected to the handling of recyclables and textile waste after separate collection. Before the used textiles can be recycled, they must be sorted. When handling recyclables and textile waste there are two levels that are commonly used, pre-sorting and sorting. Pre-sorting is the initial step of dividing collected used textiles into categories that are required by the sorting facilities in order to take in these textiles for further processing, and remove textile waste. There is currently only one actor in Denmark who pre-sorts a fraction of their collected textiles, this being Trasborg. The pre-sorting is done manually, as currently no technology exists to perform it automated. The third stage of sorting is the process of further dividing the pre-sorted textiles into different fiber compositions depending on the requirement of the recycling process. This is most commonly done by machine at automated sorting facilities, however there are currently no actors in Denmark who perform this process. The last stage of recycling the used textiles is handled by recycling facilities, there are currently no facilities that are operating in Denmark.

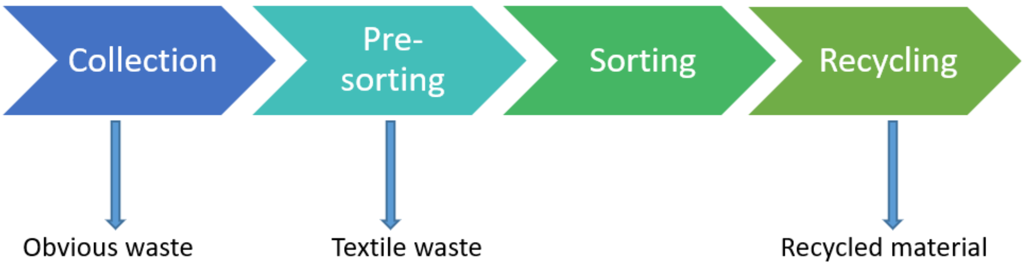

Figure 1.3: Stages from collection to recycling for used textiles

As previously described, it is assumed for this report that the method and responsibility of separate collection of recyclables and textile waste is determined. The placement of responsibility for the pre-sorting of used textiles has not yet been determined, which must be done before determining who has the responsibility of the textile sorting stage. Therefore, this report will focus on determining who will perform the pre-sorting of recyclables and textile waste in Denmark.

Currently, all recyclables and textile waste from Denmark that are not incinerated are sold and exported for pre-sorting or sale. In order to increase sustainability of the used textile system this pre-sorting should be kept within Denmark. This pre-sorting will also give the possibility to recycle these textiles instead of incinerating them, thereby following the waste hierarchy and increasing sustainability further. Sustainability is defined as 'The property of being environmentally sustainable; the degree to which a process or enterprise is able to be maintained or continued while avoiding the long-term depletion of natural resources' [11]. In regards to the used textile system, sustainability of the system means that it must be a long term solution, and not a quick fix of the current issue, while not exhausting natural resources. Keeping pre-sorting within Denmark would decrease the transportation, and recycling would decrease CO_2 emissions compared to incineration, and thereby the negative environmental impact. Additionally, keeping the pre-sorting of used textiles within Denmark can, according to a Swedish feasibility study, create jobs, which is a surplus to increasing sustainability [12,p.18]. No research has been done to find a solution to keep the pre-sorting process of recyclables and textile waste within Denmark or who is responsible for it. This report aims to fill this gap in the literature by determining if an economically feasible and sustainable solution is possible in Denmark.

Even though no research has been done regarding a solution for the pre-sorting in Denmark. There are initiatives regarding used textiles that have been started in other Nordic countries, which will be described in the following.

Used textile system initiatives

In order to increase the sustainability of the used textile industry, several initiatives have been started by different organizations and actors over the past years. Some of these initiatives are currently active whereas some have been terminated before finishing. One of these initiatives is the "Nordic textile reuse and recycling commitment" started by the Nordic Council of Ministers, which aims to decrease the negative environmental impact by increasing reuse and recycling of Nordic textiles, through collecting, sharing and establishing best practices. [13,p.9] Currently there is no system operator who is willing to take on this project, and therefore it has been on hold since 2017. Some of the individual Nordic countries have current national projects, for instance an automated sorting facility in Sweden (SIPTex) [14] and a semi-automated facility in Finland (LSJH) [15,p.64].
Another initiative is the SATIN project, which differs from the national projects as it has a focus on the collaboration between the Nordic countries, in order to achieve advantages by sharing resources and infrastructure. [16,p.1-2] The acronym SATIN is derived from the title of the research project, which is "Toward**S** **A** sus**T**ainable c**I**rcular system of textiles in the **N**ordic region". The overall goal of the SATIN project is improvement of the used textile system in the Nordic region moving towards a sustainable and circular used textile system. Its focus is therefore put on the mapping and evaluation of the current used textile system, and the development of cost-efficient collection solutions for increased collection rates. Furthermore, a circular network solution for the Nordic region should be designed to handle the increasing volumes of collected used textiles. They are investigating possibilities for shared network resources and centralized infrastructure between the Nordic countries in order to create a shared sustainable and circular used textile system. [16,p.1] Therefore, researchers from these countries collaborate with actors from different stages of the textile circular system, for example production, collection, reuse and recycling of textiles. In addition, specialists in supply chain management and simulation are taking part in the SATIN project. [16,p.7] This project is written as contribution to the SATIN project, and it is solely focused on the Danish pre-sorting system.
Based on the presented information, the following problem statement is developed in order

to guide the analysis.

1.2 Problem statement

Is it possible to design an economically feasible pre-sorting system with one or more facilities in Denmark and how large will the environmental impact be?

The following section will describe literature that is relevant for the problem statement, and through this methods that will be applied to answer the problem statement.

1.3 Literature review

The study of feasibility of setting up a sorting facility for used textiles is not a new field. Carlson et al. (2019) evaluate the feasibility of sorting textiles in Sweden [12,p.3], and they apply a financial feasibility analysis by calculating an estimated cost and estimated income per kilogram of sorted textiles. The study concludes that setting up a national sorting facility in Sweden is not financially feasible, as the estimated cost are higher than the estimated income [12,p.26]. In addition, different risk categories are suggested for the assessment of the feasibility of a sorting facility. No feasibility study has been carried out for the pre-sorting of used textiles in Denmark, however, the flows of used textiles in Denmark have been mapped by Watson et al. (2018), who determine the inputs and outputs of textiles to and from households, and identify the specific flows [1,p.30]. The current main used textile actors and the volumes of used textile these actors handle have been identified by Watson et al. (2014) [17,p.33]. Even though the field of used textiles has been studied, it has yet to be as thoroughly studied as other waste fractions. It also does not have a reverse logistic system implemented like other waste fractions in Denmark, such as plastic and cardboard.

Bing et al. (2012) investigate how to provide decision support for the flow of household plastic waste in the Netherlands by applying reverse logistics network design [18,p.1]. They developed scenarios that vary regarding the collection method and what type of plastic is collected [18,p.7-8]. To design the specific networks of the scenarios, the Mixed Integer Linear Programming (MILP) method is applied, with the goal of minimizing transportation cost and environmental impact [18,p.9-10]. In order to account for the environmental impact in the MILP, the amount of CO_2 emitted is converted into environmental cost of transporting plastic. To evaluate the environmental impact of the scenarios, the actual amount of CO_2 emissions is determined per scenario. The scenarios are then evaluated based on which has the lowest total cost of transportation and environmental impact. Alshamsi and Diabat (2015) also apply MILP [19,p.1] by formulating a model that aids in decision making when designing the reverse logistic network for consumer products. This particular model has the goal of maximizing the profit based on investment [19,p.3]. The results of the model aid in the decision making based on the cost of the different scenarios with the goal to maximize the profit when implementing the reverse logistic network.

When analysing scenarios, multiple criteria might be important for the evaluation, however not equally so, and therefore the relative importance of these must be evaluated. To do so a Multi-Criteria Decision Analysis (MCDA) can be applied. Furthermore, when applying

MCDA the overall performance of different scenarios can be determined, based on these criteria. There are a number of different MCDA methods that can be applied and the suitability of these will vary depending on the specific use case [20,p.2].

Challcharoenwattana and Pharino (2016) apply Analytical Hierarchy Process (AHP), which is a form of MCDA, to evaluate different recycling practices for municipal solid waste in Thailand and determine the optimal one regarding the ability to reduce cost, and willingness to recycle [21,p.1]. Milutinovic et al. (2017) set up scenarios for waste management in Nis, Serbia, and determine which is the best in terms of having the least negative environmental impact. Like Bing et al. (2012), also here the environmental impact is measured in CO_2 emissions, however further factors are included in this analysis like heavy metals and NH_3 emissions from biological processes. These scenarios are evaluated using a combination of Life-Cycle Assessment (LCA) and AHP. LCA is used to determine the environmental impact of the developed scenarios, called indicators, and AHP is used to evaluate and rank the scenarios according to the indicators. [22]

Methodology 2

This chapter will describe how the analytical methods that were identified through the literature review will be adapted and applied to this project along with other methods developed through knowledge from courses to answer the problem statement. It will further be described how the data was collected to conduct the research. Furthermore, the validity of the collected data will be evaluated.

2.1 Research framework

This section will describe the research framework of this project, meaning the theoretical plan for how the analysis will be conducted.
It was found that scenario analysis was used multiple times throughout literature in different fields to analyse different possible solutions for a problem. This is found suitable for the analysis of the used textile industry, as the pre-sorting of recyclables and textile waste in Denmark can be performed in a number of locations with varying capacities. Therefore, for the analysis of the pre-sorting possibilities in Denmark, the approach of scenario study will be used. Through the literature review, MILP was identified as a commonly used analytical method to determine the optimal solution of many possible combinations, with the goal of cost minimization or profit maximization. This is found to be a suitable analytical method to analyse the cost of pre-sorting in Denmark, as finding the solution with the minimum total cost will increase the likelihood of it being economically feasibility.
Furthermore, it was determined through the literature review that MCDA methods can be applied for evaluating identified scenarios performance by using multiple criteria. This is a suitable method to apply as the MILPs only has a focus on the criteria of cost, by minimizing the total cost of the scenarios, and considering different criteria might yield a different optimal solution.
The research framework for the analysis is below divided into 3 parts; preliminary analysis, scenario analysis and scenario evaluation, in which the applied analyses and used data will be described.

2.1.1 Preliminary analysis

Before analysing the scenarios the current used textile system must firstly be adequately described which will be done in the preliminary analysis. This leads to identifying and describing the shared inputs of the scenarios.
The level of required pre-sorting at any pre-sorting facility must be determined, as this will have an impact on all of the scenarios because they all have to comply with it. The current

used textile system in Denmark will be analysed to identify the actors who are currently handling textiles in Denmark, as they could potentially part take on the pre-sorting of recyclables and textile waste in the future, and thereby be a part of the scenarios of this report. The volumes of recyclables and textile waste that are currently and expected to in the future be in Denmark, must be determined to find the volumes there must be pre-sorted. Hereafter, the distribution within Denmark of these must be determined, in order to account for population distribution in Denmark when determining the transportation. Possible transportation modes will be analysed in order to identify the most suitable for the load and to decrease the cost of transportation. lastly, the costs connected to the different scenarios of pre-sorting in Denmark are investigated, in order to evaluate the economic feasibility and it will be determined how the environmental impact will be measured.

Based on this, the following 5 questions are proposed, which will guide the preliminary analysis.

1. What level of pre-sorting is required?
2. Who are the current actors in the Danish used textile system and can they pre-sort recyclables and textile waste?
3. What is the current and expected future volume of Danish recyclables and textile waste?
4. How is the volume distributed within Denmark?
5. What transportation mode is most suitable for the transport of recyclables and textile waste?
6. What costs are associated with having pre-sorting in Denmark and how is the environmental impact measured?

The level of pre-sorting will be determined through the requirements for the textiles of the following sorting process. This will be done by collecting literature and conducting interviews with possible sorting actors on the requirements of the sorting facilities and on the quantity of recyclables they can receive.

Through the literature review it was found that the current main used textile actors will be identified by Watson et al. (2014) [17,p.33], these 6 actors will be used throughout this report. Furthermore, interviews will be conducted with these identified actors to obtain knowledge on their current sorting level.

The overall volumes of recyclables and textile waste in Denmark are currently not mapped yearly, therefore the current volume of 2021 and expected future volumes can not be found in literature. To determine these volumes, historical data is used and to this a yearly average change in the collected used textiles must be applied. The historical data will be found in the report by Miljøstyrelsen (2018) [1,p.30], which documents the 2016 textile flows and volumes in Denmark divided by collection method and quality category. And the average yearly expected change in collected recyclables and textile waste will be found and applied to the historical data to find the future volume.

The volume distribution within Denmark will be determined by finding the recyclables and textile waste generated per capita. To do so it requires data on the population of the Danish municipalities, which will be found through the Danish statistics database on municipal population [23]. Furthermore, the total volume of recyclables and textile waste will be used as found through the previous question. This will further be divided into total volume per WMC by identifying what WMC services which municipalities through research on their websites.

To determine the most suitable transportation mode for used textiles within Denmark, the assumed average transportation distance and average load will be applied in a decision matrix of transportation mode choices presented by Baker et al. (2014) [2,p.412]. The size of the mode will then be decided based on a comparison of the required and available sizes, where the closest to the requirement will be chosen as it will yield the lowest cost.

When investigating different cost aspects associated to pre-sorting in Denmark, it will be divided into variable and fixed cost. The variable cost consists of transportation cost and employee wages, as these vary depending on the volume of recyclables and textile waste that is pre-sorted. The transportation cost is further divided into environmental and fuel cost, for the environmental cost the same approach as used by Bing et al. (2012) [18,p.12] is applied to convert the CO_2 emitted into monetary value, in order to take the environmental impact of a scenario into account in the MILP. Employee wages will be found through literature research on different employee wages in different regions of Denmark. The fixed costs consist of the renting cost for the potential facilities and the cost of expanding a current or opening a new facility, as this cost does not vary depending on the volume of textiles pre-sorted. Inputs to these cost calculations will be found through literature research and interviews. Lastly the environmental impact will be measured by finding the actual amount of CO_2 emitted per scenario, as it was done by Bing et al. (2012) [18,p.17].

2.1.2 Scenario analysis

In order to analyse possible solutions for the pre-sorting of recyclables and textile waste in Denmark, different scenarios must be developed as it was found through literature review. The information determined throughout the preliminary analysis will be used in addition to information found through interviews with experts in the used textile field, to set up different scenarios for the pre-sorting based on who performs it and where it takes place. The goal of this is to make it possible to find the optimal solution for the individual scenarios based on total cost.
Based on the current system, NGOs are not allowed to place a bid to perform the pre-sorting for the municipalities. However, if they partially privatize their organization and start paying VAT, they will be allowed to make a bid. The first scenario will therefore determine which of the NGOs are willing to make adjustments to be allowed to pre-sort recyclables and textile waste. Scenario 2 will have focus on setting up new pre-sorting facilities in Denmark, to give the MILP more facility location choices, which could decrease the total cost of the pre-sorting system. The third scenario will include both the current and new facility locations determined through scenario 1 and 2, and thereby create a hybrid of the two, to analyse if this will decrease the total cost. A listing of these three scenarios can be seen below.

- Current system with adjustments (Scenario 1)
- New pre-sorting facilities (Scenario 2)
- Hybrid scenario (Scenario 3)

For the scenario analysis, the following questions are defined to aid the analysis. The methods applied to answer them are described based on what was identified in the literature review.

7. What are possible locations for pre-sorting facilities?
8. What are the optimal locations and capacities for pre-sorting facilities and what is the total cost of this?
9. What is the excess capacity?
10. How much CO_2 is emitted?

When determining possible pre-sorting facility locations, different approaches will be taken for the different scenarios. For the first scenario, interviews will be conducted with the relevant actors in the field, to determine if they have any interest in making adjustments to their business. The possible pre-sorting facility locations will be based on actors' interests in making the required adjustments. The possible locations for scenario 2 will be determined based on the population centers within the regions of Denmark. For scenario 3 the possible locations will be the combination of the locations were identified in scenario 1 and 2.

The fixed- and variable-costs of the possible pre-sorting facilities will be used as an input to the MILP, to determine what the optimal locations and capacities for the pre-sorting facilities are. The MILP has the goal to minimize the total cost of the pre-sorting in order to increase its likelihood of economic feasibility. The MILP is formulated through an objective function which calculates the total cost of a scenario. Thereby the MILP minimizes the total cost by changing specified decision variables in order to comply with a set of predetermined constraints. This means that the MILP compares all possible combinations within the limits set by the constraints for a scenario, to find the optimal one for the objective function. The result of the objective function will be the minimum cost of the optimal solution. This will be executed using Excel software, in an add-in called solver, this add-in has a limited capacity of 200 for the amount of variables it can include.

Through the constraints of the MILP, excess capacity will be enforced by setting a minimum capacity limit, the amount of excess capacity varies depending on what locations the scenarios choose to open and at what sizes. This constraint will be set to ensure that the capacity of the facilities will be able to pre-sort future volumes.

To determine how much CO_2 is emitted from the scenarios, the environmental cost calculation used by Bing et al. (2012) [18,p.12] which was introduced in the literature review, is converted to find the CO_2 emitted. However, from the environmental cost formula the price per ton of CO_2 emitted is removed as the emission is needed and not the price of it.

2.1.3 Scenario evaluation

As the third part of the analysis, the scenarios will be evaluated, which is necessary to determine which of the possible scenarios is the most optimal on other criteria than solely cost. For this evaluation, a MCDA method is applied as introduced in the literature review. Through literature it was found that AHP is a commonly used MCDA method, e.g. by Challcharoenwattana and Pharino (2016) [21,p.1] who apply it in the waste management

industry. The AHP method also accounts for the consistency of its inputs [24,p.1], and for these reasons it is found suitable and will be applied for this analysis. The AHP method can be summarized in four steps. In the first step, relevant criteria will be determined through interviews with relevant actors and experts in the field of used textiles. Furthermore, literature will be reviewed to support these criteria and possibly identify new ones relevant to this project. In the second step the relative importance of the identified criteria will be determined using a pairwise comparison, which requires input from experts. This will result in a ranking of the criteria based on their relative importance. Thereafter, the different scenarios will be ranked based on their performance for each of the criteria in pairwise comparisons. In the last step an assessment will be made using the relative weight of the criteria and the rankings of the scenarios. This step will conclude which of the analysed scenarios scores the best. Throughout these steps a consistency ratio (CR) will be calculated, which evaluates the consistency of the input information.
After determining the most optimal scenario based on the chosen criteria, it must be determined if this scenario is economically feasible, and lastly barriers and benefits there are associated will be identified and described. Based on this the following questions are posed and the required methods to answer them are described using information and methods from the literature review.

11. What criteria are most suitable for evaluation of the scenarios?
12. How are these criteria ranked in terms of importance?
13. Which scenario scores the best using these criteria?
14. Is the optimal scenario economically feasible?
15. What are barriers and benefits associated with the optimal scenario?

To use the AHP for the scenarios, different criteria must be identified and ranked by their relative importance. This is done through interviews with an expert in the field to ensure that the inputs and importance is correlating with how it actually is within the field. Through the AHP a single scenario will be determined as being the best, however this scenario will not necessarily be economically feasible. This will therefore be evaluated by comparing the total cost of the system to the potential income generated through sale of recyclables, which will lead to a conclusion on whether the scenario is economically feasible or not. The evaluation will conclude by summarizing the results of the optimal scenario by highlighting the barriers and benefits that the scenario will bring.

After describing the analytical methods required to answer the problem statement throughout the research framework, the following subsections will describe the data collection and validity for this project.

2.1.4 Data collection

The data collection of this report is conducted using the following methods: literature research, interviews and secondary data collection.

If the required information is publicly available, it is collected through literature research or secondary data collection like Science Direct. Both quantitative and qualitative data was collected by reviewing different literature, such as reports on the used textile system in Denmark and its flows and volumes as described in the Danish report 'Kortlægning af tekstilflows i Danmark' by Miljøstyrelsen [1,p.30]. If the data is not publicly available then it is necessary to contact the actors or experts in the fields and conduct interviews, these were held with different actors within the textile industry, such as Kaj Pihl of UFF and Steen Trasborg who is CEO of Trasborg. Some of these interviews were held through Microsoft Teams, using the semi-structured format, which means that questions were prepared in advance but it was possible to ask additional questions that might arise during the interview. The remaining were structured interviews and conducted through e-mails, where questions were formulated and sent. Through the interviews both quantitative and qualitative data was collected. An example of qualitative data collected is information on whether the current actors are interested in making adjustments to their business to pre-sort recyclables and textile waste. Quantitative data for example the employee productivity when pre-sorting used textiles.

2.1.5 Data validity

Assessing the validity of the data used for the project is a critical step, as using invalid data will lead to the outcome of the analysis being invalid, meaning it will be unusable. In order to validate the collected data there has to be identified potential outliers and errors, and the source of the data has to be evaluated as well. If the data contains a substantial amount of errors, the validity of the used data should be questioned. This could lead to dismissing the data, and thereby new data would have to be collected and validated. The data validation process varies depending on whether the data is quantitative or qualitative.

Validating quantitative data is done by identifying errors like outliers or missing values, meaning notable deviates from the collected data. Here quantitative outliers were found in the yearly used textile generation of Denmark [25]. The data point were inconsistent with information received from actors in the field, and the source was therefore excluded as using it would lead to an invalid result. Another outlier was identified in the Danish mapping of used textile flows, here a figure published in two different languages, from the same department has two different volume of used textile for the same flow. It is assumed that there was a typing error, and therefore the source that is deemed valid had to be chosen. As the original and published source is the Danish report, therefore, this is assumed to contain the correct number, and the quantity from this source is used throughout the report.

When evaluating the validity of qualitative data, the source of the data and its credibility must be assessed. A source is deemed credible and therefore the retrieved data is deemed valid when the source is experienced in the field. An experienced source is for example Danish authorities, or experts in the field with years of experience. Through this report the Danish waste expert Nikola Kiørboe was consulted, and her information was deemed valid as she has years of experience in the waste and used textile industry.

Where possible, used data has been validated through a data validation process and the results of this report are therefore deemed valid.

Preliminary analysis 3

This chapter will describe the inputs that are shared between the scenarios MILPs. This is done by firstly determining the level to which the used textiles have to be pre-sorted to. This leads to an introduction of the current actors in the Danish used textile system, and a determination of whether they are capable of pre-sorting to the specified level. Thereafter the volume required to be pre-sorted is determined per region, here including recyclables and textile waste. Next the capacity options for a pre-sorting facility is determined, as well as the space required for these facility options. Thereafter the transportation mode and size is chosen based on which will be least costly and closest to the amount of used textiles there on average has to be transported weekly. This leads to calculating the cost of pre-sorting textiles which is determined using inputs in the form of variable- and fixed-cost factors.

3.1 Required pre-sorting level

The pre-sorting of used textiles can be done to different levels of detail, depending on the requirements of the following processes the pre-sorted textiles are to go through. These requirements have to be determined, because they have to be achieved during pre-sorting in order to get the textiles further sorted in the next step. Automated sorting facilities further sort the pre-sorted textiles in the next step, and therefore they set the required level of pre-sorting for them to take in the recyclables and textile waste. Their requirements are determined in the following.

Currently, there are 2 automated sorting facilities in the Nordics, one is located in the south-west of Finland, and it is operated by the public waste management operator Lounais-Suomen Jätehuolto Oy (LSJH). And one is in the south of Sweden is called SIPTex, which stands for Swedish Innovation Platform for Textile sorting, and it is operated by the municipal waste management company Sysav.

The required level of pre-sorting is defined by the requirements of the individual automated sorting facilities, the definitions of these requirements, whom they are defined by and in what literature can be seen in appendix A.1. In order to determine, which of the 2 sorting facilities will sort Danish recyclables, their free capacities must be looked at. The Finish sorting facility LSJH informed, that the capacity is currently full. The Swedish facility SIPTex has a total sorting capacity of 24,000 tons per year, and they are willing to receive international feed-stock, if it fits their business operations. Because SIPTex is the only automated sorting facility in the Nordics that can receive volumes from Denmark, it is assumed that the pre-sorted textiles will be sent here. Due to this, their requirement for pre-sorting will be used throughout this report. This being 'accepting pre-sorted recycling fractions from manual sorting', this results in pre-sorting in Denmark having to divide into three categories. These categories are; textile waste, which will be incinerated or landfilled in Denmark, reusable textiles, will be given back to the NGOs and recyclable textiles, which will be sent for further sorting at SIPTex.

3.2 Current actors in Denmark

In order to gain a more detailed overview of the used textile system in Denmark, the actors within it have to be determined. Watson et al (2014) identifies the following 6 actors, based on the collected volume of used textiles per year, as the main actors who separately collects used textiles in Denmark; Trasborg, Red Cross (Røde Kors), Salvation Army (Frelsens Hær), UFF, DanChurch Social (Kirkens Korshær), and Danmission [17,p.33]. These 6 actors are responsible for the separate collection of approximately 60% of the Danish used textiles. The remaining 40% are collected by various small organizations, meaning that each of them is responsible for only a small share of Danish used textiles. Therefore, the 6 identified main collectors will be used for the further analysis.
All 6 actors separately collect used textiles trough bins and shops, however the sorting processes differ between the organizations. None of the actors sort the entirety of their collected volume, but export parts of it unsorted to customers in Europe or in other locations around the world. The remaining fraction of the collected used textiles is sorted within Denmark at different levels depending on the organization, which in the table below is referred to as handled. An overview of the identified actors and their total volume of collected- and handled-textiles can be seen below in table 3.1.

Table 3.1: Collected and pre-sorted volumes of actors in Denmark

Actor (year)	Collected textiles [tons]	Handled [tons]
Trasborg (2014)	5,700 [26,p.38]	1,492 [26,p.38]
Red Cross (2019)	8,319	5,343
Salvation Army (2014)	5,750 [26,p.38]	2,012 [26,p.38]
UFF (2014)	1,467 [26,p.38]	N/A
Danmission (2014)	1,000 [17,p.33]	x
DanChurch Social (2014)	5,000 [17,p.33]	x

As previously described, Trasborg is the only actor in Denmark who pre-sorts a fraction of their collected used textiles. Trasborg has 1 sorting facility in Taastrup (E) in the region of Hovedstaden, where currently 10 employees handle the collected used textiles. The remaining 5 actors cherry pick the best quality textiles from what they collect. Red Cross has 2 sorting facilities, one in Køge (D) in the region of Sjælland and one in Horsens (A) in the region of Midtjylland , where the collected textiles are cherry picked. These cherry picked textiles are further sorted into categories for sales in the shop. The volumes as seen in the table above were informed by Claus Nielsen, who is the section leader of the reuse centers of Red Cross. Salvation Army operates 2 sorting facilities, one in Hvidovre (F) in the region of Hovedstaden and one in Kolding (B) in the region of Syddanmark where the collected textiles are cherry picked. Danmission operates a sorting facility in Vejle (C) in the region of Syddanmark, where a part of the collected textiles are cherry picked, but the volumes are unknown which is therefore noted as x in the table. UFF does not have a sorting facility in Denmark, meaning that none of their collected volume is handled in

Denmark but that all their collected used textiles are exported, which is therefore noted as N/A in the table. DanChurch Social does also not have a sorting facility in Denmark, but cherry picks part of their collected used textiles in their shops, the volumes of this are unknown and is therefore noted as x in the table. There is no information available on the number of sorting employees from actors besides Trasborg. The locations of the sorting facilities can be seen in the following figure 3.1, where the letters A-F correspond with the cities as described above.

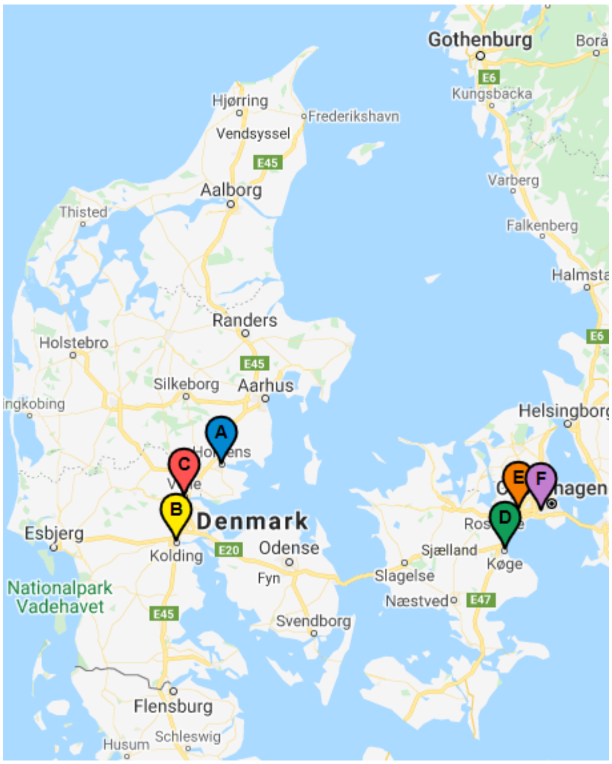

Figure 3.1: Current locations of sorting facilities

The current actors in the Danish used textile system with their current capacities can at the moment not handle the entire volume of textiles they collect. Furthermore, majority of the actors do not have a pre-sorting process, but they cherry pick. Because pre-sorting is a more detailed process than cherry picking it will require more time or more resources per ton handled, and it can therefore be assumed that the current used textile system will not be able to pre-sort the recyclables and textile waste.

After the current main actors in the used textile system are identified, the next step is to determine the volumes of recyclables and textile waste that have to be handled by the pre-sorting facilities in the new system.

3.3 Volume of recyclables and textile waste

To determine the quantity of used textiles there must be pre-sorted, the quantities of recyclables and textile waste must be determined. These quantities are determined using data from the report by the Danish environmental department from 2016, which contains ratios for specific flows of used textiles [1,p.30]. This is the most recent published report on Danish used textile quantities, and is therefore applied for this analysis. The following figure 3.2 shows the overview of textile flow from this report.

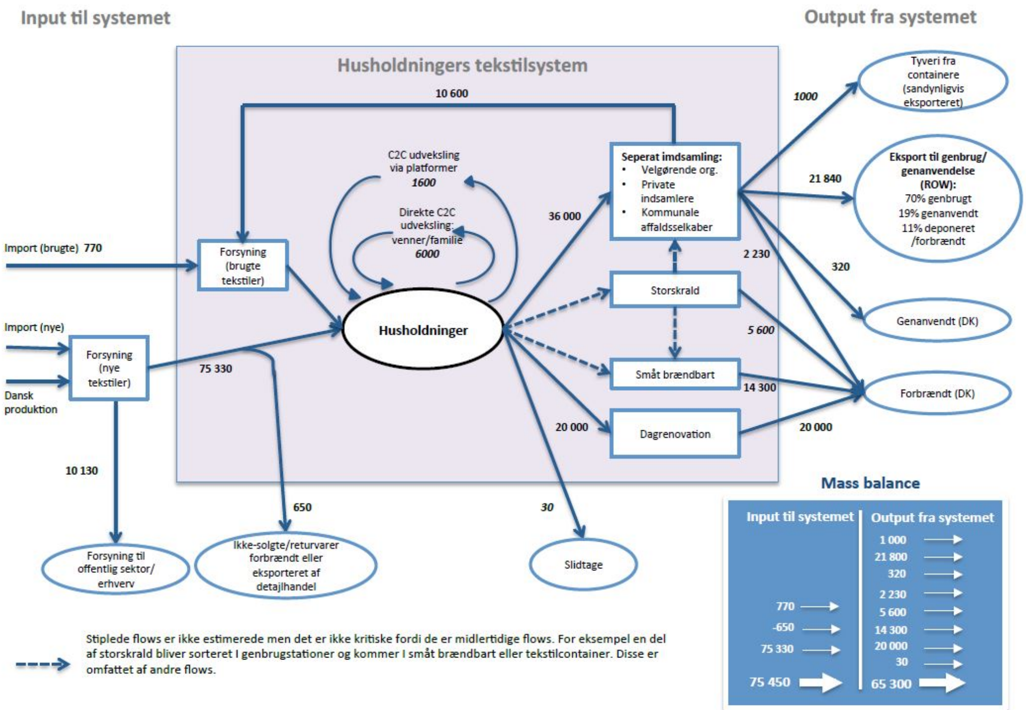

Figure 3.2: Textile flow in Denmark in tons (2016) [1,p.30]

In figure 3.2 above, ratios of different used textile quality levels can be found, which shows that from separate collection 19% of exported textiles are recycled [1,p.30]. These ratios are multiplied with the total volume of that specific flow of separate collection, which is 21,840 tons, and the amount of recyclables and textile waste is thereby determined. Additionally, the flow from separate collection to recycling in Denmark must be added, which is 320 tons, as these will also be pre-sorted in Denmark.
Furthermore, the amount of recyclables and textile waste from mixed collection must be determined. Here the report states that from the incinerated textiles approximately 23% are reusable and 26% are recyclable, and an additional 37% of textiles could be recycled in the future [1,p.5]. For this report it is assumed that the additional 37% of textiles which can be recycled in the future must also be handled by the pre-sorting facilities. These 37% are included as they no matter what will go through the pre-sorting, if they cannot be recycled they will end up as textile waste instead. It is however throughout the report assumes that they are recyclables. Therefore, a total of 63% of recyclables will be multiplied with the total combined volume of incoming textiles to incineration, which is 39,900 [1,p.5]. This leads to the following calculation of the total quantity of recyclables, that can be seen in the equation 3.1 below.

$$21,840\ tons * 19\% + 320\ tons + 39,900\ tons * 63\% = 29,606.60\ tons \quad (3.1)$$

As seen in the equation above the total amount of recyclables there must be pre-sorted in

Denmark is 29,606.60 tons.
The next step is to determine the quantity of textile waste and add this to the quantity of recyclables, as this also will be pre-sorted with the recyclables. From separate collection 11% are either landfilled or incinerated [1,p.30] of the total 21,840 tons, the volume of 39,900 tons from mixed collection to incineration contains 14% waste [1,p.5], and there is a last flow of textile waste from separate collection to incineration, which is 2,230 tons. This leads to the calculation 3.2 below, using these ratios and quantities.

$$21,840\ tons * 11\% + 39,900\ tons * 14\% + 2,230\ tons = 10,218.40\ tons \quad (3.2)$$

From equation 3.2 it can be concluded that a total quantity of 10,218.40 tons of textile waste must be pre-sorted. The sum of the two calculated volumes is now determined, $29,606.60\ tons + 10,218.40\ tons = 39,825\ tons$, and thereby a total of 39,825 tons of recyclables and textile waste must be pre-sorted.

Additionally to the recyclables and textile waste, some reusable textiles will most likely be put in the bag, because of either user error or from wrong judgement regarding quality of the used textiles. From the WMC ARWOS, who is responsible for the bag collection of used textiles in the municipalities Aabenraa and Padborg, it was informed that on average 11% of the bags content are reusable textiles. This information was found through a test sample made in 2016, and the daily operations leader estimates that this number is still accurate representation of the current ratio. The division between the quality of the collected textiles can be seen in figure 3.3 below.

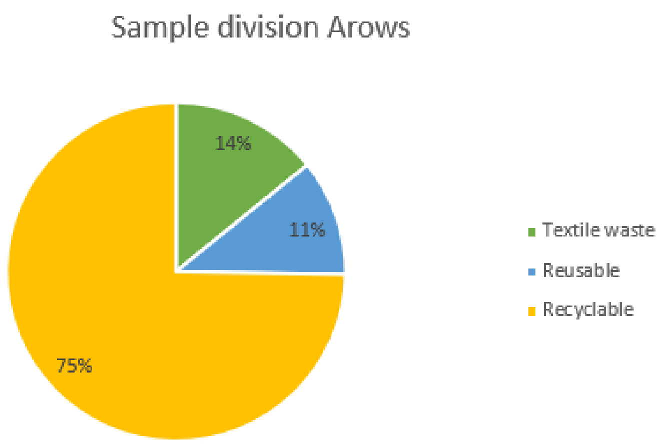

Figure 3.3: Sample size 2016 ARWOS

As it is known that approximately 11% of what is collected through bags are reusable textiles, this must be added to the 39,825 tons of recyclables and textile waste. From equation 3.3 below, it can be seen that this results in 44,206 tons of textiles in total that must be pre-sorted.

$$39,825\ tons * 111\% = 44,206\ tons \quad (3.3)$$

This means, that during the pre-sorting process these 4,381 tons of reusable textiles have to be sorted out during the pre-sorting along with the 10,218.40 tons of textile waste.

As the data used to calculate this total volume is from 2016, the current volume has to be determined by considering the yearly change in used textiles in Denmark. Furthermore, in order to ensure that the new used textile system will be able to cope with future volumes, this yearly change must then be applied to the current volume to determine the future volumes.

3.3.1 Current and future volumes

The expected yearly increase of used textiles is determined using historical data on the quantities of used textiles. Data on textile collection in Denmark is limited as seen in Eurostats' report on the historical quantity of used textiles collected in Denmark [25]. Here Eurostat reported that 1 ton of used textile was collected in 2004, which increased to 26,854 tons in 2018. Furthermore the yearly increase between 2004 and 2018 is nonlinear, as it varies from -39.91% to 3,447.62% which gives a yearly average growth of 642.56%. This does not correspond with information given by actors in Denmark, who have experienced a much smaller yearly increase in the volume of used textiles. For this reason the Danish data can not be used to give a reliable indication of the yearly expected increase in collected used textiles in Denmark.
Due to this, a different country who has this data available that is economically similar to Denmark, will be chosen and this data will be applied throughout this analysis. To determine if the country is economically similar to Denmark, a measure of median annual household income will be used. Here Denmark has the 5th highest income at 270,525.24 DKK/household and is the closest to the USA who has the 6th highest income at 265,809.29 DKK/household [27]. The USA does have data available on collection of used textiles from the United States Environmental Protection Agency (US EPA) dating back to the 1960's, and therefore this will be used. Using the data from the US EPA, the following table 3.2 is made which highlights the increase of used textiles in the US [28].

Table 3.2: Used textiles collected in the US (1990-2018)

Year	Collected textiles [tons]	Yearly growth
1990	5,810,000	
2000	9,480,000	$\frac{(9{,}480{,}000-5{,}810{,}000)}{5{,}810{,}000}/10 = 6.32\%$
2005	11,510,000	$\frac{(11{,}510{,}000-9{,}480{,}000)}{9{,}480{,}000}/5 = 4.28\%$
2010	13,220,000	$\frac{(13{,}220{,}000-11{,}510{,}000)}{11{,}510{,}000}/5 = 2.97\%$
2015	16,060,000	$\frac{(16{,}060{,}000-13{,}220{,}000)}{13{,}220{,}000}/5 = 4.30\%$
2017	16,890,000	$\frac{(16{,}890{,}000-16{,}060{,}000)}{16{,}060{,}000}/2 = 2.58\%$
2018	17,030,000	$\frac{(17{,}030{,}000-16{,}890{,}000)}{16{,}890{,}000} = 0.83\%$

As seen in the table above, the yearly increase in used textiles varies depending on the year, between 0.83% and 6.32% yearly. Using this data, an average yearly increase can be found for the past 18 years from 2000 to 2018. This calculation is as follows, $\frac{(17{,}030{,}000-9{,}480{,}000)}{9{,}480{,}000}/18 = 4.42\%$, and thereby a yearly increase in used textiles is found to be 4.42%. An increase of 4.42% per year is therefore added to the volume of 44,206 tons of used textiles in Denmark, throughout this project.

In order to determine the current volume, 4.42% is added yearly from 2016 to the current year 2021, the results can be seen in the following table 3.3. A total volume of 54,878 tons used textiles, has to be pre-sorted in 2021 is found, and this will be used throughout the report as the current volume of used textiles. According to an expert at a used textile seminar hosted by Dakofa, the expected volume of recyclables and textile waste is approximately 50,000 tons in 2021. If the added 11% of reusable are removed from the total volume, 54,878 tons * 89% = 48,841 tons, then the predicted- and actual-volume almost correlate, thereby validating using the 4.42% yearly increase.

Table 3.3: Calculation of expected textile volume for pre-sorting

Year	Collected textiles [tons]
2016	44,206.00
2017	44,206.00 + (44,206. * 4.42%) = 46,160
2018	46,159.91 + (46,160 * 4.42%) = 48,200
2019	48,200.17 + (48,200 * 4.42%) = 50,331
2020	50,330.62 + (50,331 * 4.42%) = 52,555
2021	**52,555 + (52,555 * 4.42%) = 54,878**
2022	52,555 + (52,555 * 4.42%) = 57,304
2023	57,304 + (57,304 * 4.42%) = 59,837
2024	59,837 + (59,837 * 4.42%) = 62,481
2025	62,481 + (62,481 * 4.42%) = 65,555
2026	**65,555 + (65,555 * 4.42%) = 68,127**

In addition to the current volume for 2021, the future expected volumes of the next 5 years are calculated. It is assumed that there is a yearly increase in the amount of used textiles collected in Denmark, and therefore, the capacity of the pre-sorting system should be able to cope with a higher volume than solely the 2021 volume, to factor in sustainability of the system. However, according to Nikola Kiørboe the yearly increase is likely to change as there are initiatives being developed to decrease the amount of used textiles generated in Denmark, which should be implemented sometime in the near future. To take this expected future decrease into account and thereby lower the risk of wasting resources, 5 years of extra capacity is chosen to be used, which means in 2026 a total of 68,127 tons of recyclables and textiles waste must be pre-sorted. This required a pre-sorting system established in 2021 to have an excess capacity of: $68,127\ tons - 54,878\ tons = 13,249\ tons$. Excess capacity is only considered for the work space of the facilities, and not for the number of employees or machines, as it is assumed that the facilities would hire employees and purchase equipment as needed over the years.

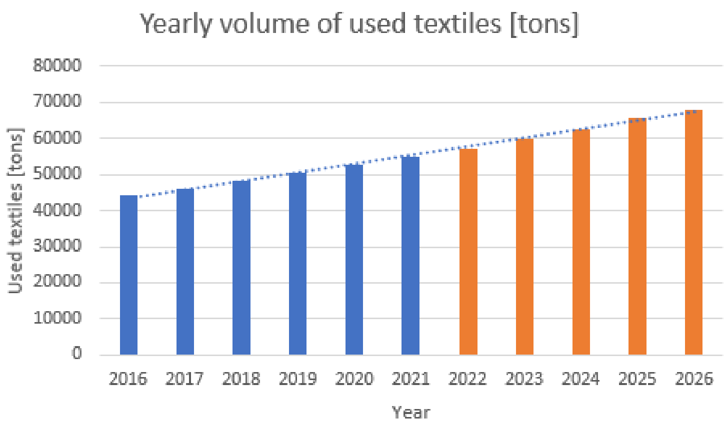

Figure 3.4: Increase in used textiles volume from 2016 - 2026 [tons]

Figure 3.4 above is a depiction of the yearly increase of used textiles in Denmark, from 2016 to 2026. All years until 2021 are blue and the future volumes from 2022 to 2026 are orange.

The volume of used textiles is not evenly distributed throughout Denmark, and therefore this will looked into in the following subsection.

Distribution of volume within Denmark

In order to aid the decision making regarding the location of pre-sorting facilities in Denmark, the current volume distribution of recyclables and textile waste must be determined. This distribution is found per WMC as they carry out the collection. To do so the total current volume of recyclables and textile waste of 54,878 tons is divided by the number of people in the Danish population to get the average amount of recyclables and textile waste per person in 2021. The calculation can be seen in the following equation 3.4, where 'R' stands for average amount of recyclables and textile waste per Danish person per year.

$$R\ (tons) = \frac{Future\ volume\ of\ recyclables\ and\ textile\ waste\ (tons)}{Number\ of\ people\ in\ the\ Danish\ population}$$
$$= \frac{54,878\ tons}{5,856,227\ people} = 0.00937\ \frac{tons}{person} \quad (3.4)$$

Hereafter, the volume of used textiles per municipality per year is found by multiplying the municipal population, which is found through Danish statistics database on the Danish population [23], with the 0,00937 tons/person. The respective data and calculations can be seen in the attached appendix B.1 in sheet 'Municipalities & volumes'. In this sheet the result of the volume of recyclables and textile waste per municipality can be seen.

Hereafter, it is determined which of the WMCs has the responsibility of collecting waste from which of the 98 municipalities. The data on what WMC serve what municipality is found by reviewing each of the municipalities publicly available information, from this 68 WMCs are found that serve the 98 municipalities of Denmark. This information is used to calculate the volume of recyclables and textile waste each WMC has to collect. The MILP is executed through the Excel solver software, which has a limit of 200 variables, seeing as there are 68 WMCs this limit may be exceeded if all WMCs are included, depending on the number of possible pre-sorting facilities. The volume of recyclables and textile waste is therefore found per region, by dividing the WMCs into regions and adding up the yearly volumes. The results of this can be seen in the following table 3.4, and the calculations can be seen in the attached appendix B.1 in sheet 'WMC & volumes'.

Table 3.4: Current volumes per region [tons]

Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
5,532.95	12,731.31	10,698.83	8,013.18	17,382.98

After determining the volume per region, that the pre-sorting facilities will have to handle, the capacity options for establishing pre-sorting facilities are determined.

3.4 Capacity options for pre-sorting facilities

Different options for capacities in pre-sorting facilities must be set, to limit the number of variable inputs to the MILP, to ensure that it does not exceed the limit. To do so, 5 different capacities are chosen as options for possible pre-sorting facilities. The low capacity facility is determined based on information available about the existing facility, Trasborg, where currently 10 employees are pre-sorting textiles, which is assumed to be a low-capacity facility. This number of employees multiplied with the expected employee productivity in pre-sorting. As informed by Steen Trasborg from Trasborg, who did a pilot project on pre-sorting recyclables and textile waste collected by the municipality Rødovre, 1 employee is able to pre-sort approximately 1,200 kg of textiles per 7-hour workday. For the further analysis, it is therefore assumed that 1,200 kg of textiles can be pre-sorted per employee. Using this productivity of 1,200 kg per workday and 254 as the amount of workdays per year results in a low capacity pre-sorting facility to sort 3,048 tons/year. The high capacity facility is assumed to be able to handle the total amount of recyclables and textile waste from Denmark, which means a total capacity of 54,878 tons/year. The average of low and high capacity gives a medium capacity facility, and following the same approach low/medium- and medium/high-capacity facility are determined. The results of this can be seen in the following table 3.5, these are the facility capacities that the MILP can choose between when determining the size of facilities.

Table 3.5: Capacities of the facility options [tons]

Facility size	Low	Low/medium	Medium	Medium/high	High
Capacity	3,048	16,006	28,963	41,921	54,878

After determining the capacities of possible pre-sorting facilities, the required space of these is calculated as this impacts the cost of the facility.

3.4.1 Space required per capacity option

In order to calculate the space that is required per capacity option for the pre-sorting, it is assumed that 17.5 m^2 of work space is required per employee. This work space is determined based on the minimum work space for one employee, which is approximately 10 m^2 [29]. However, these 10 m^2 only account for the actual work space, and to this 7.5 m^2 are added as space for equipment, inventory, and extra facilities e.g. bathrooms, break rooms and offices.

With the minimum work space required per employee determined, the space per capacity option can be calculated using the following equation 3.5.

$$Required\ space\ = \frac{Capacity}{Employee\ productivity * workdays} * \ Required\ m^2\ per\ employee \tag{3.5}$$

The results for the required space per facility for the different capacity options can be seen in table 3.6 below.

Table 3.6: Required space of the facility options [m^2]

Facility	Low	Low/medium	Medium	Medium/high	High
Space	175.00	918.95	1,662.91	2,406.86	3,150.82

After the different capacity options and space requirements have been determined, the transportation mode to transport the recyclables and textile waste to the facilities must be chosen.

3.5 Choosing transportation mode

Which transportation mode should be used is determined based on the cost connected to the delivery distance, and the required size of the transportation mode. An overview of the modes which are available, that will yield the lowest cost compared to the distance traveled and size of the mode, can be seen below in figure 3.5.

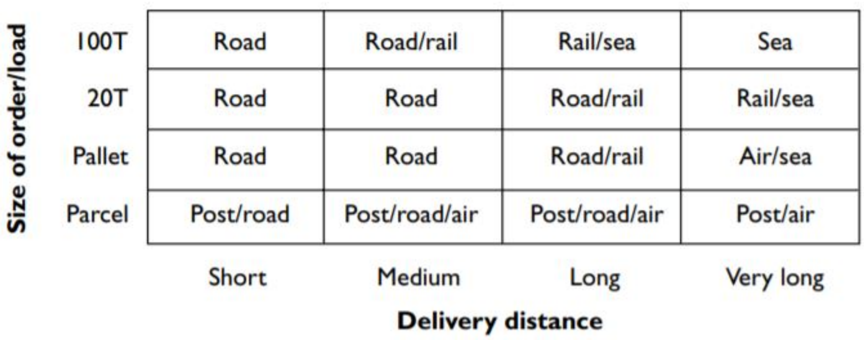

Figure 3.5: Transportation mode choice [2,p.412]

To determine what transportation mode is most optimal, the delivery distance must firstly be determined. The bags with recyclables and textile waste have to be transported from the location where they are separated from the cardboard and paper, to a pre-sorting facility. The starting points of transportation for the collected bags are determined to be the addresses of the waste management companies (WMC) that handles waste fractions for the municipalities. The delivery distance in Denmark is therefore assumed to be short as Denmark is a small country.
The size requirement of the transportation mode will vary depending on the frequency of them. The frequency of transportation may also vary depending on the specific WMC. For example a WMC servicing a high population municipality, will quickly exceed the amount of bags one transportation can carry and therefore, might require a more frequent transportation to minimize inventory cost. Contrary to this, a WMC servicing a lower population municipality might require less frequent transports of textiles to ensure that each transportation is fully utilized. It is not possible to have a variable frequency depending on the WMC in the MILP, and therefore a uniform frequency will be used assuming this will to some degree average out varying frequencies required from small and large municipalities. In this report the frequency of transportation is assumed to be once a week for all transports, as it is assumed that the inventory of a WMC for recyclables and textile waste is reached after one week of collection.

The average transportation load for each WMC is determined by dividing the yearly amount of recyclables and textile waste from each WMC by 53 weeks. The sum of these averages which is 1,035.44 tons per week, is then used as input to the following equation 3.6.

$$\begin{aligned} Average\ load\ of\ transportation\ &= \frac{Sum\ of\ average\ transportation\ per\ week}{Number\ of\ WMCs} \\ &= \frac{1,035.44\ tons/week}{68\ WMCs} = 15.23\ \frac{tons/week}{WMC} \end{aligned} \tag{3.6}$$

Equation 3.6 calculates the average transportation volume, and this equals to 15.23 tons of recyclables and textile waste. This volume is closest to the 20 tons volume in the figure 3.5, and this is used to determine the most optimal transportation mode. As the delivery distance is short and size of transportation is 20 tons, the most suitable transportation mode is on road, and due to the size of the loads using trucks is most suitable.

Determining the specific truck that will be used to transport the goods depends on the amount of textile it will transport and the loading and unloading method there should be used. The loading and unloading method excludes some common truck type such as curtain trucks and box trailers. These are excluded as they require the textiles to be packaged, and it can not be assumed that all municipalities have the required equipment available, and it will also require additional processing from the municipalities. The loading and unloading of textiles must not require a large amount of additional processing for both the municipality and the pre-sorting facility, as this would otherwise increase the cost of operations. Furthermore, it can not be assumed that all WMCs or pre-sorting facilities will have access to the same equipment, and therefore the option which require the least processing is picked. A truck loading method that does not require extra equipment and can therefore be used by all WMC is to transport the textiles in containers, which the textile bags can be placed in without use of extra equipment.

Waste management companies already use containers when storing certain waste types, and therefore it can be assumed that they have the equipment necessary to handle the loading and unloading of containers on the trucks. Containers can also be tipped for easy unloading using tipping trailers for the trucks [3], as depicted in figure 3.6 below.

Figure 3.6: Tipping container truck [3]

Container trucks are therefore chosen as the transportation mode, these containers come in two standard sizes with lengths of 20 feet and 40 feet. Only one container will be considered throughout this report and the container which is the best fit to transport the average weight of 15.23 tons will be used. This is determined in the following equations 3.7, by multiplying the internal sizes of the container as found in literature [30].

$$\begin{aligned} 20\ feet\ container\ volume &= 5.90m * 2.35m * 2.39m = 33.14\ m^3 \\ 40\ feet\ container\ volume &= 12.03m * 2.35m * 2.39m = 67.57\ m^3 \end{aligned} \tag{3.7}$$

Now that the volume of the two different containers is found, the amount of textiles that can fit into these must be determined, for this a density of 0.15 $tons/m^3$ for textiles is used [31,p.13]. This density is multiplied with each of the containers volume, to find the total load; 20 feet: $33.14m^3 * 0.15tons/m^3 = 4.97\ tons$, 40 feet: $67.57m^3 * 0.15\ tons/m^3 = 10.14\ tons$.
The 40 feet container with its 10.14 tons capacity is closest to the average weight of transportation which is 15.32 tons. Therefore the 40 ft container is chosen as the size of the transportation mode to limit the number of trucks required.

After determining the most suitable transportation mode and truck size for the transportation of recyclables and textiles waste, the next step is to investigate the economy of the system.

3.6 Costs of the pre-sorting system

Evaluating the economic feasibility requires to determine the fixed- and variable- costs that are associated with pre-sorting recyclables and textile waste, and the possibility of generating income from doing so.

3.6.1 Variable costs

Variable costs mean the costs that vary depending on the volume of recyclables and textile waste being pre-sorted, in this report these are transportation cost and employee wages.

Transportation cost

Within transportation cost there are 2 factors that are considered in this report, these being cost of fuel and the environmental cost. The inputs to the calculations of these factors will be explained to then be used in the scenario analysis.

Environmental cost
The first part of the transportation cost is the environmental cost which is added to account for the CO_2 emissions of the various options of the MILP. How environmental cost is calculated can be seen in the the following formula 3.8.

$$E_c = \frac{Price\ of\ EU\ carbon\ allowances\ (DKK/ton)}{1,000\ (kg/ton)} * \frac{Carbon\ equivalent\ conversion\ factor\ (kgCO_2e/l)}{Fuel\ efficiency\ (km/l)} \tag{3.8}$$

For the formula above, the input of price of EU carbon allowances is determined using the current price on the EU market, which as of 16/04-2021 is 44.08 €/ton which equals to 327.83 DKK/ton of CO_2 emitted [32]. Dividing by 1,000 kg/ton, This is converted into DKK/kg. Both the fuel efficiency and the carbon equivalent conversion factor vary depending on the truck used and the gross weight of the transportation, and therefore these will be determined in the following. The carbon equivalent conversion factor describes how many kg of CO_2 are emitted when per one liter of fuel.

The carbon equivalent conversion factor varies depending on the truck and the weight of a truck load. The truck will carry 10.14 tons of textiles and the container weighs 3.75 tons [30]. The truck itself weighs between 4.5 tons and 11.3 tons, and as no specific truck can be determined, the average weight of 7.9 tons will be used [33]. This therefore leads to a gross weight calculation of: $10.14\ tons + 3.75\ tons + 7.9\ tons = 21.79\ tons$. This results in using a conversion factor for Heavy Goods Vehicles (HGV) with a weight that exceeds 17 tons, from which the average load conversion factor is 0.18306 $\frac{kgCO_2e}{tons}$. This is then multiplied with the maximum goods weight of 10.14 tons, and the carbon equivalent conversion factor is determined to be 1.86 $kgCO_2e$ [34].

Now that all inputs to the environmental cost have been determined, the resulting equation can be seen in equation 3.9 below, and the environmental cost per km is determined to be 0.33 DKK/km for a fully loaded truck.

$$\frac{327.83\ DKK/tons}{1,000\ kg/ton} * \frac{1.86\ kgCO_2e/l}{1.82\ km/l} = 0.33\ DKK/km \tag{3.9}$$

When transporting a container back from a pre-sorting facility to the origin point it will weight 10.14 tons less as it is not filled. The carbon equivalent conversion factor for this transport is 0.77 $kgCO_2e/l$ [34], leading to the following equation 3.10, and an environmental cost of 0.14 DKK/km.

$$\frac{327.83\ DKK/tons}{1,000\ kg/ton} * \frac{0.77kgCO_2e/l}{1.82\ km/l} = 0.14\ DKK/km \tag{3.10}$$

CO_2 emission

The environmental impact was chosen to be measured through CO_2 emissions as this is a relevant metric for the scenario evaluation as it is a more commonly used method to measure this than environmental cost. The CO_2 emissions will be measured through the consumption of fuel required, the total distance in km, and the carbon equivalent conversion factor. To determine this, the following equation 3.11 is applied, which is derived from the previous environmental cost formula 3.8.

$$CO_2\ total = CO_2\ loaded + CO_2\ empty$$

$$\begin{aligned} CO_2\ total = &\frac{Carbon\ equivalent\ conversion\ factor\ (loaded) * total\ km\ driven}{Fuel\ efficiency} \\ &+ \frac{Carbon\ equivalent\ conversion\ factor\ (empty) * total\ km\ driven}{Fuel\ efficiency} \end{aligned} \tag{3.11}$$

This equation uses the size of the truck and the weight of a truck load to determine how many $kgCO_2$ are emitted per liter of fuel by using carbon equivalent conversion factors. The formula also requires the total distance traveled for each scenario, and the fuel efficiency of the truck. The calculation is done for both loaded and empty trucks, as the conversion factors vary depending on the weight, and both parts have to be calculated in order to determine the total amount of CO_2 emitted. The weight of the truck load when filled has previously been calculated being 10.14 tons, and the weight when the truck is empty will be 0 tons. This thereby leads to a carbon equivalent conversion factor of 1.86 $kgCO_2e/l$ for loaded trucks, and 0.77 $kgCO_2e/l$ for empty trucks.

Fuel cost

The second part of the transportation cost is fuel cost, which is determined through the cost of the fuel used to transport the recyclables and textile waste from the WMCs to the pre-sorting facilities. This cost is determined using equation 4.4 below.

$$Fuel\ cost\ =\ \frac{km\ driven}{Fuel\ efficiency\ *\ Fuel\ price} *\ 2 \tag{3.12}$$

It is assumed that the chosen trucks use diesel, and the price of 1l diesel is 10.59 DKK/l as of 23/04-2021 [35]. The chosen trucks have a fuel efficiency of 1.82 km/l [36,p.5], meaning that they can drive 1.82km using 1 liter of fuel. These inputs are used in equation 4.4 along with the km driven, which will be determined through the MILP. The result of this is multiplied by 2, in order to take the distances into account both ways.

Employee wages

There are 3 different types of employees that will be included in the variable costs of the scenarios, the employees who perform the pre-sorting, the managers who run the facilities and the drivers of the trucks. The inputs to the calculations of these wages will be explained to then be used in the scenario analysis.

Pre-sorter wage

To make it possible to determine the number of pre-sorters required to sort the 54,878 tons of recyclables and textile waste in 2021, it has to be determined how much 1 employee can pre-sort. It was informed by Steen Trasborg, the CEO of Trasborg, that 1 employee is able to pre-sort approximately 1,200 kg in one workday which is 7 hours, this employee productivity will be used throughout the report.

To determine the hourly wage for one pre-sorter in Denmark, the average hourly wages for each region must be determined, as the pre-sorting facilities can be located in different regions and therefore the wages will differ. It is assumed that unskilled employees will be hired for the pre-sorting, as no special education is required, except learning to differ between recyclables, reusables and textile waste. The minimum wage of the industry sector is used as the baseline wage for a pre-sorter, which is 123.25 DKK/hour for an unskilled employee [37]. To determine the differences in wages for the different regions, the average annual salaries for unskilled employees from 2018 are used. The lowest average wage is found in Nordjylland [38], which is therefore used as the baseline to calculate the difference between the average wages for the remaining regions in percentage. This percentage difference is then added to the hourly wage of Nordjylland for each region, in order to determine the expected hourly wage for one pre-sorter in each region. The results for hourly pre-sorter wages for the different regions can be seen in table 3.7 below.

Table 3.7: Average hourly wage per pre-sorter per region [DKK/hour]

Region	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
% difference	0%	2.82%	1.96%	19.68%	18.95%
Hourly wage	123.25	126.73	125.66	147.51	146.61

To ensure that the units are the same when doing the MILP, the hourly wage has to be converted into wage per ton pre-sorted per employee, the equation used for this can be seen below in 3.13.

$$Pre-sorter\ wage\ per\ ton = \frac{Hours\ per\ workday}{Employee\ productivity} * Hourly\ wage \quad (3.13)$$

The results per region from this calculation can be seen below in table 3.8. These inputs are used in the MILP to determine the wage of the pre-sorters required per facility for the pre-sorting of recyclables and textile waste.

Table 3.8: Average wage per pre-sorter per region [DKK/ton]

Region	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
Wage per ton	718.96	739.23	733.05	860.45	855.20

Production manager wage

When operating a pre-sorting facility, production managers are required to ensure continuous daily operations without disturbances. Determining how many production managers are required for the different facilities is based on the number of pre-sorters one manager can oversee. This decision is made based on information received from Steen Trasborg, at Trasborg their production manager can manage 50 employees if the manager has 4 team leaders. The team leaders at Trasborg participate in the sorting process, and mainly fine-sort the textiles. However, the textiles at the pre-sorting facilities of this project would not have to be sorted to this level, but rather pre-sorted into the three predefined categories. For this reason it is assumed that one production manager at the pre-sorting facility can manage 25 employees, it is furthermore assumed that there will be no team leaders at these facilities.

The next step is to determine the average wage of a production manager depending on the region they are working in, which can be seen in table 3.9 below. These inputs are used in the MILP to determine the wage of the production managers required per facility to oversee the pre-sorting of recyclables and textile waste.

Table 3.9: Average monthly wage per production manager per region [DKK/month][4]

Region	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
Monthly wage	36,470	38,300	42,200	36,125	44,725

Now that the number of employees one production manager can manage and their wage has been determined, the next step is to determine the cost of the production manager in DKK/ton of textiles, to align the units for the MILP. To do so, firstly the productivity of a production manager is calculated. This is done by multiplying the productivity of a pre-sorter with the number of pre-sorters one production manager oversees, this is thereafter divided by the number of hours in the shift of a production manager. This calculation can be seen below in equation 3.14, which shows that the productivity of 1 production manager is 4.29 tons/hour.

$$Production\ manager\ productivity\ =$$

$$\frac{1.2\ tons/workday\ *\ 25\ pre-sorters/manager}{7\ hours/workday}\ =\ 4.29\ tons/hour \quad (3.14)$$

This productivity is now used with the monthly production manager wage broken down to DKK/hour, in order to calculate the production manager wage per ton. An example of this calculation can be seen below in equation 3.15 for a production manager at Red Cross on Sjælland, who has a wage of 56.9 DKK per ton of textile pre-sorted.

$$Production\ manager\ wage\ per\ ton\ =\ \frac{\frac{36{,}125\ DKK/month}{21\ workdays/month\ *\ 7\ workhours/day}}{4.29\ tons/hour}\ =\ 56.9\ DKK/ton \quad (3.15)$$

This is done for all potential facilities, and the results can be seen in the following table 3.10

Table 3.10: Average wage per production manager [DKK/tons]

Facility	Trasborg	Red Cross (S)	Red Cross (M)	Salvation Army (H)	Salvation Army (Sd)
Wage per ton	70.4	56.9	60.3	70.4	66.5

Driver wage

The number of required drivers for the transportation of the recyclables and textile waste can not be determined for the scenarios due to a number of different unknown factors, such as the actual frequencies of transports, the number of drivers employed per WMC, and the duration per transport. However, to calculate the wage for a truck driver, the average wage per km driven in Denmark is used, because the total wage depends on the number of km driven which might differ between the scenarios. The price per km used in this report is 7.5 DKK/km when driving in Denmark [39]. The driver wage also has to be calculated per ton of transported textile, to ensure that all inputs to the MILP have correlating units. To do so, the following equation is used 3.16.

$$Driver\ wage\ =\ \frac{(\ Km\ driven\ *\ Driver\ wage\ per\ km\ )}{Truck\ load} *\ 2 \quad (3.16)$$

For this calculation it is required to know how many km have to be driven. This will be multiplied with the driver wage per km, the total of this will then be divided by 10.14 tons, which is the weight of one truck load. Finally this is multiplied with 2 to find the wage per ton for both ways driven. This calculation will be applied in the MILP, to find the driver wage when the total km driven to and from the pre-sorting facilities is found.

3.6.2 Fixed costs

Fixed costs are costs that will not change depending on the number of goods produced, meaning in this context the volume of recyclables and textile waste that is pre-sorted. In this project the fixed costs that are taken into account are renting cost, and opening and expansion cost.

Renting cost

Throughout this report it is assumed that the pre-sorting facilities will be rented instead of owning the building, this assumption is made to make it possible to include the cost of the facility itself. The renting cost is found per m^2 and then multiplied by the required m^2 for the size of a given facility. This calculation is used in the MILP to determine the fixed costs of the pre-sorting facilities, and will vary depending on the facility locations and sizes.

Opening and expansion cost

When opening a new facility or expanding an existing one there will be some cost associated with it. When opening up a new facility, an assumed opening cost of 500,000.00 DKK is added to the total cost per facility that has to be opened, this price includes expenses such as the deposit when renting a facility, and the purchase of new equipment required for the pre-sorting processes. If an existing facility is chosen for pre-sorting, it is assumed that an expansion of the facility is required and therefore an expansion cost of 200,000.00 DKK is added to the total cost per facility that has to be expanded. These costs are used in the MILP through the objective function, after it has been determined how many facilities should be opened, and whether they are existing or new ones.

3.7 Sub-conclusion preliminary analysis

The requirements for the pre-sorting were determined to correlate with the requirements of SIPTex in Sweden, as they are the only automated sorting facility in the Nordics who can currently receive volumes from Denmark. These requirements are that they only receive manually pre-sorted recyclables, meaning that reusables and textile waste are removed. It was further determined that the current 6 main actors being, Trasborg, Red Cross, Salvation Army, UFF, Danmission and DanChurch Social cannot currently pre-sort the recyclables and textile waste of Denmark, as they do not handle the entire volume of their collected textiles.

The current volume of recyclables and textile waste was determined using 2016 data from literature and applying a yearly increase of 4.42%, resulting in 54,878 tons of recyclables and textile waste in 2021. The future volume for the 5 following years was hereafter found by further applying the yearly increase. The volume distribution was identified both per WMC and per region, this was determined by applying the total generation of recyclables and textile waste per municipality.

The most suitable transportation mode was found to be tipping container trucks with a possible load weight of 10.14 tons.

When investigating the costs associated with having pre-sorting in Denmark, it was found that it is divided into the 2 parts of variable- and fixed-costs, which consist of different factors. Variable costs are divided into transportation cost, meaning environmental and fuel cost, and employee wages, meaning pre-sorter, production manager, and driver wages. The fixed costs consist of the renting cost, and opening and expansion cost. The environmental impact of the scenarios is measured through CO_2 emissions, however it is also accounted for in the MILP through the environmental cost.

This concludes that the questions for the preliminary analysis proposed in the research framework were answered, and therefore the preliminary analysis is concluded. The following chapter will develop the MILP for the first scenario which will use the inputs determined throughout this chapter to find the best solution using existing facilities.

Scenario 1 4

This chapter will analyse the first scenario, which is the current state of used textile system with adjustments leading to more actors being able to pre-sort collected recyclables and textile waste. This is done by identifying the current actors who are willing to make these adjustments, in order to determine their current facility locations. This leads to determining the inputs to the MILP which consists of the variable- and fixed-costs. Thereafter the objective function, decision variables and constraints are formulated for the MILP and it is then executed using the determined inputs, the results, future costs, and CO_2 emission will be presented.

4.1 Current system with adjustments

In this section it will be evaluated which of the current used textile actors are willing to make adjustments in order to be able to pre-sort the recyclables and textile waste. The actors that are investigated are the 6 main actors identified in the preliminary analysis in section 3.2, and the information is collected through interviews. The adjustment that the actors are questioned on is; privatizing part of their activities to accommodate the legislative pre-sorting requirement.

There are currently 2 actors who are legally allowed to bid on the pre-sorting process, these being Trasborg and Salvation Army. Trasborg is the only existing private actor in Denmark for collection and sorting of used textiles. Steen Trasborg has provided information that if noticeable and long-term financial support from the Danish government is provided, then Trasborg would be interested in receiving and pre-sorting recyclables and textile waste for the municipalities.

Gert Pedersen, who is chief of reuse for Salvation Army, informed that Salvation Army already pays VAT which means they are allowed to make a bid and pre-sort the recyclables and textile waste without having to make further adjustments. It was furthermore informed that if there is an economic incentive, they have an interest in participating in the pre-sorting of recyclables and textile waste as well.

Claus Nielsen, who is a section leader at Red Cross, informed that Red Cross' primary focus is on reusable textiles. However, they would be interested in investigating the possibilities of participating in the pre-sorting for the municipalities. For this reason Red Cross is considered a possible pre-sorting actor of recyclables and textile waste in this scenario.

Kaj Pihl who is an environment and recycling advisor for UFF informed that currently, UFF does not have any sorting facility in Denmark, but they are evaluating setting up a facility in Denmark. This facility would be small and only be used for the textiles they

collect themselves, and he does not believe that UFF will be interested in pre-sorting recyclables and textile waste for the municipalities. Therefore, UFF will not be considered as a possible pre-sorting facility throughout this scenario.
Jannie Zillig who is leader of reuse and sales at Danmission was contacted twice and asked about the possibility of making adjustments to Danmission to be able to pre-sort the recyclables and textile waste, however no answer was received. Based on this, the assumption is made that Danmission is not interested in making the required adjustments, and therefore is not included further in this scenario.
Dorthe Hansen, who is chief of reuse at DanChurch Social, informed that they have no interest in making adjustments in order to pre-sort recyclables and textile waste. She argues this as they are exempt from paying VAT, and have no plan on changing this, which makes the pre-sorting impossible, and that their focus is on the collection and sale of reusable textiles.
Through the interviews with the main actors in Denmark, 3 were identified as potential pre-sorting actors of recyclables and textile waste; Trasborg, Salvation Army, and Red Cross. Currently Trasborg has 1 sorting facility, Red Cross has 2 and Salvation Army also has 2. These actors, their 5 facilities and their locations can be seen in the following table 4.1.

Table 4.1: Possible facility locations S1

Nordjylland	**Midtjylland**	**Syddanmark**	**Sjælland**	**Hovedstaden**
-	Red Cross (Horsens)	Salvation Army (Kolding)	Red Cross (Køge)	Trasborg (Taastrup)
-	-	-	-	Salvation Army (Hvidovre)

For this scenario it is assumed that the pre-sorting will take place at the same address where the facilities are currently located at, this assumption is made as existing facilities are required for this scenario. However it was not possible to determine their current capacities or number of employees, meaning it cannot be identified how much these locations have to expand by. Due to this, the assumption is made that only the locations of the existing facilities will be used for the pre-sorting and that it is possible to expand the current facility to any required size. For these possible sizes, the 5 capacity options described in the preliminary chapter in section 3.4 are used in this analysis.

With the possible pre-sorting facilities identified, the next step is to determine the inputs to the MILP. The MILP has the goal to find the location combination with the lowest total cost, while complying with given constraints.

4.2 Inputs to MILP

The methods to determine the inputs there will be used in the MILP have been described throughout the preliminary analysis in chapter 3, these methods and calculations described will now be applied to this scenario. Therefore, both variable and fixed costs are calculated in the following.

4.2.1 Variable costs

As described in the preliminary chapter, the variable costs consist of two main parts, transportation and employee cost, these will be analysed in the following.

Transportation cost

In order to calculate the transportation cost, firstly all distances between origin points and possible pre-sorting facility locations for this scenario have to be found. There are 68 WMCs responsible for the collection of waste in Denmark, from January 1st 2022 this includes recyclables and textile waste as a separate fraction. These WMCs are therefore viewed as the origin point for the transportation of these textiles to the pre-sorting facility. The first step in determining the transportation cost is to find the distances between each WMCs and the possible pre-sorting facilities. To do so the address of each WMC is found, and the distances between these and the 5 possible pre-sorting facilities are determined using the Google Maps platform, the results can be seen in the attached appendix B.1 in sheet 'MILP Scenario 1'.
The Excel software used to execute the MILP can only contain 200 variables. If all 68 WMCs, 5 capacity options, and 5 potential pre-sorting facilities are included, $(68\,WMCs + 5\,\textit{capacity options}) * 5\,facilities = 365\,variables$, a total of 365 variables would be required. Therefore the number of variables should be decreased, to do so the 5 regions of Denmark are used as origin points of the recyclables and textile waste. Therefore, the determined distances from all WMCs to all possible pre-sorting facilities have to be aggregated per region. To do so the average number of km driven from each region to each of the potential facilities must be calculated, for this, the number of trips required to be taken must firstly be determined. This is calculated based on how many fully loaded trucks are required to transport each WMCs total yearly volume from their location. Therefore, the yearly volume of each WMC is divided by the volume of one full truck load, which was determined to be 10.14 tons as described in the preliminary chapter in section 3.5. The results are rounded up in order to account for fractional trips, meaning a trip always have to be completed, and it can be seen in the attached appendix B.1 in sheet 'MILP Scenario 1'. Then the total amount of trips required per region is determined by adding the results of all WMCs within one region, and the results can be seen in the following table 4.2. This means for example that from the region of Nordjylland 549 trips have to be taken to transport all recyclables and textile waste generated in Nordjylland, no matter which facility it is pre-sorted at.

Table 4.2: Number of trips required from each region S1

	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
Trips	549	1,261	1,119	793	1,723

The weighted km is calculated in order to account for the varying frequency of trips and loaded weight of the WMCs. By accounting for this WMCs who serve a smaller population, e.g. Læsø which only requires 2 transports a year with its yearly volume of 16.53 tons. This trip distance should not be weighted equally to e.g. København which requires 590 trips a year. To determine the weighted km for each region, these distances have to be added together for all WMCs within one region to each of the possible pre-sorting facilities, using the following equation 4.1.

$$Weighted\ km \ = \sum\left(\frac{Number\ of\ trips}{Total\ trips\ of\ region} * \ Distance\right) \tag{4.1}$$

The calculations of the weighted km can be seen in the attached appendix B.1 in sheet 'MILP Scenario 1', and the results an be seen in the following table 4.3. These results mean, that for example a truck on average has to drive 402 km from Nordjylland to the facility of Trasborg in Hovedstaden.

Table 4.3: Weighted km per facility per region S1

to/from	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
Trasborg (H)	402	298	217	51	34
Red Cross (S)	391	276	194	42	51
Red Cross (M)	178	70	97	222	265
Salvation Army (H)	418	303	223	60	27
Salvation Army (Sd)	210	102	59	186	235

The weighted km from regions to possible pre-sorting facilities are used to calculate the fuel and environmental cost per ton of transported textile from a region to a pre-sorting facility.

Environmental cost

Firstly, the environmental cost of transportation is calculated, based on the CO_2 emissions of the chosen transportation mode. It is assumed, that the trucks are driving the calculated number of weighted km twice, once loaded from the region to the pre-sorting facility, and once empty back to the region. This means that the environmental cost of transportation consists of 2 parts, one with loaded trucks and one with empty trucks, which have to be added together in order to determine the total environmental cost of transportation, this can be seen in the following equation 4.2.

$$Environmental\ cost \ = \frac{(\ E_c\ loaded\ *\ weighted\ km\ +\ E_c\ empty\ *\ weighted\ km\ )}{Truck\ load} \tag{4.2}$$

In the preliminary chapter in section 3.5 the environmental cost per km driven with a full load was determined to be $E_C = 0.33$ DKK/km, and $E_C = 0.14$ DKK/km is used for distances driven with no load. By multiplying these costs with the weighted km, adding the results together, and dividing this by 10.14 tons which is one full truck load, the environmental cost per trip is determined. An example of this calculation can be seen below in equation 4.3 using the transportation from Nordjylland to Trasborg (N-T), meaning it will cost 18.63 DKK to transport one ton of recyclables and textile waste in environmental cost.

$$Environmental\ cost\ (N-T)\ =$$

$$\frac{0.33\ DKK/km\ *\ 402\ km\ +\ 0.14\ DKK/km\ *\ 402\ km}{10.14\ tons}\ =\ 18.63\ DKK/ton \tag{4.3}$$

Fuel cost

As the second part of the transportation cost, the fuel cost is calculated for each weighted km. For this calculation, the fuel efficiency of 1.82 km/l and the fuel price of 10.59 DKK/l, which were both determined in the preliminary chapter in section 3.6.1 is used. In order to determine the transportation cost per transported ton of recyclable and textile wasre, the result of this calculation is then divided by 10.14 tons, which is the amount of tons transported per full truck load. The calculations and results can be seen in the attached appendix B.1 in sheet 'MILP Scenario 1'. The following equation 4.4 shows the calculation of the fuel cost per ton for a round trip from Nordjylland to Trasborg (N-T), meaning that it costs 461.67 DKK in fuel to transport 1 ton of recyclables and textile waste.

$$Fuel\ cost\ (N-T) = \frac{(\ \frac{420\ km}{1.82\ km/l\ *\ 10.59\ DKK/l}\ *\ 2\ )}{10.14\ tons}\ =\ 461.67\ DKK/ton \tag{4.4}$$

Employee wages

Another part of the variable cost is the wages of employees, this includes pre-sorters, production managers and drivers. The pre-sorting and production manager wages have been determined in the preliminary chapter in DKK per ton of recyclables and textile waste pre-sorted, per region where they are working. When executing the MILP, it will be determined how large of a volume each opened pre-sorting facility should sort. These volumes will then be multiplied with the wages identified for the pre-sorter and production manager per ton sorted, to determine the total pre-sorter and production manager wage. The driver wage per ton of recyclables and textile waste transported is found by inputting the weighted km found previously for the respective facility option into the previously described equation 3.16 in the preliminary chapter in section 3.6.1.

After determining the transportation cost and employee wages for all combinations of each region and each possible pre-sorting facility, the total variable cost can be calculated by adding the determined sub-costs together. The results can be seen in the following table 4.4 below, which will be used as inputs to the MILP.

Table 4.4: Variable costs per facility per region S1 [DKK/ton]

	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
Trasborg (H)	2,001.03	1,722.75	1,506.69	1,060.75	1,015.57
Red Cross (S)	1,962.67	1,654.32	1,437.13	1,030.86	1,052.99
Red Cross (M)	1,275.08	985.62	1,057.99	1,394.19	1,508.35
Salvation Army (H)	2,042.13	1,735.35	1,521.71	1,085.96	998.54
Salvation Army (Sd)	1,361.09	1,071.12	957.65	1,296.03	1,428.74

These results mean for example if 1 ton of textiles from Nordjylland is pre-sorted at Trasborg, then it will cost 2,001.03 DKK in variable cost, consisting of fuel-, environmental-, production manager-, pre-sorter- and driver-cost.

Now that the total variable cost per facility per region has been decided the next step is to specify the fixed costs associated with scenario 1.

4.2.2 Fixed costs

The fixed cost in this context consists of the cost of renting the facilities there is used for pre-sorting and the opening and expansion cost. As described in the preliminary analysis, it is assumed that all actors will rent the number and sizes of facilities that are assigned to them by the MILP. Therefore, firstly the average renting cost for 1 m^2 has to be found for each of the cities where the current facilities are located. This is done by finding an available location with the required space in each of the cities, and using the m^2 price of this for the analysis, these m^2 prices used in the analysis can be seen in the following table 4.5.

Table 4.5: Average renting cost per facility S1 [DKK/m_2]

Facility	Price
Trasborg (H)	400
Red Cross (S)	439
Red Cross (M)	365
Salvation Army (H)	597
Salvation Army (Sd)	360

In order to calculate the total renting cost per possible pre-sorting facility, the required space for the different capacity options, there was determined in the preliminary chapter in section 3.4, is used. This required space is multiplied with the determined renting cost for 1 m^2 in every city where a facility is located, this results in the total renting cost per facility per capacity option. These results can be seen in the following table 4.6, and the calculations can be found in the attached appendix B.1 in sheet 'MILP Scenario 1'.

Table 4.6: Fixed cost per facility per capacity option S1 [DKK/year]

	Low	Low/medium	Medium	Medium/high	High
Trasborg (H)	70,000.00	367,591.86	665,160.76	962,752.62	1,260,321.52
Red Cross (S)	76,825.00	403,432.07	730,013.94	1,056,621.01	1,383,202.87
Red Cross (M)	63,875.00	335,427.58	606,959.19	878,511.77	1,150,043.39
Salvation Army (H)	104,475.00	548,630.86	992,752.44	1,436,908.29	1,881,029.87
Salvation Army (Sd)	63,000.00	330,832.68	598,644.69	866,477.36	1,134,289.37

These results means for example if a low capacity facility is at Red Cross in Midtjylland, then a fixed cost of 63,875.00 DKK/year will be the fixed cost of a facility with low capacity at this location.
In addition to these renting costs, an expansion cost of 200,000 DKK is added as an input to the MILP, this cost is an estimated one time investment necessary when an actor is changing an existing facility to a pre-sorting facility. As the total expansion cost of this scenario depends on the number of facilities there will be opened, which is decided by the MILP, the expansion cost is added to the MILP as a part of the objective function, and thereby included in the total cost.

After the variable cost and the fixed cost of this scenario are determined, the next step is to formulate the MILP so that it determines the most optimal number of presorting facilities to open and their locations while minimizing the total cost. This will be described in the following.

4.3 MILP scenario 1

The MILP is modeled in three parts which are a set of decision variables, an objective function which connects the decision variables to the desired outcome, and constraints which limits the amount of suitable solutions. These parts make up the model formulation by inputting the data found in the previous steps and then the MILP will be executed, using Excel Solver. In the following the inputs, decision variables, objective function, and constraints can be seen, hereafter these will be further described. All MILP calculations for this scenario can be found in the attached appendix B.1 in the sheet called 'MILP Scenario 1'.

Inputs used in the MILP:

$$
\begin{aligned}
&n \quad = \; Number\ of\ potential\ pre-sorting\ facility\ locations\\
&m \quad = \; Number\ of\ WMC\\
&D_j \quad = \; Annual\ volume\ from\ region\ j\\
&Df_j \; = \; Future\ annual\ volume\ in\ 5\ years\ from\ region\ j\\
&K_i \quad = \; Capacity\ of\ facility\ i\\
&c_{f_i} \quad = \; Annual\ fixed\ cost\ of\ keeping\ facility\ i\ open\\
&c_{v_{ji}} \quad = \; Variable\ cost\ of\ transporting\ and\ pre-sorting\ 1\ ton\ of\ textiles\\
&from\ region\ j\ to\ facility\ i\\
&ep_i \quad = \; Excess\ capacity\ at\ facility\ i\\
&ep_{T_i} \quad = \; Total\ excess\ capacity\ at\ facilities\ i\\
&c_{e_i} \quad = \; Expansion\ cost\ of\ expanding\ an\ existing\ facility\ i
\end{aligned}
\tag{4.5}
$$

Decision variables:

$$y_i \; = \; 1\ if\ facility\ is\ open,\ 0\ if\ closed \tag{4.6}$$

$$x_{ji} \; = \; volume\ transported\ from\ j\ to\ i \tag{4.7}$$

Objective function:

$$Minimize \sum_{i=1}^{n} c_{f_i} y_i + \sum_{i=1}^{n} \sum_{j=1}^{m} c_{v_{ji}} x_{ji} + \sum_{i=1}^{n} c_{e_i} y_i \tag{4.8}$$

Subject to:

$$\sum_{i=1}^{n} x_{ji} \; = \; D_j \qquad for \;\; j = 1, ..., \; m \tag{4.9}$$

$$\sum_{j=1}^{m} x_{ji} \leq K_i y_i \qquad for \;\; i = 1, ..., \; n \tag{4.10}$$

$$y_i \in \{0, 1\} \qquad\qquad for \;\; i = 1, ..., \; n, \; x_{ij} \geq 0 \tag{4.11}$$

$$ep_{T_i} \geq (Df_j - D_j) \qquad for \;\; j = 1, ..., \; m \tag{4.12}$$

$$x_{ji} \wedge ep_i \geq 0 \;\; for \;\; j \wedge i = 1, ..., \; n \wedge m \tag{4.13}$$

The objective function is formulated as seen in equation 4.8, and its goal is to minimize the total cost of the transportation and pre-sorting of recyclables and textile waste in Denmark. The constraint seen in equation 4.9 ensures that the total volume of used textiles from all WMCS in each region is transported to the pre-sorting facility, and therefore assumed to be pre-sorted. Constraint 4.10 specifies that the amount of textiles that any facility can pre-sort is not greater than its capacity. Constraint 4.11 ensures that either the facility is open, denoted by a value of 1, or closed, denoted by a value of 0. Constraint 4.12 ensures that the total excess capacity of the system is equal to or higher than the 5 year increase in recyclables and textile waste of 13,249 tons as determined in section 3.3.1 in the preliminary analysis. Constraint 4.13 specifies that the volumes transported (x_{ji}) and excess capacity (ep_i) are equal to or above 0. All of the described constraints are added to the Excel Solver software, used to execute the MILP, the solver can be seen in the attached appendix B.1 in sheet 'Solver Scenario 1'.
The objective function connects the decision variables to the inputs of fixed and variable costs, and thereby is used to determine what solution will yield the most optimal result meaning the lowest total cost. In this MILP there are two types of decision variables; which facilities are opened and tons of textiles sorted in these. The opened facility decision variables are connected to the fixed costs and expansion cost, and the tons of textiles sorted are connected to the variable costs. By calculating and adding together these cost parts, the objective function results in the total cost of the scenario.

Through the goal of minimizing the total cost of the objective function, the MILP determines what combination of open facilities and capacities will lead to the lowest total cost while meeting the constraints.

4.3.1 Results

After determining all inputs to the MILP, the solver is executed, and the results of the MILP can be seen in the attached appendix B.1 in sheet 'MILP Scenario 1'. The optimal solution for this scenario results in a total cost of 58,970,141.75 DKK. In the following figure 4.1 it can be seen, which decision variables were chosen by the MILP that lead to this total cost.

	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden	Low	Low/medium	Medium	Medium/high	High
Trasborg H	-	-	-	8.013,18	17.382,98	-	-	1,00	-	-
RedCross S	-	-	-	0,00	-	-	-	-	-	-
RedCross M	5.532,96	12.731,31	-	-	-	-	-	1,00	-	-
Salvation Army H	-	-	-	-	-	-	-	-	-	-
Salvation Army SD	-	-	11.217,74	-	-	-	-	1,00	-	-

Figure 4.1: Decision variables for MILP S1

The results of the MILP show that the solution for this scenario with the lowest total cost is opening 1 medium facility at Trasborg in Taastrup in Hovedstaden that sorts the entire volume from Sjælland and Hovedstaden, which is a total of 25,396.16 tons. There is also 1 medium facility opened at Red Cross in Horsens in Midtjylland that sorts the entire volume from Nordjylland and Midtjylland which is 18,264.27 tons. Lastly 1 medium facility is opened at Salvation Army in Kolding in Syddanmark that sorts the entire volume from Syddanmark which is 11,217.74 tons. These locations in Denmark can be seen in the following figure 4.2.

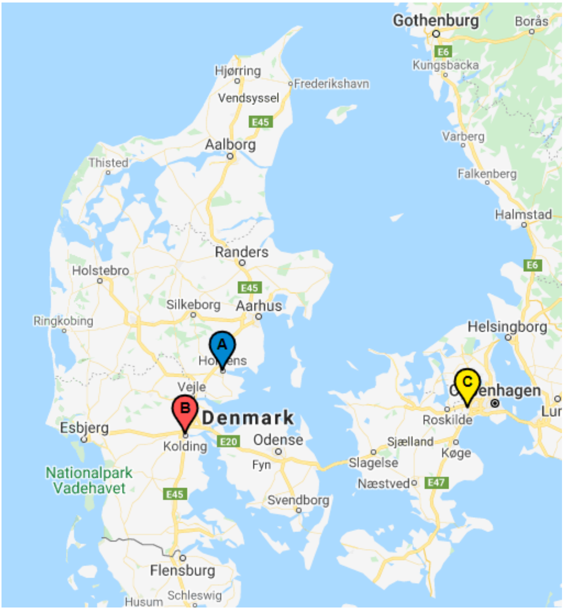

Figure 4.2: Location results for S1

Opening these 3 facilities will employ 181 pre-sorters and 9 production managers, and they will have a total excess capacity of 32,011 tons. This equals to an extra 58.33% capacity compared to the required capacity of 54,878 tons in 2021. However, when compared to the required capacity in 2026 of 68,127 tons, the excess capacity will be 18,762 tons, which then is an extra capacity of 27.54%. How the excess capacity is divided between the 3 facilities can be seen in the following table 4.7.

Table 4.7: Number of employees and excess capacity per facility S1

Location	Volume pre-sorted [tons]	Number of pre-sorters	Number of production managers	Excess capacity [tons]
Trasborg (H)	25,396.16	84	4	3,567
Red Cross (M)	18,264.27	60	3	10,699
Salvation Army (Sd)	11,217.74	37	2	17,745
Total	54,878	181	9	32,011

The following table 4.8 breaks down the total cost of this scenario into the sub-parts it is composed of, and the percentage that each part makes up of the total cost.

Table 4.8: Cost overview S1

Category	Cost type	Cost [DKK]	% of total cost
Variable costs			
	Environmental cost	163,328.52	0.28
	Fuel cost	4,044,070.61	6.86
	Pre-sorter wage	43,443,533.56	73.67
	Production manager wage	3,635,832.17	6.17
	Driver wage	5,212,612.26	8.83
Fixed costs			
	Renting cost	1,870,764.64	3.17
	Expansion cost	600,000.00	1.02
Total		58,970,141.75	100.00

From table 4.8 it can be calculated that the variable costs make up for 95.81% of the total cost, and the fixed costs for 4.19%. Due to the high level of manual labour in pre-sorting, the total cost will be distributed as such until and if a more automated solution can be implemented.

Based on the chosen facilities the CO_2 emitted from transportation can be calculated. This is done by multiplying the weighted km of the chosen route with the number of trips required, this is done for all the chosen combinations. This calculation can be seen below in equation 4.14 using the weighted km for the facilities chosen and the region(s) they pre-sort for, and the number of trips required.

$$\begin{aligned} Total\ km\ driven \ &= \ 178\ km * 549\ trips + 70\ km * 1,261\ trips + 59\ km * 1,119\ trips \\ &+ 51\ km * 793\ trips + 34\ km * 1,723\ trips = 351,038\ km \end{aligned} \tag{4.14}$$

Through this the total km driven for this scenario in 2021 is determined, and this is thereafter multiplied with the CO_2 equation previously described in section 3.6.1 in the preliminary analysis. The calculation for this scenario can be seen in the following equation 4.15, which results in scenario 1 emitting 507,269.2 $kgCO_2$. The calculations and results can be seen in the attached appendix B.1 in sheet 'CO2 Emissions Scenario 1'

$$\begin{aligned} CO_2 emitted \ &= \ \frac{351,038\ km * 1.86\ kgCO_2e/l}{1.82\ km/l} + \frac{351,038\ km * 0.77\ kgCO_2e/l}{1.82\ km/l} \\ &= 507,269.2\ kgCO_2e \end{aligned} \tag{4.15}$$

This concludes the MILP for scenario 1, as the optimal number of existing pre-sorting facilities, their locations and the total cost for 2021 is determined.
Over the next 5 years, the total cost of 58,970,141.75 DKK will increase due to the yearly increase in the collected volume of textiles of 4.42%, and thereby the number of employees

and trucks needed. However, this increase only affects the variable cost, as the 2026 future volume was used to determine the required space for the facilities, meaning the renting cost will stay the same, and there is no more expansion cost added. The formula used to find the yearly cost for the next 5 years, can be seen in the following equation 4.16.

$$Future\ cost\ =\ Fixed\ cost\ +\ Variable\ cost\ *\ 1.0442^{\#\ years\ after\ 2021} \tag{4.16}$$

By applying this calculation, the future costs for the next 5 years are determined these can be seen in table 4.9 below.

Table 4.9: Future total cost S1

Year	Cost [DKK]
2021	58,970,141.75
2022	60,867,414.21
2023	63,475,066.13
2024	66,197,976.25
2025	69,041,239.00
2026	72,010,173.97

When comparing the future cost from 2026 with the current cost for 2021 it can be seen that over the 5 years, the total cost will increase by 13,040,032.22 DKK due to the increasing volume of recyclables and textile waste.

4.4 Sub-conclusion scenario 1

Throughout this scenario analysis it was found that 3 actors are interested in performing pre-sorting in Denmark, them being Red Cross, Salvation Army and Trasborg. From these 3 actors, there are 5 possible pre-sorting facilities; Red cross in Horsens (M), Red Cross in Køge (S), Salvation Army in Kolding (Sd), Salvation Army in Hvidovre (H), and Trasborg in Taastrup (H). From these possible locations it is assumed that pre-sorting facilities would open at the same address, however any existing capacities or resources are not considered for the analysis.
Through the MILP it was determined that the optimal solution is to open 3 medium facilities respectively at Red Cross in Horsens (M), Trasborg in Taastrup (H), and Salvation Army in Kolding (Sd). This solution resulted in a total cost of 58,970,141.75 DKK for 2021, with a total excess capacity of 32,011 tons, and 507,269.2 $kgCO_2$ emitted.

This concludes that the questions for scenario analysis proposed in the research framework were answered, and therefore it concludes the analysis of scenario 1. The following chapter will analyse scenario 2 which evaluates setting up entirely new pre-sorting facilities.

Scenario 2 5

This chapter will analyse the second scenario, which is the set up of new pre-sorting facilities in Denmark in order to decrease the variable and fixed costs and therefore the total cost of the scenario. For each region, 3 municipalities are identified as possible facility locations. The fixed- and variable-costs are then determined using these locations, and used as inputs to the MILP. Thereafter the objective function, decision variables and constraints are formulated for the MILP and it is then executed using the determined inputs, the results, the future costs and the CO_2 emissions will be presented.

5.1 New pre-sorting facilities

This scenario is set up to analyse the optimal solution for new pre-sorting facilities in Denmark. To do so it is assumed that a company or a person will invest in setting up and running these facilities, however who will take on this assignment will not be specified. This section will determine the locations where it is possible to locate pre-sorting facilities which will be used as inputs to the MILP.
Due to the constraint of the number of variables the Excel software can handle, it is not possible to evaluate all municipalities in every region as possible facility locations, therefore the amount of evaluated locations per region has to be limited. For each region, 3 municipalities are picked, to ensure that each region has multiple locations to evaluate, while the total amount still does not exceed the constraint of the Excel software. These possible locations will be determined based on the municipalities with the largest populations per region, and thereby largest volume of textiles required to be pre-sorted. This is done based on the assumption that the population centers generate the highest volumes of recyclables and textile waste, meaning that from these locations a higher number of trips to the pre-sorting facilities are required. Therefore, by picking these population centers the transportation of the scenario will be decreased.
However, this cannot be done for the region of Hovedstaden, as for its 3 largest municipalities, København, Frederiksberg and Gentofte, no price could not be found for these locations at the time of this analysis as no production facilities were found. This is most likely due to the fact that prices in the capital are very high and thereby no production is located here as it would be too expensive. Therefore the next 3 municipalities are chosen, these being; Gladsaxe, Rudersdal and Helsingør.
All the possible facility locations can be seen in table 5.1 below, arranged from the largest municipality first to the smallest of the three.

Table 5.1: Possible facility locations S2

Nordjylland	**Midtjylland**	**Syddanmark**	**Sjælland**	**Hovedstaden**
Aalborg	Århus	Odense	Roskilde	Gladsaxe
Hjørring	Randers	Esbjerg	Næstved	Rudersdal
Frederikshavn	Viborg	Vejle	Slagelse	Helsingør

With the possible pre-sorting facilities locations defined, the next step is to find the variable and fixed cost of these possible options.

5.2 Inputs to MILP

The inputs to the MILP have been described in the preliminary analysis chapter 3, and in scenario 1 section 4.2 the approach to find the inputs were described. The same approach will be taken to find the inputs for this scenario and calculations will therefore not be explained again, however results will be presented and all calculations can be seen in the attached appendix B.2 in sheet 'MILP Scenario 2'.

5.2.1 Variable costs

The variable cost per ton of textile handled is calculated through the cost of transportation and the employee wages, following the same approach as described in scenario 1 in the previous chapter 4.

With the possible facility locations picked, the distances from each WMC to the possible facility locations are determined using the Google Maps platform as it was done in scenario 1. No specific address is picked for the possible facility location, but the city itself is used as the destination. With the distances from each WMC to each possible facility location determined, the next step is to aggregate these distances into region specific distances and to find the weighted km from each region to each possible facility, using equation 4.1 from section 4.2 in chapter 4. The results of this can be seen in table 5.2 below and the calculations can be found in the attached appendix B.2 in sheet 'MILP Scenario 2'.

	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
Aalborg (N)	32.28	126.06	251.40	376.48	425.55
Hjørring (N)	55.63	179.08	289.73	427.79	472.32
Frederikshavn (N)	67.71	189.05	314.40	439.98	488.59
Århus (M)	138.36	51.50	140.57	265.98	311.98
Randers (M)	100.86	64.25	171.44	296.98	345.56
Viborg (M)	94.91	59.26	153.67	287.11	334.20
Odense (Sd)	268.27	154.19	74.57	128.09	175.60
Esbjerg (Sd)	280.23	142.32	96.49	258.06	306.79
Vejle (Sd)	196.19	81.20	74.32	198.51	249.44
Roskilde (S)	396.42	281.11	198.96	42.77	42.64
Næstved (S)	367.09	252.48	170.25	42.33	98.24
Slagelse (S)	338.18	222.79	142.39	57.24	103.28
Gladsaxe (H)	430.93	315.45	233.19	68.07	18.64

Rudersdal (H)	442.42	301.04	244.65	79.43	23.47
Helsingør (H)	467.25	351.82	269.62	104.35	43.98

Table 5.2: Weighted km per facility per region S2

The weighted km are now used to determine the and fuel and environmental cost, the result of this can be seen in the attached appendix B.2, in sheet 'MILP Scenario 2'. The employee wages are thereafter calculated based on the region that the facilities are located in. All these results are added and the variable cost per region and facility in DKK/ton can be seen in the following table 5.3.

Table 5.3: Variable costs per facility per region S2 [DKK/ton]

	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
Aalborg (N)	862.69	1,113.39	1,448.46	1,782.84	1,914.02
Hjørring (N)	922.42	1,255.13	1,550.94	1,920.01	2,039.05
Frederikshavn (N)	957.40	1,281.77	1,616.88	1,952.58	2,082.54
Århus (M)	1,169.44	937.24	1,175.35	1,510.58	1,633.57
Randers (M)	1,069.19	971.30	1,257.85	1,593.46	1,723.35
Viborg (M)	1,053.26	957.96	1,210.36	1,567.07	1,692.96
Odense (Sd)	1,516.67	1,211.71	998.86	1,141.94	1,268.93
Esbjerg (Sd)	1,548.64	1,179.96	1,057.45	1,489.38	1,619.64
Vejle (Sd)	1,324.00	1,016.58	998.20	1,330.20	1,466.34
Roskilde (S)	1,977.10	1,668.84	1,449.23	1,031.68	1,031.32
Næstved (S)	1,898.68	1,592.29	1,372.47	1,030.51	1,179.98
Slagelse (S)	1,821.39	1,512.92	1,298.00	1,070.37	1,193.43
Gladsaxe (H)	2,077.64	1,768.92	1,549.01	1,107.61	975.45
Rudersdal (H)	2,108.37	1,730.40	1,579.65	1,137.98	988.38
Helsingør (H)	2,174.74	1,866.15	1,646.42	1,204.60	1,043.22

Now that the variable cost has been determined, the following subsection will determine the fixed cost per region and facility for this scenario.

5.2.2 Fixed costs

The fixed cost in this scenario is based on the cost of rent, this is calculated using a m^2 price found for each capacity option in every chosen city. The calculations can be seen in the attached appendix B.2 in sheet 'MILP Scenario 2', and the results can be seen in the following table 5.4.

Table 5.4: Average renting cost per facility S2 [DKK/m_2]

Facility	Price
Aalborg (N)	322
Hjørring (N)	225
Frederikshavn (N)	200
Århus (M)	493
Randers (M)	400
Viborg (M)	192
Odense (Sd)	135
Esbjerg (Sd)	345
Vejle (Sd)	426
Roskilde (S)	400
Næstved (S)	289
Slagelse (S)	375
Gladsaxe (H)	448
Rudersdal (H)	531
Helsingør (H)	600

The total fixed cost per facility and capacity option can be seen in the following table 5.5.

Table 5.5: Fixed cost per facility per capacity option S2 [DKK/year]

	Low	Low/medium	Medium	Medium/high	High
Aalborg (N)	56,350.00	295,903.13	535,456.26	775,009.39	1,014,562.52
Hjørring (N)	39,375.00	206,764.61	374,154.22	541,543.83	708,933.44
Frederikshavn (N)	35,000.00	183,790.76	332,581.53	481,372.29	183,790.76
Århus (M)	86,275.00	453,044.23	819,813.47	1,186,582.70	1,553,351.94
Randers (M)	70,000.00	367,581.53	665,163.06	962,744.59	1,260,326.12
Viborg (M)	33,600.00	176,439.13	319,278.27	462,117.40	604,956.54
Odense (Sd)	23,625.00	124,058.77	224,492.53	324,926.30	425,360.06
Esbjerg (Sd)	60,375.00	317,039.07	573,703.14	839,367.21	1,087,031.27
Vejle (Sd)	74,550.00	391,474.33	708,398.66	1,025,322.98	1,342,247.31
Roskilde (S)	70,000.00	367,581.53	665,163.06	962,744.59	1,260,326.12
Næstved (S)	50,575.00	265,577.65	480,580.31	695,582.96	910,585.62
Slagelse (S)	65,625.00	344,607.68	623,590.37	902,573.05	1,181,555.73
Gladsaxe (H)	78,400.00	411,691.31	744,982.62	1,078,273.94	1,411,565.25
Rudersdal (H)	92,925.00	487,964.48	883,003.96	1,278,043.44	1,673,082.92
Helsingør (H)	105,000.00	551,372.29	997,744.59	1,444,116.88	1,890,489.17

Additionally to the renting cost, an opening cost of 500.000 DKK is added as an input to the MILP of this scenario. Like the expansion cost in scenario 1, these opening cost are an assumed to be a one time investment for each facility that has to open. As the total opening cost of this scenario depends on the number of facilities chosen by the MILP, it is determined through the total cost when the MILP has been executed.

After determining the inputs to the MILP, the next step is to formulate and execute the MILP in order to find the most optimal amount of pre-sorting facilities and their locations while minimizing the total cost of this scenario. The MILP will be described in the following section.

5.3 MILP scenario 2

The MILP is as scenario 1 composed of 3 parts which are decision variables, an objective function, and constraints. This MILP varies from scenario 1 by having an opening cost rather than expansion cost. The contents of the MILP can be seen in the following.

Inputs used in the MILP:

$$\begin{aligned}
&n \quad = Number\ of\ potential\ pre-sorting\ facility\ locations \\
&m \quad = Number\ of\ WMC \\
&D_j \quad = Annual\ volume\ from\ region\ j \\
&Df_j \quad = Future\ annual\ volume\ in\ 5\ years\ from\ region\ j \\
&K_i \quad = Capacity\ of\ facility\ i \\
&c_{f_i} \quad = Annual\ fixed\ cost\ of\ keeping\ facility\ i\ open \\
&c_{v_{ji}} \quad = Variable\ cost\ of\ transporting\ and\ pre-sorting\ 1\ ton\ of\ textiles \\
&from\ region\ j\ to\ facility\ i \\
&ep_i \quad = Excess\ capacity\ at\ facility\ i \\
&ep_{T_i} \quad = Total\ excess\ capacity\ at\ facilities\ i \\
&c_{o_i} \quad = Opening\ cost\ of\ opening\ a\ new\ facility\ i
\end{aligned} \tag{5.1}$$

Decision variables:

$$y_i \ = \ 1\ if\ facility\ is\ open,\ 0\ if\ closed \tag{5.2}$$

$$x_{ji} \ = \ volume\ transported\ from\ j\ to\ i \tag{5.3}$$

Objective function:

$$Minimize \sum_{i=1}^{n} c_{f_i} y_i + \sum_{i=1}^{n} \sum_{j=1}^{m} c_{v_{ji}} x_{ji} + \sum_{i=1}^{n} c_{o_i} y_i \tag{5.4}$$

Subject to:

$$\sum_{i=1}^{n} x_{ji} \ = \ D_j \qquad for \ \ j = 1, ..., \ m \tag{5.5}$$

$$\sum_{j=1}^{m} x_{ji} \leq K_i y_i \qquad for \ \ i = 1, ..., \ n \tag{5.6}$$

$$y_i \in \{0, 1\} \qquad for \;\; i = 1, ..., \; n, \; x_{ij} \geq 0 \tag{5.7}$$

$$ep_{T_i} \geq (Df_j - D_j) \qquad for \;\; j = 1, ..., \; m \tag{5.8}$$

$$x_{ji} \wedge ep_i \geq 0 \;\; for \;\; j \wedge i = 1, ..., \; n \wedge m \tag{5.9}$$

After all inputs to the MILP are determined, the constraints and the decision variables are linked to the objective function in the solver in the Excel software, the solver can be seen in attached appendix B.2 in sheet 'Solver Scenario 2'. This is then executed and the MILP, the inputs and results can be seen in the attached appendix B.2 in sheet 'MILP Scenario 2'.

5.3.1 Results

The total cost of the optimal solution for this scenario is 57,347,348.29 DKK, and the decision variables chosen by the MILP can be seen in the following figure 5.1.

	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden	**Low**	**Low/medium**	**Medium**	**Medium/high**	**High**
Frederikshavn (N)	-	-	-	-	-	-	-	-	-	-
Aalborg (N)	5.532,96	-	-	-	-	-	1,00	-	-	-
Randers (M)	-	-	-	-	-	-	-	-	-	-
Århus (M)	-	-	-	-	-	-	-	-	-	-
Esbjerg (Sd)	-	-	-	-	-	-	-	-	-	-
Vejle (Sd)	-	-	-	-	-	-	-	-	-	-
Roskilde (S)	-	-	-	-	-	-	-	-	-	-
Slagelse (S)	-	-	-	-	-	-	-	-	-	-
Helsingør (H)	-	-	-	-	-	-	-	-	-	-
Rudersdal (H)	-	-	-	-	-	-	-	-	-	-
Viborg (M)	-	12.731,31	-	-	-	-	1,00	-	-	-
Odense (Sd)	-	-	11.217,74	-	-	-	1,00	-	-	-
Næstved (S)	-	-	-	0,00	-	-	-	-	-	-
Gladsaxe (H)	-	-	-	8.013,18	17.382,98	-	-	1,00	-	-
Hjørring (N)	-	-	-	-	-	-	-	-	-	-

Figure 5.1: Decision variables for MILP S2

The results of the MILP in the above figure show that the most optimal solution for scenario 2 with the lowest total cost is to open 4 new facilities, 3 with low/medium capacity and 1 with medium capacity. 1 low/medium facility is opened in Aalborg that sorts the entire volume coming from Nordjylland which is 5,532.96 tons. 1 low/medium facility is opened in Viborg that sorts the entire volume form Midtjylland which is 12,731.31 tons. 1 low/medium facility is opened in Odense that will sort the entire volume for Syddanmark, which is 11,217.74 tons. And 1 medium facility is opened in Gladsaxe that sorts the entire volume from Sjælland and Hovedstaden which is a total of 25,396.16 tons. Where these facilities are located in Denmark can be seen in the following figure 5.2.

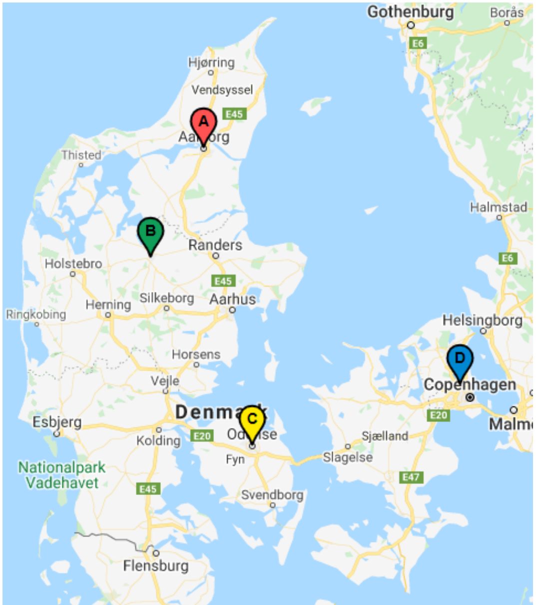

Figure 5.2: Location results for S2

This solution will employ 182 pre-sorters and 9 production managers, and it results in a total excess capacity of 22,103 tons. This equals to an extra 40.28% capacity compared to the required capacity of 54,878 tons in 2021. For 2026, the required capacity is 68,127 and the excess capacity then is 8,854 tons, which equals to an extra capacity of 12,99%. The distribution of this excess capacity and the number of employees between the chosen facilities can be seen in the following table 5.6.

Table 5.6: Number of employees and excess capacity per facility S2

Location	Volume pre-sorted [tons	Number of pre-sorters	Number of production managers	Excess capacity [tons]
Aalborg (N)	5,532.96	19	1	10,473
Viborg (M)	12,731.31	42	2	3,275
Odense (Sd)	11,217.74	37	2	4,788
Gladsaxe (H)	25,396.16	84	4	3,567
Total	54,878	182	9	22,103

How the total cost is broken down into its different sub-parts, and what percentage they make up of the total cost can be seen in the following table 5.7.

Table 5.7: Cost overview S2

Category	Cost type	Cost [DKK]	% of total cost
Variable costs			
	Environmental cost	122,317.86	0.21
	Fuel cost	3,028,632.44	5.28
	Pre-sorter wage	43,331,352.22	75.56
	Production manager wage	3,619,886.57	6.31
	Driver wage	3,903,761.36	6.81
Fixed costs			
	Renting cost	1,341,397.85	2.34
	Opening cost	2,000,000.00	3.49
Total		57,347,348.29	100.00

Similar to scenario 1, the variable costs make up 94.17% of the total cost, while fixed costs make up 5.83%. All percentages vary when comparing scenario 1 to scenario 2, as different locations are chosen, and the total cost is lower.

The CO_2 emitted will be calculated by applying the same method as gone through in scenario 1. The following equation 5.10 calculates the total km driven using the weighted km of the chosen routes, and the trips required per chosen route for this scenario.

$$\begin{aligned} Total\,km\,driven\; &= \;32\,km * 549\,trips + 59\,km * 1,261\,trips + 75\,km * 1,119\,trips \\ &+ \;68\;km\;*\;793\;trips\;+\;19\;km\;*\;1,723\;trips \\ &= \;261,989\;km \end{aligned} \tag{5.10}$$

In equation 5.10 the total km driven was determined being 261,989 km, which is used to determine the CO_2 emitted. The calculation for this can be seen in the following equation 5.11.

$$\begin{aligned} CO_2emitted \;&=\; \frac{261,989\;km\;*\;1.86\;kgCO_2e/l}{1.82\;km/l} + \frac{261,989\;km\;*\;0.77\;kgCO_2e/l}{1.82\;km/l} \\ &=\; 378,589\;kgCO_2e \end{aligned} \tag{5.11}$$

Through equation 4.15 it was determined that scenario 2 emits 378,589 $kgCO_2$ through transportation. The calculations and results can be seen in the attached appendix B.2 in sheet 'CO2 Emissions Scenario 2'

This concludes the MILP for scenario 2, as the optimal number of new pre-sorting facilities, their locations and the total cost for 2021 is determined.
The future cost is found by applying the same method as used in scenario 1. Again the fixed cost does not increase, but the variable cost increases according to the yearly 4.42% increase in collected recyclables and textile waste. The results for the yearly cost for the next 5 years can be seen in the following table 5.8.

Table 5.8: Future total cost S2

Year	Cost [DKK]
2021	57,347,348.29
2022	57,734,411.30
2023	60,226,982.49
2024	62,829,725.34
2025	65,547,509.41
2026	68,385,419.54

For scenario 2, the total cost will increase by 11,038,071.25 DKK over the next 5 years when comparing the cost for 2021 and 2026.

When opening new pre-sorting facilities in Denmark, the optimal solution of number of facilities, locations and sizes with the minimum cost have been found, which concludes this scenario.

5.4 Sub-conclusion scenario 2

For the scenario analysis of new facilities for pre-sorting in Denmark, the 3 main population centers per region were identified to possibly have pre-sorting facilities, which resulted in 15 possible locations. Due to locations not being available in the 3 main population centers in the region of Hovedstaden, here the following 3 locations were used.
Through the MILP it was determined that the optimal solution is to open 3 low/medium facilities respectively in Aalborg (N), Viborg (M) and Odense (Sd) and one medium facility in Gladsaxe (H). This solution resulted in a total cost of 57,347,348.29 DKK for 2021, with a total excess capacity of 22,103 tons, and 378,589 $kgCO_2$ emitted.

This concludes that the questions for scenario analysis proposed in the research framework were answered, and therefore it concludes the analysis of scenario 2. The following chapter will analyse scenario 3 which evaluates if a hybrid of scenario 1 and 2 will lead to a more optimal solution.

Scenario 3 6

The third scenario will have a focus on determining if creating a hybrid between the first and second scenario will lead to a lower total cost. Firstly the inputs to the MILP will be determined through finding the variable and fixed costs. Then the MILP will be formulated and executed, the results, future costs, and CO_2 emissions will be presented.

6.1 Hybrid scenario

This scenario will compare and evaluate if a hybrid between the chosen locations from the MILP in scenario 1 and 2 will lead to a lower total cost. Therefore, all the existing facilities identified in scenario 1 will be used along with all the municipalities identified in scenario 2, all possible facility locations can be seen in table 6.1 below.

Table 6.1: Possible facility locations S3

Nordjylland	**Midtjylland**	**Syddanmark**	**Sjælland**	**Hovedstaden**
Aalborg	Red Cross (Horsens)	Salvation Army (Kolding)	Red Cross (Køge)	Trasborg (Taastrup)
Hjørring	Århus	Odense	Roskilde	Salvation Army (Hvidovre)
Frederikshavn	Randers	Esbjerg	Næstved	Gladsaxe
-	Viborg	Vejle	Slagelse	Rudersdal
-	-	-	-	Helsingør

6.2 Inputs to MILP

The inputs to the MILP have been described in the preliminary chapter, and in scenario 1 the approach to find the inputs were described. The same approach will be taken to find the inputs for this scenario and calculations will therefore not be explained again. The results of the weighted km, variable and fixed cost will not be shown again as these are the same as in scenario 1 and 2, however they can be found in the appendix A.2, and the calculations for the MILP can be found in the attached appendix B.3 in the sheet 'MILP Scenario 3'.

6.2.1 Variable costs

The variable cost per ton of textile consists of the cost of transportation and the employee wages, which are calculated following the same approach as in scenario 1 in chapter 4. With all possible facility locations identified, the distances from all WMCs to all existing facilities from scenario 1 and all municipalities identified in scenario 2 are found using the Google Maps platform. This is then used to calculate the weighted km using equation 4.1 from section 4.2 in chapter 4. The results of these calculations can be seen in table A.2 in appendix A.2 and the calculations can be seen in the attached appendix B.3 in sheet 'MILP Scenario 3'.

6.2.2 Fixed costs

The fixed costs is determined based on the rent cost of the capacity options and possible facility locations, these can be seen in table A.4 in appendix A.2. However, in this scenario the optimal solution might include both an existing and a new facility, meaning both expansion and opening cost have to be included in this scenario. The fixed costs can be seen in table A.5 in appendix A.2.

6.3 MILP scenario 3

The MILP for this scenario has the same structure as scenario 1 and 2, as it consists of the three parts, decision variables, objective functions, and constraints. However, this MILP is different as it includes both expansion cost and opening cost in its objective function, seeing as both new and current facilities are options for this scenario. In the following the inputs, decision variables, objective function, and constraints of this scenarios MILP can be seen.

Inputs used in the MILP:

$$
\begin{aligned}
n &= Number\ of\ potential\ pre-sorting\ facility\ locations\\
m &= Number\ of\ WMC\\
D_j &= Annual\ volume\ from\ region\ j\\
Df_j &= Future\ annual\ volume\ in\ 5\ years\ from\ region\ j\\
K_i &= Capacity\ of\ facility\ i\\
c_{f_i} &= Annual\ fixed\ cost\ of\ keeping\ facility\ i\ open\\
c_{v_{ji}} &= Variable\ cost\ of\ transport\ and\ pre-sorting\ 1\ ton\ of\ textiles\\
&\ from\ region\ j\ to\ facility\ i\\
ep_i &= Excess\ capacity\ at\ facility\ i\\
ep_{T_i} &= Total\ excess\ capacity\ at\ facilities\ i\\
c_{e_i} &= Expansion\ cost\ of\ expanding\ an\ existing\ facility\ i\\
c_{o_i} &= Opening\ cost\ of\ opening\ a\ new\ facility\ i
\end{aligned}
\tag{6.1}
$$

Decision variables:

$$y_i \;=\; 1\, if\; facility\; is\; open,\; 0\, if\; closed \tag{6.2}$$

$$x_{ji} \;=\; volume\; transported\; from\; j\; to\; i \tag{6.3}$$

Objective function:

$$Minimize \sum_{i=1}^{n} c_{f_i} y_i + \sum_{i=1}^{n} \sum_{j=1}^{m} c_{v_{ji}} x_{ji} + \sum_{i=1}^{n} c_{e_i} y_i + \sum_{i=1}^{n} c_{o_i} y_i \tag{6.4}$$

Subject to:

$$\sum_{i=1}^{n} x_{ji} \;=\; D_j \qquad for\;\; j = 1, ..., \; m \tag{6.5}$$

$$\sum_{j=1}^{m} x_{ji} \leq K_i y_i \qquad for\;\; i = 1, ..., \; n \tag{6.6}$$

$$y_i \in \{0, 1\} \qquad\qquad for\;\; i = 1, ..., \; n, \; x_{ij} \geq 0 \tag{6.7}$$

$$ep_{T_i} \geq (Df_j - D_j) \qquad\quad for\;\; j = 1, ..., \; m \tag{6.8}$$

$$x_{ji} \wedge ep_i \geq 0 \;\; for\;\; j \wedge i = 1, ..., \; n \wedge m \tag{6.9}$$

After all inputs to the MILP are determined, the solver is formulated using the constraints and the decision variables are linked to the objective function in the Excel software, the solver can be seen in attached appendix B.3 in sheet 'Solver Scenario 3'. This is then executed and the MILP, the inputs and results can be seen in the attached appendix B.3 in sheet 'MILP Scenario 3'.

6.3.1 Results

The total cost for the optimal solution for this scenario is 56,671,842.11 DKK, and the decision variables chosen by the MILP can be seen in figure 6.1.

Decision variable										
	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden	Low	Low/medium	Medium	Medium/high	High
Frederikshavn (N)	-	-	-	-	-	-	-	-	-	-
Aalborg (N)	0,00	-	-	-	-	-	-	-	-	-
Randers (M)	-	-	-	-	-	-	-	-	-	-
Århus (M)	-	12.731,31	-	-	-	-	1,00	-	-	-
Esbjerg (Sd)	-	-	-	-	-	-	-	-	-	-
Vejle (Sd)	-	-	-	-	-	-	-	-	-	-
Roskilde (S)	-	-	-	-	-	-	-	-	-	-
Slagelse (S)	-	-	-	-	-	-	-	-	-	-
Helsingør (H)	-	-	-	-	-	-	-	-	-	-
Rudersdal (H)	-	-	-	-	0,00	-	-	-	-	-
Viborg (M)	-	-	-	-	-	-	-	-	-	-
Odense (Sd)	-	-	-	-	-	-	-	-	-	-
Næstved (S)	-	-	-	-	-	-	-	-	-	-
Gladsaxe (H)	-	-	-	-	16.005,55	-	1,00	-	-	-
Hjørring (N)	5.532,96	-	-	-	-	-	1,00	-	-	-
Trasborg (H)	-	-	-	-	-	-	-	-	-	-
RedCross (S)	-	-	-	8.013,18	1.377,43	-	1,00	-	-	-
RedCross (M)	-	-	-	-	-	-	-	-	-	-
Salvation Army (H)	-	-	-	-	-	-	-	-	-	-
Salvation Army (Sd)	-	-	11.217,74	-	-	-	1,00	-	-	-

Figure 6.1: Decision variables for MILP S3

In the figure above it can be seen that there in total is opened 5 low/medium facilities. 1 is opened at the existing facility at Red Cross in Køge, that sorts the entire volume from Sjælland, 8,013.18, and some of the volume from Hovedstaden, 1,377.43, which totals to 9,390.61 tons. 1 facility should be opened at the existing facility at Salvation Army in Kolding that sorts the entire volume of Syddanmark which totals to 11,217.74 tons. 1 facility is opened in Gladsaxe that sorts the remaining of the volume from Hovedstaden which is 16,005.55 tons. 1 new facility is opened in Århus that sorts the entire volume of Midtjylland which is 12,731.31 tons. And 1 new facility is opened in Hjørring that sorts the entire volume from Nordjylland which is 5,532.96 tons.

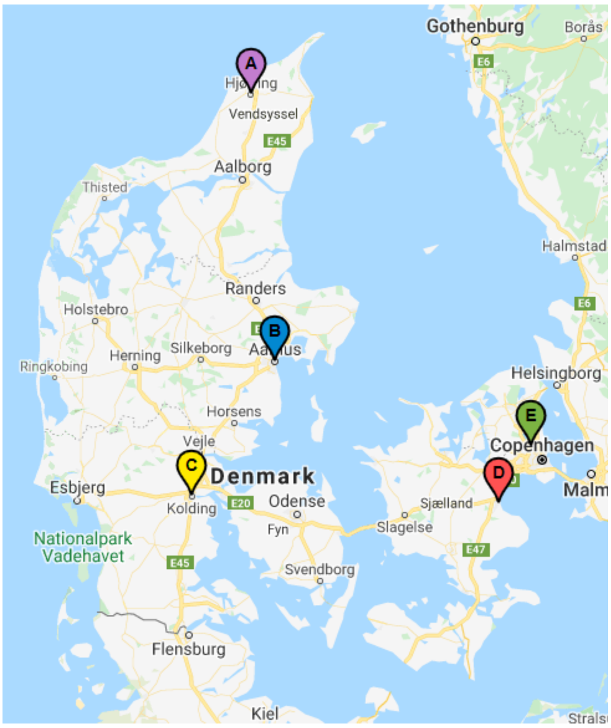

Figure 6.2: Location results for S3

This solution will employ 182 pre-sorters and 10 production managers, the facilities combined will have a total excess capacity of 25,150 tons, which equals an extra 45.83% capacity compared to the required capacity of 54,878 tons in 2021. However, when compared to the 2026 volume of 68,127 tons where the excess capacity will be 11,901 tons, this leads to an extra capacity of 17.47%. The distribution of this excess capacity between the facilities can be seen in the following table 6.2.

Table 6.2: Number of employees and excess capacity per facility S3

Location	Volume pre-sorted [tons]	Number of pre-sorters	Number of production managers	Excess capacity [tons]
Århus	12,731.31	42	2	3,274.24
Gladsaxe	16,005.55	53	3	0
Hjørring	5,532.96	19	1	10,472.59
Red Cross (S)	9,930.61	31	2	6,614.94
Salvation Army (SD)	11,217.74	37	2	4,787.81
Total	54,878	182	10	25,150

The sub-parts that the total cost consists of can be seen below in table 6.3.

Table 6.3: Cost overview S3

Category	Cost type	Cost [DKK]	% of total cost
Variable costs			
	Environmental cost	107,997.10	0.19
	Fuel cost	2,674,045.51	4.72
	Pre-sorter wage	43,380,637.84	76.55
	Production manager wage	3,492,706.69	6.16
	Driver wage	3,446,715.88	6.08
Fixed costs			
	Renting cost	1,669,739.09	2.95
	Opening/Expansion cost	1,900,000.00	3.35
Total		56,671,842.11	100.00

From table 6.3 it can be calculated that the variable costs make up a total of 93.7% of the total cost, and fixed costs make up 6.3%.

The CO_2 emitted will be calculated using the same method as gone through in scenario 1 and 2, and the results of this can be seen in the following equation 6.12. This calculation is done using the weighted km of the chosen routes, and the trips required of the individual route for this scenario. In this scenario some of the textiles from Hovedstaden go to Red Cross on Sjælland, and some go to Gladsaxe in Hovedstaden. To determine the total km, the number of trips going to Gladsaxe and Red Cross must firstly be determined. To do so, the ratio of trips going to each facility is firstly determined based on the volume of textiles the receive. This is done in equation 6.10

$$Gladsaxe\ \%\ received\ =\ \frac{16,005.55\ tons}{1,337\ tons\ +\ 16,005.55\ tons}\ *\ 100\% =\ 92.08\%$$

$$Red\ Cross\ \%\ received\ =\ \frac{1,337\ tons}{1,337\ tons\ +\ 16,005.55\ tons}\ *\ 100\% =\ 7.92\% \tag{6.10}$$

These percentages are now applied to the amount of trips from Hovedstaden to divide the amount of trips. This can be seen in the following equation 6.11, which shows 1,587 trips are required from Hovedstaden to Gladsaxe, and 137 trips are required from Hovedstaden to Red Cross on Sjælland.

$$Gladsaxe\ trips\ =\ 1,723\ trips\ *\ 1,586.47\ trips$$

$$Red\ Cross\ trips\ =\ 1,723\ trips\ *\ 136.53\ trips \tag{6.11}$$

Using the weighted distances and number of trips the following equation 6.12 is made calculating the total km driven.

$$\begin{aligned} Total\ km\ driven\ &=\ 56\ km * 549\ trips + 52\ km * 1,261\ trips + 59\ km * 1,119\ trips \\ &+\ 42\ km\ *\ 793\ trips\ +\ 51\ km\ *\ 137\ trips\ +\ 34\ km\ *\ 1,587\ trips \\ &=\ 255,754\ km \end{aligned} \tag{6.12}$$

Through equation 5.10 the total km driven was determined being 255,754 km. This is hereafter used to determine the CO_2 emitted by transporting the recyclables and textile waste from WMCs to the assigned pre-sorting facilities. The calculation for this can be seen in the following equation 6.13.

$$\begin{aligned} CO_2emitted\ &=\ \frac{255,754\ km\ *\ 1.86\ kgCO_2e/l}{1.82\ km/l} + \frac{255,754\ km\ *\ 0.77\ kgCO_2e/l}{1.82\ km/l} \\ &=\ 369,579.12\ kgCO_2e \end{aligned} \tag{6.13}$$

Through equation 4.15 it was determined that the CO_2 emission of scenario 3 equals 369,579.12 $kgCO_2$ through transportation. The calculations and results can be seen in the attached appendix B.3 in sheet 'CO2 Emissions Scenario 3'.

By applying the same method as described in scenario 1 the future cost is determined. In this method the fixed cost does not change, but the variable cost increases according to the yearly increase of the volume of recyclables and textile waste of 4.42%.

Table 6.4: Future total cost S3

Year	Cost [DKK]
2021	56,671,842.11
2022	57,118,955.07
2023	59,569,810.41
2024	62,128,993.56
2025	64,801,292.61
2026	67,591,707.28

Based the future cost as seen in table 6.4, the future cost will increase by 10,919,865.17 DKK in 2026.

6.4 Sub-conclusion scenario 3

For the scenario analysis of this hybrid scenario for pre-sorting in Denmark, the possible locations of existing facilities from scenario 1 and new facilities from scenario 2 were used in combination. This resulted in 20 possible locations for pre-sorting facilities in Denmark for this scenario.
Through the MILP it was determined that the optimal solution is to open 5 low/medium facilities respectively in Århus (M), Gladsaxe (H), Hjørring(N), Red Cross in Køge (S), and Salvation Army in Kolding (Sd) . This solution resulted in a total cost of 56,671,842.11 DKK for 2021, with a total excess capacity of 25,150 tons, and 369,579.12 $kgCO_2$ emitted.

This concludes scenario 3 as the proposed questions of from the research framework have been answered. The following chapter will evaluate which of these scenarios is the most optimal.

Scenario evaluation 7

This chapter will use the results of the 3 scenarios to evaluate them and determine what scenario is most optimal based on other criteria than solely cost. This is done using AHP which evaluates the scenarios using multiple criteria and ensures consistency in the inputs. The economic feasibility is thereafter evaluated by determining the possible income generated, and comparing that to the total cost of the system. Thereafter the chapter is concluded by describing the barriers for setting up pre-sorting in Denmark.

Through the analysis of the 3 scenarios, the goal was to determine the number of pre-sorting facilities and their sizes in Denmark, with the minimum cost. In table 7.1 below it can be seen that the first scenario is the most expensive, the second scenario is the second most expensive and lastly the third scenario is the cheapest.

Table 7.1: Total cost of scenarios [DKK]

Scenario	1 Current system with adjustments	2 New pre-sorting facilities	3 Hybrid scenario
Cost	58,970,141.75	57,347,348.29	56,671,842.11

Therefore, if the scenarios are solely evaluated based on total cost, scenario 3 will be the best option. However, more parameters should be considered when evaluating these scenarios, to be able to assess the overall performance of these scenarios, to do so AHP is applied.

7.1 AHP

The AHP is applied as previously described, because it ensures that the inputs are consistent, using consistency index (CI) and consistency ratio (CR). The AHP analysis is carried out through the following four steps:

1. Determining the criteria
2. Ranking the criteria based on their importance
3. Ranking the scenarios based on their performance for each of the criteria
4. Quantitative assessment as to which scenario is the most optimal

The first step is to identify the criteria that the AHP will use to determine the performance of the scenarios. In the second step the criteria are ranked in a pairwise comparisons using their relative weight, by scoring the importance of the identified criteria from 1-9 [24,p.86]. The definitions and explanations of these scores can be seen in the following figure 7.1.

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important.	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed

Figure 7.1: AHP scale by Saaty

When comparing criteria A to criteria B, a score of 1 means the two criteria are equally important. Meanwhile a score of 9 means criteria A has extreme importance over criteria B. A reciprocal score is used when comparing criteria B to criteria A, in this example the reciprocal score for criteria B compared to criteria A will be 1/9. The consistency of these input values are hereafter checked by calculating their CI and CR. The third step is to rank the performance of the scenarios for each criteria using the same pairwise comparison. The last step combines the criteria weight and ranked performance of the scenarios to determine what scenario is most optimal based on all criteria.

7.1.1 Determining the criteria

The criteria used for this AHP analysis are identified through brainstorming on important factors to set up and implement pre-sorting in Denmark, literature research, and an interview with Nikola Kiørboe. All criteria that have been considered can be seen in table 7.2 below, along with a brief explanation of them.

Criteria	Explanation	Is it used?
Environmental sustainability	The EU regulation has a focus on decreasing the negative environmental impact, thereby increase environmental sustainability. The environmental sustainability is measured in CO_2 emissions.	Yes
Economic sustainability	A pre-sorting system that is not economically sustainable will not be feasible. If that is the case, then textiles will be incinerated rather than recycled and thereby decreasing the environmental sustainability. The economic sustainability is measured in the total cost of the scenario.	Yes

Circularity	A circular pre-sorting system which follows the waste hierarchy decreases the negative environmental impact. This is measured by the percentage of textiles that are recycled.	No
Excess capacity	Excess capacity allows the system to cope with increased volumes in the future, however too high of an excess capacity could mean resources wasted. Excess capacity is measured by how many extra tons can be pre-sorted.	Yes
Social sustainability	A social sustainable system creates jobs for the community it is placed in.	No
Risk	The risks that are associated with setting up a pre-sorting system should be evaluated to make it possible to have contingency plans for these the risks are measured in severity.	Yes

Table 7.2: Possible criteria for scenario evaluation

Two criteria mentioned in the table are excluded from the AHP analysis, these are Social sustainability and Circularity. Social sustainability is excluded as the employment of employees, living conditions, and medical accessibility do not vary depending on the scenarios, due to the size of Denmark. Circularity is excluded as none of the scenarios will ensure a fully circular system, but determines the first part of a circular system. It is still required to decide how the detailed sorting and recycling of used textiles should be done and by whom, to determine if a circular system is a possibility. The remaining criteria will be used in the AHP, and it will be described in the following how these are measured.

CO_2 emissions

The amount of CO_2 emitted is a critical criteria when evaluating the scenarios, as environmental sustainability is a focus point of political parties in both Denmark and in EU, as seen through the EU climate directive on waste [5], and the Danish governments climate plan [7].

Total cost

The cost of setting up and operating the pre-sorting facilities, is a critical criteria to consider for the scenarios, as too high of a total cost can make it economically unfeasible to do so. If it is not economically feasible for the companies to pre-sort the textiles, then some of the textiles will inevitably end up being incinerated rather than recycled. This goes against both the EU directive and the Danish climate plan, and must therefore be prevented. However, the AHP will not determine whether the scenarios are economically feasible, but it will clarify which is the best scenario based on this criteria, and thereby the most likely to be economically feasible.

Excess capacity

Having excess capacity can have both a negative and positive impact on a company. It can ensure that a company who is working in a field with rapid growth, has capacity to grow without having to expand their facility. However, having a high excess capacity can also cause issues because of the investment in resources that could potentially never be utilized. The excess capacity for each scenario will be evaluated by the amount of tons of textiles that can still be pre-sorted based on the size of the picked facilities.

Risk

For all of the scenarios, the risks connected are important to consider as they can have an impact on the success of the scenarios. The scenarios differ regarding the locations picked and whether the locations are NGO operated or require a new facility. Due to this, the risks connected and their severity will vary, and therefore it will have an impact on what scenario is most optimal. The risks will be measured based on their severity, which is impacted by the picked locations and operators.

7.1.2 Ranking of criteria

Now that the criteria are determined, the next step is to find the relative weight of these criteria in order to rank them based on their importance. This is done in a pairwise comparison from which the results can be seen in the following figure 7.2 which is from the attached appendix B.4 in the sheet 'Criteria'.

Criteria Number	**Criteria**	1	2	3	4
	Criteria Description	CO2 Emissions	Total cost	Excess capacity	Risk
1	CO2 Emissions	1,00	0,33	3,00	5,00
2	Total cost	3,00	1,00	5,00	7,00
3	Excess capacity	0,33	0,20	1,00	3,00
4	Risk	0,20	0,14	0,33	1,00
	Sum	4,53	1,68	9,33	16,00

Figure 7.2: Criteria scoring

When a criteria is compared to itself it is given a score of 1, meaning it is equally as important. When comparing CO_2 emissions to the total cost it is given a score of 1/3, meaning that CO_2 emissions is slightly less important than the total cost. This score is given as the total cost of the scenarios can make them economically unfeasible and thereby the scenario would not be further considered. Therefore, CO_2 emissions are weighted less important than the total cost of pre-sorting in Denmark. A reciprocal score is given for the inverted comparison, meaning when total cost is compared to CO_2 emissions it is given a score of 3. The reciprocal scores are not further explained for the remaining criteria, as the same method is used. Comparing CO_2 emissions to excess capacity a score of 3 is given, meaning that CO_2 emissions is slightly more important than excess capacity, as

having excess capacity will not necessarily make the scenario unfeasible, but having very high CO_2 emissions will be more likely to make it unfeasible. Comparing CO_2 emissions to risk is given a score of 5, meaning CO_2 emissions has a higher impact on which of the scenarios is the best option. This score is given as risks may not have any impact if there are no risks of a higher severity.
When comparing total cost to excess capacity a score of 5 is given, meaning total cost has a slightly higher impact, as excess capacity will not necessarily make the scenario unfeasible, while total cost may. When comparing total cost to risk a score of 7 is given, meaning total cost is more important than risk, as risks might not have any impact on the scenarios. When comparing excess capacity to risk a score of 3 is given, meaning excess capacity has a slightly higher impact than risk.
After having scored all criteria, next these scores are used to determine the relative weight of the criteria. To do so the sums of these scores are firstly calculated, which can be seen in figure 7.2 above, in the bottom row. This sum is used to calculate an input to the standardized matrix, this is done by the given score of a comparison being divided by the sum of the column. For CO_2 emissions compared to CO_2 emissions the calculation would be $\frac{Pairwise\ comparison\ value}{Sum\ of\ column} = \frac{1}{4.53} = 0.22$. This is done for all scores in the matrix, and the results can be seen in the following figure 7.3.

		CO2 Emissions	Total cost	Excess capacity	Risk	Weight
1	CO2 Emissions	0,22	0,20	0,32	0,31	26,3%
2	Total cost	0,66	0,60	0,54	0,44	55,8%
3	Excess capacity	0,07	0,12	0,11	0,19	12,2%
4	Risk	0,04	0,09	0,04	0,06	5,7%

Figure 7.3: Standardized matrix criteria

The weight of each criteria is then calculated based on these inputs, this is done by dividing the sum of the row by the number of evaluated criteria. For the CO_2 emissions row, the calculations can be seen in equation 7.1. This is done for all rows, and the results can be seen in figure 7.3 in the column 'Weight'. Based on these inputs the most important criteria is the total cost (55.8%), followed by CO_2 emissions (26.3%), then excess capacity (12.2%), and lastly risk (5.7%).

$$Weight\ (criteria) = \frac{Row\ values}{Number\ of\ criteria}$$
$$Weight\ (CO_2\ emissions) = \frac{0.22 + 0.20 + 0.32 + 0.31}{4} * 100\% = 26.3\% \quad (7.1)$$

To determine if these inputs are consistent, the CR should be calculated. The inputs are consistent if $0 \leq CR < 0.1$, meaning the CR must be more than or equal to 0 and less than 0.1. Before the CR can be calculated, the CI must be determined. To determine the CI the following formula is firstly applied to calculate the weighted sum $\{W_s\} = [C]\{W\}$, where [C] is the pairwise comparisons from figure 7.2, and {W} is the weight of the criteria from figure 7.3. For CO_2 emissions compared to itself the calculation would be the following: $\{W_s\} = [C]\{W\} = 1 * 26.3\% = 0.26$. This is done for all combinations of the matrix and the results can be seen in the following figure 7.4.

	CO2 Emissions	Total cost	Excess capacity	Risk	Sum(W_s)	Consistency vector
CO2 Emissions	0,26	0,19	0,37	0,28	1,10	4,17
Total cost	0,79	0,56	0,61	0,40	2,36	4,22
Excess capacity	0,09	0,11	0,12	0,17	0,49	4,04
Risk	0,05	0,08	0,04	0,06	0,23	4,04

Figure 7.4: W_s input to the CI & CR calculations

Hereafter, the row sum $Sum(W\_s)$ for each criteria is calculated, the results can be seen in figure 7.4 in the '$Sum(W\_s)$' column. This is used to calculate the consistency vector using the following formula: $Consistency\ vector = \{\frac{Sum(W\_s)}{W}\}$, and the results of this calculation is seen in figure 7.4 in the 'Consistency vector' column. This is now used to calculate the average value of the consistency vectors, the calculation of this can be seen in equation 7.2 below.

$$Average\ value\ of\ consistency\ vectors = \frac{4.17 + 4.22 + 4.04 + 4.04}{4} = 4.118 \quad (7.2)$$

Now these values can be used to calculate the CI which uses the following formula 7.3, where n is the number of criteria [40,p.965].

$$CI = \frac{Average\ value\ of\ consistency\ vectors\ -\ n}{n-1} = \frac{4.118-4}{4-1} = 0.039 \quad (7.3)$$

With the CI calculated to be 0.039, the next step is to calculate the CR, which is done in the following equation 7.4. In this formula, the 'Random Consistency Index' depends on the number of criteria that are evaluated, and it is given by Thomas L. Saaty who invented the AHP method. Seeing as there are 4 criteria used in the AHP, the random index is 0.90.

$$CR = \frac{CI}{Random\ Consistency\ Index} = \frac{0.039}{0.90} = 0.044 \quad (7.4)$$

With the CR calculated to be 0.044 the input values are considered consistent, as the CR fulfills its constraints: $0 \leq CR < 0.1$. This concludes the second step of the AHP of ranking of the criteria by their importance.

7.1.3 Ranking of scenarios

The third step of the AHP is to rank the scenarios for each criteria, using the same method as in the previous step. Seeing as the AHP method was described in detail in the previous step, these subsections will only present the scores and CR values. The full calculations can be seen in the attached appendix B.4.

CO_2 emissions

Through the scenarios the amount of CO_2 emitted was determined. The results of this can be seen summarized in the following table 7.3, which shows the total distance in km and the $kgCO_2$ emitted per scenario.

Table 7.3: Distance [km] and $kgCO_2$ emitted per scenario

Scenario	Distance [km]	$kgCO_2e$
1	351,038	507,269
2	261,989	378,589
3	255,754	369,579

As seen in table 7.3 scenario 3 emits the least CO_2, and therefore performs best regarding this criteria. These results are now used to score the scenarios and calculate the CR, the full calculations for this can be seen in the attached appendix B.4 in sheet 'CO2 Emissions'. When scenario 1 is compared to scenario 2 it is given a score of 1/4, meaning scenario 1 performs worse than scenario 2. This score is given seeing as scenario 1 emits the most CO_2 and roughly 127,000 kg more than scenario 2. When scenario 1 is compared to scenario 3 it is given a score of 1/5, meaning scenario 1 performs much worse than scenario 3. When scenario 2 is compared to scenario 3 it is given a score of 1/2, meaning scenario 2 performs slightly worse than scenario 3. This score is given as scenario 3 emits roughly 9,000 $kgCO_2$ less.

Option number		1	2	3
	Alternative options	Scenario 1	Scenario 2	Scenario 3
1	Scenario 1	1,00	0,25	0,20
2	Scenario 2	4,00	1,00	0,50
3	Scenario 3	5,00	2,00	1,00
	Sum	10,00	3,25	1,70

Figure 7.5: Scores per scenario for CO_2 emissions

With the scores given as seen in figure 7.5, the same method is applied as with the criteria to calculate the CR. The results of this results in a CR of 0.021 meaning the inputs are validated as being consistent. This concludes the CO_2 emissions comparison, and the following subsection will evaluate the total cost of the scenarios.

Total cost

Through the scenarios the total cost of setting up a pre-sorting system was determined, these costs can be seen below in table 7.4.

Table 7.4: Total cost per scenario [DKK]

Scenario	Total cost
1	58,970,141.75
2	57,347,348.29
3	56,671,842.11

Based on the results seen in table 7.4, scores are given for each scenario. When scenario 1 is compared to scenario 2 it is given a score of 1/3, meaning scenario 1 performs slightly worse than scenario 2 in terms of total cost. This score is given seeing as there is difference of roughly 1,600,000 DKK between the two scenarios. When scenario 1 is compared to scenario 3 a score of 1/5 is given, meaning scenario 1 performs much worse than scenario 3. When comparing scenario scenario 2 with scenario 3 a score of 1/2 is given, meaning scenario 2 performs slightly worse than scenario 3, due to the roughly 700,000 DKK difference between the two scenarios. The following figure 7.6 contains all the scores, and the calculations can be seen in the attached appendix B.4 in the sheet 'Total cost'.

Option number		1	2	3
	Alternative options	Scenario 1	Scenario 2	Scenario 3
1	Scenario 1	1,00	0,33	0,25
2	Scenario 2	3,00	1,00	0,50
3	Scenario 3	4,00	2,00	1,00
	Sum	8,00	3,33	1,75

Figure 7.6: Scores per scenario for total cost

Using these scores a CR of 0,016 is found, the inputs are therefore validated as being consistent, and this concludes the cost comparison. The following subsection will evaluate the excess capacity of the scenarios.

Excess capacity

Through the MILP the excess capacity was determined for each of the scenarios, a summary of these results can be seen below in table 7.5.

Table 7.5: Excess capacity per scenario [tons]

Scenario	Excess capacity
1	32,011
2	22,102
3	25,150

As seen in table 7.4 scenario 1 has the highest amount of excess capacity. The closer a scenario is to the required excess amount of 13,249 tons, the better it will perform. This is because having a lot of unnecessary excess capacity will tie up monetary resources, based on these excess capacities the following scores are given. When scenario 1 is compared to scenario 2 a score of 1/5 is given, meaning scenario 1 performs much worse than scenario 2. This score is given seeing as scenario 1 has roughly 10,000 tons more excess capacity than scenario 2. When scenario 1 is compared to scenario 3 a score of 1/3 is given, meaning scenario 1 performs slightly worse than scenario 3. This score is given seeing as scenario 1 has roughly 7,000 tons more excess capacity. When scenario 2 is compared to scenario 3 a score of 3 is given, meaning scenario 2 performs slightly better than scenario 3. This score is given seeing as scenario 2 has roughly 3,000 tons less excess capacity. A full list of these scores and the reciprocal scores can be seen in figure 7.8, and the calculations can be seen in attached appendix B.4 in sheet 'Excess capacity'.

Option number		1	2	3
	Alternative options	Scenario 1	Scenario 2	Scenario 3
1	Scenario 1	1,00	0,20	0,33
2	Scenario 2	5,00	1,00	3,00
3	Scenario 3	3,00	0,33	1,00
	Sum	9,00	1,53	4,33

Figure 7.7: Scores per scenario for excess capacity

The CR for these inputs equals 0.033, thereby validating the consistency of these. This concludes the excess capacity comparison, the following subsection will compare the risk of the scenarios.

Risk

To determine if the risk varies between the scenarios, all the risks and the severity associated with them must be identified. Through brainstorming and literature research the following risks were identified.

- Incorrect citizen use
- Low per-capita disposal
- Low future demand for recyclables
- Political focus
- Investment risk
- Negative growth of recyclables in the market

The first identified risk is incorrect citizen use of the used textile system, this risk occurs when citizens deliver used textiles to the wrong actor, e.g. WMCs receiving reusable textiles. The next risk is low per-capita disposal of used textiles through the separate collection system. This occurs when citizens keep textiles in their home rather than disposing of them or dispose of them through systems that are not intended for used textiles such as household waste. Low future demand of recyclables impacts the pre-sorters by having fewer potential buyers, and thereby decreasing the potential income made from selling these recyclable textiles. These risks do not vary depending on the scenarios, and they are therefore not included in the scoring of the scenarios.

Three risks were identified where the severity is higher for new facilities then for NGOs with existing facilities, these are risk of shift in political focus, risk of investment, negative growth of recyclables in the market, and low future demand for recyclables. If the political focus shifts and for example the requirement of the pre-sorter to be a private company is removed, there is a chance the WMCs will perform the pre-sorting themselves. If that is the case, then all pre-sorting facilities will receive less recyclables and textile waste, resulting in higher excess capacity for pre-sorting. The NGOs could use this capacity for sorting reusable textiles instead, whereas new facilities would have to set up entirely new processes. The investment required is also lower for a NGO as they will only expand their facilities instead of setting up entirely new ones, making the investment risk higher for new facilities. If the future volume of recyclables and textile waste is decreasing, then the allocated capacity for a NGO facility can still be used to sort reusable textiles, while new facilities would have higher excess capacities. For these reasons, scenarios that use new facilities rather than existing facilities from NGOs will have higher risks associated.

Based on this information the following scores are given. When comparing scenario 1 to scenario 2 a score of 4 is given, as scenario 2 only uses new facilities while scenario 1 only expands established facilities, therefore the risks associated are lower for scenario 1. When comparing scenario 1 with scenario 3 a score of 3 is given, as some of the facilities in scenario 3 are new and some are expansions. When comparing scenario 2 to scenario 3 a score of 1/3 is given, meaning scenario 2 performs slightly worse than scenario 3 based on risks. This score is given as scenario 2 only uses new facilities, and scenario 3 uses some of both. Below in figure 7.8 a full list of the input values can be seen, and the calculations can be seen in the attached appendix B.4 in sheet 'Risk'.

Option number		1	2	3
	Alternative options	Scenario 1	Scenario 2	Scenario 3
1	Scenario 1	1,00	4,00	3,00
2	Scenario 2	0,25	1,00	0,33
3	Scenario 3	0,33	3,00	1,00
	Sum	1,58	8,00	4,33

Figure 7.8: Scores per scenario for risk

Based on the input scores, the CR is calculated being 0.064 which thereby validates the consistency of the inputs. This concludes the second step of the AHP, and the next step will assess the overall performance of the scenarios.

7.1.4 Assessment

The following figure 7.9 summarizes the scores given for each of the scenarios and the weight of the criteria. This information is used to determine the overall sum of these inputs, this indicates which scenario is the most optimal based on the criteria. This is calculated by multiplying the individual score of the scenario in each criteria with the weight of the criteria from figure 7.3. An example of this calculation for scenario 1 would be the following; $0.10 * 26.3\% + 0.12 * 55.8\% + 0.11 * 12.2\% + 0.61 * 5.7\% \;=\; 14.18\%$. This is done for all scenarios, and the results can be seen in the 'Sum' column of figure 7.9.

Alternative options	CO2 Emissions	Total cost	Excess capacity	Risk	Sum
Scenario 1	0,10	0,12	0,11	0,61	0,14179051
Scenario 2	0,33	0,32	0,63	0,12	0,350609827
Scenario 3	0,57	0,56	0,26	0,27	0,507599663
Weight	26,3%	55,8%	12,2%	5,7%	

Figure 7.9: AHP results

From this it can be concluded that scenario 3 is most optimal based on the criteria, with a score of 51.08% of a total 100% given. Scenario 3 performs best in the two most important criteria CO_2 emissions and total cost, in the other two criteria excess capacity and risk it performs second best. This concludes the AHP assessment, and the following section will now evaluate the economic feasibility of the optimal scenario as found by through the AHP.

7.2 Economic feasibility

The AHP analysis concluded that scenario 3 was the best scenario of the 3 based on the chosen criteria, however whether it is economically feasible is yet to be determined. To establish this, it must be identified if there are any additional costs occurring after the pre-sorting has been done and if there is any income from the recyclable textiles. The scenario is economically feasible when the generated income outweighs the total cost, meaning there is a profit instead of a loss.

In section 3.3 in the preliminary chapter it was determined that in 2016, 10,218.40 tons of textile waste are part of the volume that must be pre-sorted. When applying the yearly growth of 4.42 % for 5 years, the amount of textile waste in 2021 is 12,685.32 tons. After being sorted out during the pre-sorting process, this volume of textile waste has to be sent to be incinerated or landfilled which will result in additional cost. It was informed by Steen Trasborg, that this costs approximately 60 €/ton of textile waste, which equals to 446.19 DKK/ton. When applying this cost to the volume of textile waste from 2021, an additional 5,660,063 DKK have to be added to the total cost. This means that the pre-sorting of all received textiles and the handling of textile waste results in a total loss of 62,331,905.11 DKK as opposed to the previous loss of 56,671,842.11 DKK.

In addition to the textile waste, also the assumed 11% of reusable textiles are sorted out during the pre-sorting process and have to be handled afterwards. In 2021, the amount of reusables corresponds to 5,438.35 tons, which are in accordance with the new law, presumably given to NGOs. Therefore, no additional income nor cost is assumed for the reusable textiles.

In the preliminary chapter in section 3.1 it was specified that the recyclable textiles will be sent to SIPTex in Malmø. It is informed from actors that it costs approximately 60 €/ton of recyclable textile to be sorted at SIPTex, which equals to 446.19 DKK/ton. In order to determine the total cost associated with getting the recyclable textiles sorted at SIPTex, only the actual volume of recyclables will be considered. In 2016, the volume of recyclables was 29,606.60 tons as determined in section 3.3 in the preliminary analysis chapter, and when applying the yearly growth of 4.42% for 5 years, the volume of recyclables for 2021 is 36,754.2 tons. When these 36,754.2 tons are sorted at SIPTex for 446.19 DKK/ton, it results in an additional cost of 16,399,356.5 DKK. When this is added to the cost of pre-sorting of 62,331,905.11 DKK in 2021 which includes handling waste, it results in a total loss of 78,731,261.61 DKK as there is assumed to be no income generated.
Having the recyclables sorted at SIPTex is what should be done to keep transportation at a minimum, as it is the only automated sorting facility in the Nordics with available capacity to receive recyclables. However, because there is currently no income when pre-sorting recyclables and textile waste, the recyclables could be sold to other countries where they could generate a small income, depending on whom they are sold to.

It is known that the price for recyclable textiles has rapidly decreased over the past years, as it can be seen in figure 7.10 below. This graph shows the price development over the past 4 years, when ARWOS sells one ton of recyclables, as informed by Kresten Thomsen.

Figure 7.10: Price development

In the figure it can be seen, that the price for 1 ton of recyclables is rapidly decreasing and reached 0 DKK/ton in 2021. The orange columns show the price per ton per year, and the dotted blue line is a trend-line which indicates how ARWOS assumes the future development of prices for recyclables to be. If it is assumed that this is the price there is payed for recyclables it will give a total loss of 62,331,905.11 DKK.

Steen Trasborg informed that their current income from selling recyclable textiles to customers in Eastern Europe is 0.003 DKK/kg, and similar to ARWOS they are seeing a rapidly declining price development. If the income of 0.003 DKK/kg or 3 DKK/ton is applied to the current volume of recyclables, an income of 110,262.60 DKK will be generated when pre-sorting and selling 36,754.2 tons in 2021. Out of the total cost of 62,331,905.11 DKK for scenario 3 including the cost for handling textile waste, the income of recyclables will cover 0.18% and thereby result in a total loss of 62,221,642.51 DKK.

After having investigated all the possibilities of what can happen to the recyclable textiles after the pre-sorting of them has been done, it can be concluded that all of the options will end out in an economically unfeasible solution. This is because all options currently available for disposing of the pre-sorted recyclables will generate a total loss for the company. This loss is assumed to be the responsibility of the municipality as they are the ones paying for having the recyclables and textiles waste pre-sorted.

7.3 Barriers and benefits for pre-sorting in Denmark

The largest barrier for setting up pre-sorting facilities in Denmark is the economic feasibility because the income of selling recyclable textiles does not cover the cost of pre-sorting and handling the pre-sorted textiles. The results depending on where the recyclables are sent after pre-sorting can be seen in table 7.6 below.

Table 7.6: Summary of economics

Option	-446.19 DKK/ton SIPTex	0 DKK/ton ARWOS customer	3 DKK/ton Trasborg customer
Total loss	78,731,261.61 DKK	62,331,905.11 DKK	62,221,642.51 DKK

Knowing how large of a loss there is associated with operating pre-sorting facilities, it can be investigated how much income there hypothetically is required to break-even. This will be done using two different approaches, one where the government is assumed to cover the loss of the facilities by compensating per ton of textile pre-sorted. Because it is in the interest of the Danish government to ensure that textiles are reused and recycled, it can be assumed that they might have incentive to support the companies who set up pre-sorting facilities through financial aid. The other approach is assuming that SIPTex would pay the pre-sorting facilities per received ton of recyclables. In the current market, this approach does not have a high likelihood of occurring. However if the demand of recyclables does increase so will the number of sorting facilities, and thereby the price of sorting will decrease or even turn into a profit.

Firstly, the required income from the government per ton of pre-sorted textile in 2021 to break-even, is determined in the following equation 7.5, following the assumption that recyclables are sorted at SIPTex for the current cost of 446.19 DKK/ton. This calculation is done also assuming that if the facilities receive money from the government they will be payed per ton pre-sorted and not receive a fixed income.

$$Required\ income\ from\ government = \frac{Total\ cost}{Volume\ of\ pre-sorted\ textiles}$$

$$= \frac{78,731,261.61\ DKK}{54,878\ tons} = 1,434.66\ DKK/ton \quad (7.5)$$

Secondly it can be determined what the income per ton of recyclables from SIPTex should be in order to cover the total cost of pre-sorting and break-even. For 2021, the calculation can be seen in equation 7.6 and it results in a required income of 1,695.91 DKK per ton of recyclables.

$$Required\ income\ from\ SIPTex = \frac{Total\ cost}{Volume\ of\ recyclables}$$

$$= \frac{62,331,905.11\ DKK}{36,754.20\ tons} = 1,695.87\ DKK/ton \quad (7.6)$$

Another barrier that was identified through interviews with actors and experts in the used textile industry, is that the politicians have put the responsibility of taking the next steps for setting up this system onto the actors. However, these actors are not willing to take this responsibility, as there is currently no possibility to generate an income, which makes it economically unfeasible for them to take part in the pre-sorting. Therefore, the actors are waiting for further law changes to be made or development of a monetary compensation system, which would aid the economic feasibility. The separate collection system will be implemented from January 1st 2022, and currently there are no actors to perform the pre-sorting, sorting and recycling of the used textiles after the collection. This means that there are uncertainties in the future for all involved actors in the industry, resulting in them not wanting to make major changes and investments. This is further impacted by the lack of R&D in the used textile industry, therefore making it hard to make well informed decisions. This lack of R&D also limits the innovation in the pre-sorting process, thereby forcing the pre-sorting to be carried out in manual processes which are costly. Automated processes could decrease the cost per tons of pre-sorted textile, and thereby increase the likelihood of a economic feasible pre-sorting system in Denmark.

There are potential benefits of pre-sorting recyclables within Denmark for the purpose of further recycling the textiles. The main possible benefit is the CO_2 savings that recycling can bring, this is because the recycled textiles will be used for production of products that has the potential to replace the production of new ones. This will thereby reduce the amount of CO_2 emitted from producing new textiles, and no virgin materials will be used for this process which delimits the depletion of natural resources. The exact CO_2 saving will vary depending on two parameters; the fiber composition of the textile and the recycling process applied. Currently there is no accurate data on the general fiber compositions of Danish used textiles, which thereby makes it impossible to accurately determine the CO_2 savings. The exact recycling process applied is also unknown, as currently no established facilities are doing this process in Denmark. It is assumed that there will be a CO_2 benefit of pre-sorting, it is however not possible to determine this exact scale.

7.4 Sub-conclusion scenario evaluation

For the evaluation of the analysed scenario, AHP was applied. As the first step of the AHP, the following 4 criteria were determined to be suitable for the evaluation of the scenarios; environmental sustainability, economic sustainability, excess capacity, and risk. Of these the environmental sustainability is measured in CO_2 emissions, and economic sustainability in total cost.
When ranking these criteria in terms of their relative importance, it was found that total cost is most important with a weight of 55.8%, followed by CO_2 emissions with 26.3% and excess capacity with 12.2%, and risk is least important with a weight of 5.7%.
After scoring the scenarios for each criteria, the AHP assessment showed that scenario 3 scores best overall regarding the 4 criteria, followed by scenario 2, and scenario 1 scored worst.
Through the comparison of the total cost and possible income for scenario 3 it was found that it is not economically feasible to set up pre-sorting facilities in Denmark, as the cost is much higher than any potential income.
The economic feasibility was determined to be the largest barrier for pre-sorting in Denmark. It was found that an income of 1,434.66 DKK per ton of pre-sorted textile is required from the government in order to cover the total costs, or an income of 1,695.87 DKK per ton of recyclables from SIPTex. Another barrier was seen in neither politicians nor actors wanting to take on responsibility for changes in the system. Also the lack of R&D in the field of used textiles was found to impact the economic feasibility, and therefore as another barrier. As a possible benefit from pre-sorting in Denmark it was found that there might be CO_2 savings from recycling compared to new production of textiles, however it was not possible to quantify the impact of this.

Discussion 8

The purpose of this chapter is to discuss the results found throughout the report, and it is divided into the 3 parts; preliminary analysis, scenario analysis, and scenario evaluation.

8.1 Preliminary analysis

Required pre-sorting level
In the preliminary chapter it was assumed that all recyclables from the pre-sorting will be sent to SIPTex for further sorting. This assumption was made because it was the only automated sorting facility in the Nordics who at the time had capacity available to receive volumes. However, SIPTex currently has a capacity of 24.000 tons per year, meaning that they can not receive the full Danish volume of 36,754.2 tons in 2021 for further sorting, as it has been assumed throughout the report. Through research it was not possible to find any automated sorting facility that is capable of receiving the full Danish volume. If the recyclables were to go to another automated sorting facility, it could change the level that the textiles should be pre-sorted to and thereby the employee productivity, which could decrease the feasibility of the pre-sorting system. Sending the recyclables to a different automated sorting facility can also mean a different price per ton sorted and thereby end up in a different total cost.

Current actors
For the scenario analysis, the 6 main actors in the current used textile industry in Denmark were included as found in literature, which are responsible for the separate collection and handling of approximately 60% of the Danish used textiles. Additional actors could have been included in the analysis, seeing as actors who make up 40% of the current separate collection are not included such as Blue Cross and Folkekirkens Nødhjælp (DanChurchAid). Adding these actors would increase the number of potential pre-sorting facilities, which could lead to a different optimal solution.

Current and future volumes
When determining the volume of used textiles for pre-sorting in the preliminary analysis, the fractions of recyclables and textile waste from different waste streams were added together as found in data from 2016. From this, overall quality ratios are applied for the streams of separate collection, being 19% recyclables and 11% textile waste, and mixed collection, being 63% recyclables and 14% textile waste. Instead of applying these overall ratios to find the volumes of recyclables and textile waste, these quantities could be researched in more detail by investigating the individual actors of each stream. For the volumes in separate collection, all collection actors e.g. Red Cross and Trasborg, could be contacted and questioned on the amount of recyclables and textile waste in their collected

used textiles. For the mixed collected, which consists of bulky waste, small combustibles, and household waste, the ratios of recyclables and textile waste in the 3 streams could be investigated separately. For this report, this detailed approach could not be applied, as some actors do not collect this required data, and it is not available for some waste streams e.g. bulky waste. If the data was available, a more accurate volume of recyclables and textile waste could have been found, which could have lead to a change in the required capacity, and therefore a different total cost.

Furthermore, an additional 11% were added to these volumes of recyclables and textile waste, in order to account for reusable textiles that are disposed of wrongfully. These 11% was based on information received from by an actor in the industry based on their observations. This number could be validated by collecting observations from other actors if available, or conducting test studies. If a different fraction of reusables were to be found, the required capacity of pre-sorting facilities could change due to changing volumes, and therefore affect the total cost of the scenarios.

In order to determined the expected future volume for pre-sorting in Denmark, a yearly change of used textile collection had to be determine in the preliminary analysis. As there was no valid data available for Denmark, numbers from a comparable country with available and consistent data had to be found. For this, the USA was found being economically similar to Denmark and therefore the yearly growth for the US was calculated and applied to the Danish used textile volume. The results for expected future volumes could be more accurate if there was data available about the yearly changes in Denmark, or if a more fitting country in comparison had data available. For the calculation of the expected future volume in Denmark it was then assumed that the found yearly growth of 4.42% continues to occur yearly in the future, leading to a linear increase of used textiles over the next years. This assumption was made due to missing information about changes in the increase, however there are growing numbers of measures taken nationally and internationally to decrease the textile consumption. This means that the applied yearly increase of 4.42% could be set to high for the future years, meaning that the calculated future volumes could be too high. If a more accurate, possibly lower yearly change was applied, the future volume might be lower and therefore the required excess capacity would also be lower. This would thereby lead to lower capacity options being chosen for the scenarios and less employees required, leading to a lower total cost.

Capacity options for pre-sorting facilities

A set number of capacity options were used for the MILP to choose from to ensure that the inputs to the MILP did not exceed the input limitations from the Excel solver software. A more optimal solution might be possible to find if more capacity options were included, or no limitations were set at all, seeing as the total excess capacity could be closer to the required and thereby the total cost could decrease. This was however not possible due to the software limitations, and the 5 capacity options were therefore applied for the scenarios. The set capacities were determined based on the 2021 volume of used textiles, however if instead the required 2026 volume was used, different facility sizes might have been chosen throughout the MILP. This could have impacted the final result of the scenarios through the total cost and excess capacity, however it is uncertain whether the impact would have been beneficial or disadvantageous.

In the preliminary analysis it was assumed that the pre-sorting facilities would operate with one shift a day. This assumption impacted the size of the facilities and thereby the fixed cost. If multiple shifts were used instead it could have lead to smaller facilities being required, and thereby decrease the fixed and total cost.

Variable cost

When calculating the environmental cost, a carbon equivalent conversion factor had to be used as input to the formula. To determine this carbon equivalent conversion factor, the weight of the truck and load had to be assumed, and an average weight of 17 tons or greater was used. However, it was not specified in the used source if the applied weight is only load weight or gross weight including the truck weight. For this report, the gross weight was used in order to account for the worst case scenario, as the higher weight lead to a higher carbon equivalent conversion factor and therefore higher environmental cost. If instead the carbon equivalent conversion factor of the truck load weight was used, the environmental cost would have decreased. However, it would not have lead to a great difference in the total cost as the environmental cost is only a small fraction of the total cost. However, the environmental impact would vary as the CO_2 emissions will differ depending on this.

When finding employee wages, there are three types of employees considered in the analyses; pre-sorters, production manager and drivers. However, when running a pre-sorting facility there are more employees required that were not considered, like cleaning and administrative staff. If these employees were taken into account the cost of running the pre-sorting facilities would increase.

When calculating the pre-sorter wage as part of the variable costs, an employee productivity of 1,200 kg per workday was used. These numbers were used because it was the information there was provided by Steen Trasborg, who is an actor in the industry. However, the results for pre-sorter wages could be more accurate if the employee productivity would instead have been measured in a test study using the determined pre-sorting level required. A different employee productivity could have lead to a different pre-sorter wage per ton of pre-sorted textile, and thereby change the total cost of the scenarios.

The employee wages for pre-sorters and production managers were determined using average wages from the positions in the industry that were assumed to fit the requirement for the employees in the pre-sorting system. For the pre-sorters it was the hourly wage of an unskilled employee, and for the production managers it was the monthly wage of a general production manager. However, the requirements for these employees could be different, in regards to e.g skill level, which could result in different average wages and therefore in different total costs for the scenarios. More accurate inputs for the hourly wages could be found by conducting test studies, or by further research on existing positions in the used textile industry.

The driver wages were calculated using the weighted kilometers multiplied by the average pay per km driven. This calculation was used because it could not be determined how many drivers were needed to transport the used textile volumes as it is assumed that all WMCs have their own drivers hired, also defining how long the required trips would take was not possible. If it was possible to find these inputs to determine the driver wage through average salary and distances driven, the drivers salary could vary, however whether this difference would be beneficial or disadvantageous in terms of cost cannot be determined.

Fixed cost
It is assumed that the facilities will be rented by the company, however in real life the facilities will most likely be bought by the companies operating them. This would lead to a much higher opening cost, and the monthly payment would most likely be the payment on the loan. If this is the case, then after a certain amount of years there will no longer be a monthly payment on a loan, which could result in a different total cost.

In the preliminary chapter it was assumed that expanding a facility would cost 200,000 DKK, and opening a new facility would cost 500,000 DKK. It would have been more accurate to find examples of these costs, however as no comparable costs were found they had to be assumed. If examples were found the cost of these may have increased, which could impact the MILP choices of facilities by choosing to open or expand fewer facilities. In contrast, if examples were found where the cost was lower, then the MILP could have chosen to open or expand more facilities.

8.2 Scenario analysis

In scenario 2 and 3 the 3 biggest cities København, Frederiksberg and Gentofte of the Hovedstaden region were not included as no suitable production facilities were found. The three following largest cities were therefore chosen which impacted the MILP by increasing the cost of transportation. However, if a renting price was assumed for these cities they could be included in the MILP analysis. This could lead to different facilities being chosen, which could decrease the transportation cost. It is however uncertain if this would outweigh the renting cost, so the total impact can not be determined.

Weighted km was used as the average distance from each region to each possible facility in the MILP analysis. This distance had to be used as the WMCs were divided into regions to limit the number of variables in the MILP. If the individual WMCs were included in the MILP it could have resulted in a different optimal solution, which could have decreased the total cost and thereby the economic feasibility of the solution. To do this, software that has a higher limit for the number of variables it allows would have to be used.

In the MILP, one of the constraints was that the excess capacity of the total system has to be larger or equal to the required volume in 2026. As the excess capacity is set for the entire system and not the individual facilities, the excess capacity will not necessarily be evenly distributed between the facilities. This could mean that the facilities who have a high excess capacity are the ones who are located in regions with a low population and thereby low volume of recyclables and textile waste. Which will mean the higher populated area facilities will quicker reach the capacity limit and then the textiles have to be sent to a different facility resulting in higher future cost impacted by the transportation. To ensure that the excess capacity will be evenly distributed according to the volume of the regions, there can be set a capacity requirement per region. However doing this will require the MILP to set up a minimum of one facility in every region. This could contradict the goal of minimizing the total cost, due to higher employee wages in some regions and therefore might not necessarily yield in the most optimal result in terms of cost.

8.3 Scenario evaluation

When evaluating the scenarios and the chosen criteria, the AHP method was used. The scores for the AHP were determined through interviews with experts in the field and careful consideration, however the validity of inputs could be increased further in order to get a more accurate result. To increase the validity the subjectivity of the scores would have to be decreased, to do so more experts would have to be consulted to validate the given scores. By consulting additional experts more criteria could be identified, which could result in a different optimal scenario.

Throughout the report the facilities were chosen to decrease the total cost through minimizing cost of transportation and pre-sorting, however in real life the closest facility may not necessarily be the one which offers the lowest bid. In real life the lowest bid will always be chosen, unless there are other incentives to effect this decision, e.g. CO_2 emission of the transportation. It is however not possible to further analyse this in this project, and therefore the choice of pre-sorting facilities are based on the fixed and variable costs, because these costs are assumed to be used as an input to determine the bids.

It was assumed that the reusable textiles would be given to the NGO, as according to the Danish regulations NGO should receive reusable textiles. It is however uncertain what NGO the textiles should go to and how this would be determined. The choice of what NGO it is sent to could also impact the economic feasibility of the pre-sorting facility depending on who pays for the transportation, packing, and whether the NGOs should pay for the reusable textiles.

The number of employees required for each facility is determined based on the yearly volume of textiles that each facility must pre-sort. It is however uncertain if this number of employees will vary throughout the year, based on seasonal variation in the generation of used textiles. If there is a variation in the volume of textiles throughout the year, then the number of workers required will also vary throughout the year. To determine this a further analysis is required which evaluates the seasonal variation. This is however not possible within the scope of this report, and an uniform distribution of the textile volume throughout the year is therefore assumed.

Conclusion 9

The goal of this project was to evaluate if setting up a pre-sorting system in Denmark is economically feasible and how large its environmental impact will be. To answer this, literature was reviewed to identify analytical methods that should be applied. A research framework was developed, which described the theoretical plan of how the identified methods would be adapted and applied, to the three scenario that were developed.
Throughout the preliminary analysis, it was determined that the required pre-sorting level of the system will be the same as the requirements of SIPTex, meaning that the textiles have to be manually pre-sorted into recyclables, reusables and textile waste. This was determined as SIPTex was the only automated sorting facility in the Nordics who can receive volumes from other countries. Hereafter 6 current main actors were identified as, Trasborg, Red Cross, Salvation Army, UFF, Danmission and DanChurch Social. None of these actors were deemed capable of pre-sorting the recyclables and textile waste, without any adjustments being made to their business. Using historical data from 2016, the current volume of recyclables and textile waste was determined by applying a yearly increase of 4.42% to be 54,878 tons in 2021 and the expected volume in 2026 was also calculated. Hereafter the most suitable transportation mode was determined to be a 40 ft tipping container truck on road which can contain a load of 10.14 tons.
The costs for pre-sorting was divided into variable- and fixed-costs, which consist of different sub parts. Variable cost consisted of transportation cost, which is further divided into environmental- and fuel-cost, and employee wages, which are further divided into pre-sorter-, production manager-, and driver-wages. The fixed cost was found to consist of the renting-, opening-, and expansion-cost. The environmental impact of the scenarios were determined to be measured through CO_2 emissions.

The first scenario investigated the possibilities of pre-sorting in Denmark using the current system with adjustments. Throughout this scenario analysis it was found that 3 of the current main actors were interested in making adjustments and perform pre-sorting in Denmark, these being Red Cross, Salvation Army and Trasborg. Through the MILP it was determined that for this scenario, the optimal solution is to open 3 medium facilities respectively at the locations of Red Cross in Horsens (M), Trasborg in Taastrup (H), and Salvation Army in Kolding (Sd). This solution resulted in a total cost of 58,970,141.75 DKK for 2021, with a total excess capacity of 32,011 tons, and 507,269.2 $kgCO_2$ emitted.
The second scenario looked into setting up new facilities for pre-sorting in Denmark, the possible locations were determined based on population centers. Through this scenario analysis it was determined that the optimal solution is to open 3 low/medium facilities respectively in Aalborg (N), Viborg (M) and Odense (Sd) and one medium facility in Gladsaxe (H). This solution resulted in a total cost of 57,347,348.29 DKK for 2021, with

a total excess capacity of 22,103 tons, and 378,589 $kgCO_2$ emitted.
The third scenarios analysed if a hybrid of scenario 1 and 2 would result in a more optimal solution, meaning a lower cost. The optimal solution of this scenario was to open 5 low/medium facilities respectively in Århus (M), Gladsaxe (H), Hjørring(N), Red Cross in Køge (S), and Salvation Army in Kolding (Sd). This resulted in a total cost of 56,671,842.11 DKK for 2021, with a total excess capacity of 25,150 tons, and 369,579.12 $kgCO_2$ emitted.

AHP was applied for the evaluation of the scenarios and the following 4 criteria were determined to be suitable for this evaluation; environmental sustainability, economic sustainability, excess capacity, and risk. Of these the environmental sustainability was measured in CO_2 emissions, and economic sustainability in total cost. When these criteria were ranked regarding their importance, it was found that total cost was most important, followed by CO_2 emissions, then excess capacity, and lastly risk. After the scenarios were scored for each criteria, the AHP assessment determined that scenario 3 was overall the best solution based on the 4 criteria.
After the pre-sorting the recyclables and textile waste must be handled further. If all recyclables are sorted at SIPTex and the textile waste is burned in Denmark there will be a total cost of 78,731,261.61 DKK associated with scenario 3. It was found that currently only a very small income can be generated, if the recyclables are sold to Eastern Europe. Using these numbers it was found that it is not economically feasible to set up pre-sorting facilities in Denmark, based on a comparison between the total cost and possible income for scenario 3.

The largest barrier for pre-sorting recyclable and textile waste in Denmark was found to be the economic in-feasibility of the system. An additional barrier was identified in the fact that neither politicians nor actors are wanting to take on responsibility for making changes in the current system. Also the lack of R&D in the field of used textiles was found to impact the economic feasibility, and therefore it is found to be another barrier. There was a potential benefit identified when pre-sorting recyclables through possible CO_2 savings, by using the recycled materials instead of using virgin materials to produce new products. It was however not possible to determine the amount of possible CO_2 savings in this context, as it depends on the fractions of fiber composition and the recycling process applied.

Based on the analysis it can thereby be concluded that it is currently not possible to set up an economically feasible pre-sorting system in Denmark. However if the system were set up there would be emitted 369,579.12 $kgCO_2$, and whether this negative environmental impact could be outweighed by the possible benefits of the new system will require further analysis to be determined.

10 Reflection

This chapter will reflect on the direction of the project and possible other directions that the project could have taken. Furthermore it will describe further studies that are suggested to be made within the field of increasing sustainability of the used textile system in Denmark.

Throughout this project it was assumed that from January 1st 2022, recyclables and textile waste will be separately collected by the WMCs from households using bags. This was done as it was informed by Nikola Kiørboe, an expert in the used textile field, that it was proposed to the Danish Environmental Department to implement the bag collection method nationwide. If this assumption is incorrect, the results of this report could be invalid. If the collection method of the WMCs would differ from the assumed bag collection, then the origin points of the transports of recyclables and textile waste to the pre-sorting facilities could change, thereby leading to a different optimal solution.

In this report, the current capacities of the main current actors were not allocated to the pre-sorting of recyclables and textile waste, but instead it was assumed that their capacities and resources are continued to be used for the handling of their received reusables. This was done as it was informed through the interviews that the main actors would continue to collect and sell reusable textiles, and therefore their current capacities will still be necessary to sort these textiles. If instead their current capacities were to be used for pre-sorting recyclables and textile waste, the direction of this project could have changed to investigating the accurate existing capacities of all possible actors for pre-sorting. This would be necessary as the actors would not have to expand their facilities as much when using the existing capacities, which would lead to a decrease of the total cost.

The analysis could have taken a different direction by analysing the impact of having recyclables and textile waste in inventory at the WMCs and pre-sorting facilities. This could affect the required frequencies of transports to the pre-sorting facilities and the capacities of the pre-sorting facilities. It has been informed by experts and found in literature that a critical issue of holding inventories of used textiles can be contamination. Wet textiles or waste from other waste fractions can contaminate the recyclable- and reusable-textiles, meaning that they then cannot be recycled or reused anymore and would have to be incinerated as textile waste. This would lead to a lower CO_2 saving and potentially decrease the economical feasibility of the scenarios. However, additional analysis is required on the impact of such inventories and how often contamination would occur. Based on these results, the optimal solution could differ by e.g. increasing the frequency of transports or the capacities of the pre-sorting facilities to avoid inventory contamination.

When analysing the pre-sorting system scenarios, CO_2 emissions were accounted for through the environmental cost calculated for the transports between the regions and pre-sorting facilities. However, these transports are only a part of a larger supply chain where CO_2 is emitted throughout. For example, the recyclables and textile waste are collected by the WMCs from households in Denmark, and these transports between households and WMCs mean further CO_2 emissions. Also processes required after the pre-sorting lead to CO_2 emissions, for example the transportation of recyclables from the pre-sorting facilities to a sorting facility. A different direction of the project could be the analysis of all CO_2 emissions connected to the system, like from operating the pre-sorting facility, with the goal to minimize the total CO_2 emitted. By including further CO_2 emissions in the analysis, the optimal solution could differ by e.g. choosing different pre-sorting facility locations due to increased focus on transports.

In the preliminary analysis chapter it was assumed that the transports between WMCs and pre-sorting facilities would occur weekly. However the frequency of transports would vary depending on the specific WMC, due to the different volumes of recyclables and textile waste that they receive. In order to determine the optimal frequency, the available inventory of the WMCs and incoming volumes must be evaluated, which is a different direction that this project could have taken. In general all facilities would want to fully load each truck to increase the utilization of the transport and thereby decrease the cost of transporting the used textiles.

10.1 Further studies

The total cost of setting up a pre-sorting system within Denmark could be put into perspective by identifying similar costs associated with sorting systems of other waste fractions. Because currently the pre-sorting of used textiles is a manual process, the cost for handling 1 ton of recyclables and textile waste might be significantly higher than for other waste fractions, such as plastics, where some processes are automated. If other waste fractions result in an equally high cost of operating their system, inspiration could be taken from how they generate an income that outweighs the costs. This could aid in improving the system for recyclables and textile waste and in determining possible other ways to make setting up a pre-sorting system in Denmark economically feasible.

As it can be seen throughout the scenario analysis, the employee wages make up approximately 80% of the total cost, and majority of this is the pre-sorter wage. There could be made an MILP that has the focus on further decreasing this pre-sorter wage instead of minimizing the total cost, which the MILPs in this project have had as their focus. To do so, a scenario could be developed that focuses on decreasing the pre-sorter wages by picking less populated areas for possible pre-sorting facility locations. This would decrease the employee wages as these costs are lower in less populated areas than in population centers. To make this analysis, the regional employee wages would have to be broken down further into wages per municipality which should then be used as inputs to the MILP. This could lead to possibly different locations being chosen for pre-sorting facilities, and to a decrease of the employee wages.

Throughout the scenario evaluation chapter it was determined that pre-sorting recyclables and textile waste in Denmark is economically unfeasible, as the total cost is higher than the possible income. It could be further studied how and where the pre-sorting can be feasibly performed. Here the environmental impact of sending the pre-sorted textiles to the NGOs' current customers in Eastern Europe could be investigated, as this was found to currently by the only option where income can be generated. Furthermore it could be looked into whether or not this system would fulfill the requirements of following the waste hierarchy stated by the government, and if it is economically feasible.

This report solely focuses on the pre-sorting of recyclables and textile waste within Denmark, however this is only a part of creating a circular system for used textiles. It has to be further investigated if the following steps of sorting and recycling the pre-sorted textiles are feasible to keep within Denmark or if these processes should be outsourced. The same conclusion of economic in-feasibility was drawn after investigation possibilities for a textile sorting system in Sweden [12,p.26]. A study could be made looking into if a collaboration between Nordic countries regarding setting up and possibly sharing pre-sorting facilities would aid the economic feasibility of a pre-sorting system by for example sharing resources or develop new technologies.

When collecting recyclables and textile waste using the bag collection method, it is assumed that the textiles are collected in plastic bags that have to be opened and removed at the pre-sorting facilities. The amount of plastic bags and what happens with them after the pre-sorting has to be further studied, as this also has an influence on the environmental impact and the economic feasibility of the system.

The results of the MILP could be verified using a simulation which would account for the real life variation in regards to the collected volumes. To do so it would be required to have historical data on daily or weekly collections of recyclables and textile waste as inputs. This would make it possible to show the variation of required truck loads throughout the year, and to determine if there will always be textiles to pre-sort for the number of employees determined in the MILP.

A further study could be done to determine whether the negative environmental impact of a scenario can be outweighed by the possible benefits of the pre-sorting system. This would require analysis on the general fiber composition of recyclable textiles in Denmark, and on the recycling process that should be applied. By doing so it can be determined how much CO_2 could be saved by replacing new products with ones made of recycled textiles. Thereby it can be determined if the overall environmental impact will be positive or negative.

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Appendix A

A.1 Appendix 1

Author	Source	Definition
Lounais-Suomen Jätehuolto Oy (LSJH) municipal waste management company in Finland	Towards 2025: Separate collection and treatment of textiles in six EU countries [15]	4 levels of pre-sorting: 'The basic level is to manually remove contaminants and non-textiles from the separately collected textile waste. The second level of manual pre-sorting includes additional removal or reusable/rewearable items – either by the municipalities themselves or by local partners. The third level of manual pre-sorting is removal of items not suitable for mechanical textile recycling, multilayer garments. The fourth and last level of pre-sorting includes sorting of mixed textile waste into different recycling products with specific material compositions (100% cotton, polyester, wool and viscose as well as 50:50 polycotton) using handheld infra-red (IR) scanners plus a remaining sorting rest.' [15,p.64]
Swedish Innovation Platform for Textile sorting (SIPTex), textile sorting in Sweden	Towards 2025: Separate collection and treatment of textiles in six EU countries [15]	Accepting 'pre-sorted recycling fractions from manual sorting'

Table A.1: Pre-sorting definitions from literature

A.2 Appendix 2

Table A.2: Weighted km per facility per region S3

	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
Aalborg (N)	32.28	126.06	251.40	376.48	425.55
Hjørring (N)	54.63	179.08	289.73	427.79	472.32
Frederikshavn (N)	67.71	189.05	314.40	439.98	488.59
Århus (M)	138.36	51.50	140.57	265.98	311.98
Randers (M)	100.86	64.25	171.44	296.98	345.56
Viborg (M)	94.91	59.26	153.67	287.11	334.20
Odense (Sd)	268.27	154.19	74.57	128.09	175.60
Esbjerg (Sd)	280.23	142.32	96.49	258.06	306.79
Vejle (Sd)	196.19	81.20	74.32	198.51	249.44
Roskilde (S)	396.42	281.11	198.96	42.77	42.64
Næstved (S)	367.09	252.48	170.25	42.33	98.24
Slagelse (S)	338.18	222.79	142.39	57.24	103.28
Gladsaxe (H)	430.93	315.45	233.19	68.07	18.64
Rudersdal (H)	442.42	301.04	244.65	79.43	23.47
Helsingør (H)	467.25	351.82	269.62	104.35	43.98
Trasborg (H)	402.27	298.17	217.35	50.54	33.64
Red Cross (S)	391.03	275.68	194.44	42.46	50.74
Red Cross (M)	177.88	69.60	96.68	222.44	265.14
Salvation Army (Sd)	210.07	101.60	59.15	185.73	235.38
Salvation Army (H)	417.64	302.89	222.97	59.97	27.27

Table A.3: Variable cost per facility per region S3 [DKK/ton]

to / from	Nordjylland	Midtjylland	Syddanmark	Sjælland	Hovedstaden
Aalborg (N)	862.69	1,113.39	1,448.46	1,782.84	1,914.02
Hjørring (N)	922.42	1,255.13	1,550.94	1,920.01	2,039.05
Frederikshavn (N)	957.40	1,281.77	1,616.88	1,952.58	2,082.54
Århus (M)	1,169.44	937.24	1,175.35	1,510.58	1,633.57
Randers (M)	1,069.19	971.30	1,257.85	1,593.46	1,723.35
Viborg (M)	1,053.26	957.96	1,210.36	1,567.07	1,692.96
Odense (Sd)	1,516.67	1,211.71	998.86	1,141.94	1,268.93
Esbjerg (Sd)	1,548.64	1,179.96	1,057.45	1,489.38	1,619.64
Vejle (Sd)	1,324.00	1,016.58	998.20	1,330.20	1,466.34
Roskilde (S)	1,977.10	1,668.84	1,449.23	1,031.68	1,031.32
Næstved (S)	1,898.68	1,592.29	1,372.47	1,030.51	1,179.98
Slagelse (S)	1,821.39	1,512.92	1,298.00	1,070.37	1,193.43
Gladsaxe (H)	2,077.64	1,768.92	1,549.01	1,107.61	975.45
Rudersdal (H)	2,108.37	1,730.40	1,579.65	1,137.98	988.38
Helsingør (H)	2,174.74	1,866.15	1,646.42	1,204.60	1,043.22
Trasborg (H)	2,001.03	1,722.75	1,506.69	1,060.75	1,015.57
Red Cross (S)	1,962.67	1,654.32	1,437.13	1,030.86	1,052.99
Red Cross (M)	1,275.08	985.62	1,057.99	1,394.19	1,508.35
Salvation Army (Sd)	1,361.09	1,071.12	957.65	1,296.03	1,428.74
Salvation Army (H)	2,042.13	1,735.35	1,521.71	1,085.96	998.54

Table A.4: Average renting cost per facility S3 [DKK/m_2]

Facility	Price
Aalborg (N)	322
Hjørring (N)	225
Frederikshavn (N)	200
Århus (M)	493
Randers (M)	400
Viborg (M)	192
Odense (Sd)	135
Esbjerg (Sd)	345
Vejle (Sd)	426
Roskilde (S)	400
Næstved (S)	289
Slagelse (S)	375
Gladsaxe (H)	448
Rudersdal (H)	531
Helsingør (H)	600
Trasborg (H)	400
Red Cross (S)	439
Red Cross (M)	365
Salvation Army (H)	597
Salvation Army (Sd)	360

Table A.5: Fixed cost per facility per capacity option S3 [DKK/year]

to / from	Low	Low/medium	Medium	Medium/high	High
Aalborg (N)	56,350.00	295,903.13	535,456.26	775,009.39	1,014,562.52
Hjørring (N)	39,375.00	206,764.61	374,154.22	541,543.83	708,933.44
Frederikshavn (N)	35,000.00	183,790.76	332,581.53	481,372.29	183,790.76
Århus (M)	86,275.00	453,044.23	819,813.47	1,186,582.70	1,553,351.94
Randers (M)	70,000.00	367,581.53	665,163.06	962,744.59	1,260,326.12
Viborg (M)	33,600.00	176,439.13	319,278.27	462,117.40	604,956.54
Odense (Sd)	23,625.00	124,058.77	224,492.53	324,926.30	425,360.06
Esbjerg (Sd)	60,375.00	317,039.07	573,703.14	839,367.21	1,087,031.27
Vejle (Sd)	74,550.00	391,474.33	708,398.66	1,025,322.98	1,342,247.31
Roskilde (S)	70,000.00	367,581.53	665,163.06	962,744.59	1,260,326.12
Næstved (S)	50,575.00	265,577.65	480,580.31	695,582.96	910,585.62
Slagelse (S)	65,625.00	344,607.68	623,590.37	902,573.05	1,181,555.73
Gladsaxe (H)	78,400.00	411,691.31	744,982.62	1,078,273.94	1,411,565.25
Rudersdal (H)	92,925.00	487,964.48	883,003.96	1,278,043.44	1,673,082.92
Helsingør (H)	105,000.00	551,372.29	997,744.59	1,444,116.88	1,890,489.17
Trasborg (H)	70,000	367,581.53	665,163.06	962,744.59	1,260,326.12
RedCross (S)	76,825	403,420.73	730,016.46	1,056,612.18	1,383,207.91
RedCross (M)	63,875	335,418.15	606,961.29	878,504.44	1,150,047.58
Salvation Army (Sd)	104,475	548,615.43	992,755.86	1,436,896.30	1,881,036.73
Salvation Army (H)	63,000	330,823.38	598,646.75	866,470.13	1,134,293.50