Wageningen University - Department of Social Sciences

Operations Research and Logistics

MSc Thesis

Decision support model for optimizing the complex and wet waste valorisation chain

Abstract

A growing world population leads to higher demand of products and increased generation of complex and wet waste streams, which are currently incinerated or landfilled. Valorisation of these waste streams into high-valuable products would decrease CO2 emissions and resource scarcity. Many research is performed for the technical complications, but decision support models are lacking. In this research, the structure of the complex and wet waste supply chain is described and its bottlenecks are identified by means of a literature review. A multi-objective mixed integer linear programming model is proposed that integrates multi-feedstock valorisation and makes separated pretreatment facilities optional based on economic and environmental objective functions. The model is able to make decisions based on the quality and quantity of the waste and products, available locations and valorisation options and quantify the effects of these decisions in economic and environmental impact. An illustrative example for corn stover and paper sludge valorisation is setup to demonstrate the capabilities and managerial insights of the proposed model. The results suggest that multi-feedstock valorisation and separated pretreatment facilities lead to economic and environmental benefits. Future research is advised to include scaling.

Key words: complex and wet waste, waste valorisation, multi-objective optimization, multi-feedstock valorisation, decision support tool

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1. Introduction

Currently, complex and wet waste is not yet fully recycled, resulting in environmental problems and inefficient resource use (Sharma et al., 2019). With an ever-growing population, this problem is likely to worsen (Maja & Ayano, 2021; United Nations' World Population Prospects Report, 2017). Improved valorisation processes can be used to recycle and convert these types of waste into valuable products, replacing the use of virgin resources (Pereira & Silva, 2023). Furthermore, valorisation instead of landfilling or incineration reduces CO_2 emissions, which is essential for a sustainable planet (Roberts et al., 2022). An example of a successful valorisation is PET recycling, which reduced the carbon footprint by 1.9 CO_2-eq. per kg PET (Bergsma & Imholz, 2022).

The complex and wet streams are combinations of several compounds which are hard to convert, such as metals, lignin, cellulose, and plastics and besides contain a high moisture content (Zeeman & Sanders, 2001). Examples are agro/food residues, mixed biomass/plastic, and sludges. It is expected that valorisation of these waste streams is environmentally beneficial as it decreases incineration and landfilling. Additionally, the reintroduction of valuable components in a supply chain may be economically beneficial (Gemar et al., 2021). While there is plenty research related to the technical side of the complex and wet waste valorisation, research regarding the supply chain design is limited (Esparza et al., 2020; Nayak & Bhushan, 2019).

However, optimal decisions at the strategic level of the supply chain network design are essential for the success of the implementation of the valorisation in our society (Salema et al., 2009). A few of these decisions are the facility locations, the quantity of materials transported, and the valorisation techniques. The decisions lead to many different combinations to design the supply chain, all with different performances. How a supply chain performs can be measured in different dimensions, such as the economic and environmental, and depends on the chosen indicators, such as profit and energy consumption, respectively (Espinoza Pérez & Vásquez, 2023).

To gain an optimal performance of the supply chain, optimal decisions have to be made (Espinoza Pérez & Vásquez, 2023). However, this is extremely complex as integral decisions have to be made, regarding the location, valorisation techniques and flow size, and there are trade-offs between the performance indicators (Bilir, 2019; Salema et al., 2009). One of these integral decisions is the degree of decentralisation of the supply chain. A more decentralised supply chain gives reduces the transportation costs due to nodes closer to the supplier and consumer. However, operational costs are often higher as the processes are less efficient (Chiu & Kremer, 2014). Decentralisation affects the environmental performance as well, depending on the indicator used. Although decentralization can reduce emissions by reducing the transport length, it may increase the overall energy usage due to the additional energy necessary of managing multiple smaller facilities (Bazan et al., 2015).

Furthermore, multi-feedstock valorisation, where multiple types of waste are valorised at the same time, influences the supply chain as well (Sharma et al., 2020). Multi-feedstock valorisation has the benefit over handling each feedstock as a separate supply chain, the single-feedstock approach. These benefits arise in cost reduction because resources are used more efficiently. As waste streams are treated in one supply chain, costs can be reduce in storage as less space is required. Additionally, equipment and labour costs can be reduced, since all waste is processed at the same time.

To optimise the supply chain of the complex and wet waste, a decision support tool is necessary. This model should be able to help decision makers with questions regarding location, valorisation options and quantity, while meeting capacity constraints and considering multi-feedstock valorisation and decentralisation to optimise economic and environmental performance. This thesis aims to develop

such a decision support model and to illustrate how it can be used to design a network for complex and wet waste valorisation supply chain. This resulted in the following main research question: How to develop a decision support model and demonstrate its usage for the centralisation and multi-feedstock approach of the complex and wet waste valorisation supply chains?

To answer this question, four sub research questions were raised.

1) What are the challenges and decision problems of the multi-feedstock complex and wet waste valorisation supply chain?
2) What models are currently available in literature for optimising the degree of centralisation for the multi-feedstock complex and wet supply chains?
3) What are the components and the mathematical formulation of a model to support the decision making to which the degree of centralisation should be applied for the supply chain design of the multi-feedstock complex and wet waste supply chain?
4) What are the type of managerial insights that could be obtained from such a model?

Section 2 discusses the most promising valorisation options for multi-feedstock valorisation, presenting their bottlenecks and possible solutions, including decentralisation and finally giving a schematic overview of the supply chain. Section 3 presents the available models found after a systematic literature review to handle the most important bottlenecks found in section 2. Section 4 describes the developed decision support model. Then, section 5 gives an illustrative example of a complex and wet supply chain in Illinois by describing scenarios and found data. Section 6 presents the results of the illustrative example, while section 7 compares the results with literature, generalises them and reflects on the study in a discussion. Lastly, section 8 presents the conclusions systematically by answering the research questions and presenting recommendations for future research.

2. Literature review on the complex and wet waste supply chain network design

In this section, the challenges for multi-feedstock complex and wet waste management will be given based on a literature review. First, a short overview of the supply chain of complex and wet waste valorisation will be presented. Next, opportunities for the supply chain are given, together with the complexities and challenges they present for the network design. Finally, modelling approaches that aim to address some complexities and challenges are shown based on a systematic literature review.

2.1. Overview of the waste valorisation supply chain

A schematic overview of the waste valorisation supply chain, including wet and complex waste, is given in Figure 1 (ReBBloCS project, 2023). The supply chain starts with the waste collectors. They provide a waste stream, e.g. orange peels or sludges, which contains one or more fractions which can be used for valorisation into a valuable product. The waste is brought to a facility, stored and processed afterwards. These waste streams undergo one of many possible valorisation processes to make a valuable product. The products are then stored and afterwards distributed to the customers.

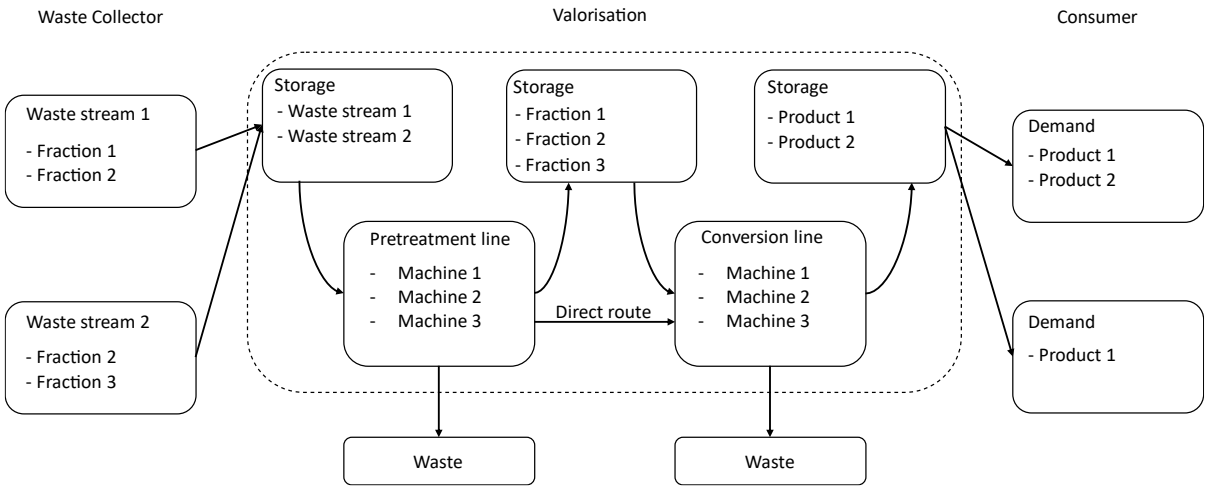

Figure 1. Schematic presentation of the (complex and wet) waste valorisation supply chain.

Valorisation processes are typically comprised of two parts: a pretreatment step and a conversion step. An overview of common conversion processes frequently researched for the complex and wet waste valorisation are given in Table 1 (How et al., 2018). The conversion techniques require certain qualities of the feedstock, such as chemical composition, to be a feasible process. Pretreatment is able to provide these qualities, such as moisture content and particle size, to the waste. Of the mentioned conversion technologies in Table 1, gasification, pyrolysis and hydrolysis have the most potential to start being implemented into society (Ouyang et al., 2021; Shah et al., 2023). Aerobic digestion does not show potential to be implemented in upcoming years, while anaerobic digestion is already implemented (Vasco-Correa et al., 2018). The current characteristics of gasification, pyrolysis and hydrolysis, their capabilities and bottlenecks will be discussed next.

Table 1. Overview of conversion technologies for valorisation (How et al., 2018).

Technology	Description
Aerobic Digestion	Micro-organisms digest feedstock with oxygen into bio-methane
Anaerobic Digestion (AD)	Micro-organisms digest feedstock without oxygen into bio-methane
Gasification	High temperature and high pressure process to produce syngas and bio char
Pyrolysis	High temperature and high pressure process to produce bio-oil and bio char
Hydrolysis	Water splits macro-molecules into micro-molecules, such as cellulose in sugar

2.1.1. Gasification

Gasification is a process in which carbonaceous materials are converted into gaseous products, depending on multiple parameters, such as the system conditions and the starting material. It is performed under high temperatures and high pressures, between 600°C–1000°C and 10-40 bar, respectively (Lopez et al., 2018; Rodrigues et al., 2020). The main product is known as syngas. Often, a carbonaceous solid, like bio charcoal, is obtained as a by-product. Syngas can be used as a starting material for the production of (bio-)plastics as a sustainable replacement of fossil fuel or the generation of electricity. Bio char is applicable as soil amendment or water filter (Tharaka Rama & Kikas, 2021).

A benefit of this process is its ability to convert a broad amount of waste streams, like plastic and electronic waste (Lopez et al., 2018; Rodrigues et al., 2020; Tharaka Rama & Kikas, 2021). Especially the metals in plastic/electronic waste are often hard to handle by other processes (Nikolopoulos et al., 2021). Furthermore, the gasification produces syngas, being able to partly provide its own process with energy to reduce energy costs (Swanson et al., 2010).

However, gasification also has a few bottle-necks. Firstly, it requires waste with a moisture content between 15% and 20% (Faisal et al., 2023; Mohanty & Padhiary, 2018). Too much water decreases yields significantly and improves tar forming. Furthermore, even though a lot of metals are in the charcoal, ash is still produced. Ash contains heavy metals which are harmful to the environment and need therefore proper disposal measures (Swanson et al., 2010). Lastly, the investment and operational costs of gasification is relatively high. The equipment necessary is relative expensive. The operational costs are high due to the high energy usage as high temperatures and pressures are mandatory (Lourinho et al., 2023).

2.1.2. Pyrolysis

The second is pyrolysis, where organic materials are converted into bio-oils or coal, depending on the system conditions and the starting material (Wright et al., 2010). The reaction is performed under high temperatures, ranging between 300°C and 850°C (Grycová et al., 2016; Ray et al., 2005). Pyrolysis results in bio char and bio-oil as main products. The ratio in which these are yielded depends on the specific conditions. In general, lower temperatures favour bio-oil, while higher temperatures yield more bio char (Shah et al., 2023). The bio-oil obtained is often a high-valuable product, with higher selling prices. Nevertheless, the price depends heavily on the quality of the product and therefore the quality of the feedstock (Al-Salem, 2019; Haeldermans et al., 2020).

Pyrolysis has the advantage of being a relative simple process. Therefore, it is easy to scale to different sizes, and has lower investment costs (Chandraprakash, 2020). Furthermore, pyrolysis has in general a high yield. This leads that not a lot of disposable waste is left after the valorisation (Yang et al., 2018).

However, pyrolysis also faces some challenges. To start, pyrolysis is not able to handle metals. Metals are not wanted in any of the products. However, metals end up in the oil, decreasing the yield and the quality of the products (Liu et al., 2014; Tian et al., 2019). The process is also relative energy intensive due to the system conditions. This makes it a process with high operational costs (Wright et al., 2010).

2.1.3. Hydrolysis + anaerobic digestion

The last process is hydrolysis followed by anaerobic digestion. During hydrolysis, macromolecules, such as sugar chains, are split into smaller molecules with the help of water. With the help of acid or a catalyst, water breaks these sugar chains into sugar molecules. This sugar can be sold, but more often it is used for anaerobic digestion. Sugars are then converted into bio-methanol by micro-organisms. The bio-methanol can be used as fuel, but also as a chemical starting material to produce formaldehyde or acetic acid. Besides the bio-methanol, the remaining digestion is suited as fertilizer due to the nutrient high composition (Jain et al., 1992).

Hydrolysis and anaerobic digestion are suitable for the wet waste streams, making use of the water instead of being hindered by it. Moreover, hydrolysis and anaerobic digestion are easy implementable due to the relative simple technology. The investment costs are also relatively low. This process is already used in real-life applications (Guo et al., 2021).

Nevertheless, just as gasification and pyrolysis, hydrolysis and anaerobic digestion also face challenges. The processes are not versatile for the complex waste streams. The chemical composition of the

complex waste streams includes often inorganic material. These materials, such as plastic, glass or metals, can disrupt the hydrolysis as well as the micro-organisms (Cano et al., 2014). Furthermore, a high level of control engineering is necessary due to the micro-organisms. They require specific temperatures and waste qualities for optimal yields (Mitra & Murthy, 2022).

2.2. Opportunities and bottlenecks of the supply chain

The developments made in the valorisation techniques give rise to two logistical changes in terms of multi-feedstock valorisation and decentralisation. To start, quite some technical improvements have been made in co-processing various complex and wet waste streams, resulting in the option for multi-feedstock valorisation (Okoro et al., 2021). Multi-feedstock valorisation has some practical advantages. Firstly, as multiple feedstocks can be converted with the same technique, the process has an increased resource utilisation (Roni et al., 2019). A broader range of materials can be used, meaning that resources that would be discarded can now be utilized. This reduces the waste and helps creating a more circular economy (Paini et al., 2022). Economically, the resource utilisation improves productivity by maximizing the output of the equipment and materials (Roni et al., 2019). This could increase production volumes, increasing the revenue. Furthermore, multi-feedstock valorisation enhances the process stability. Dependence on one complex and wet waste that experience seasonality, like agro/plastic residues, could impact the production negatively. Spreading the dependence on multiple waste streams increases the stability of the process (Paini et al., 2022).

However, multi-feedstock valorisation also present complexities. These challenges concern the quality of different parts of the supply chain. First of all, it is hard to maintain a consistent quality of the feedstock (Robles et al., 2020). The different waste streams have varying chemical compositions, leading to possible inconsistencies in feedstock quality. Furthermore, all the different types of waste needs to be stored. However, research shows that certain types of waste, mainly organic waste, can influence the quality of one another or each other negatively when stored together (Latif et al., 2023). Consequently, fluctuating quality in feedstock leads to a fluctuating product quality, fluctuating the selling price as well (López-Molina et al., 2020). Thus, the first key feature of the model should be the ability to define the quality of the different material flows for incorporation of the multi-feedstock valorisation and examine how it affects the performance of the supply chain.

Besides the option for multi-feedstock valorisation, decentralisation of the system is considerable as well. As mentioned before, the conversion efficiency depends on the quality of the feedstock. Pretreatment is therefore often necessary (Moretti et al., 2021). The pretreatment are often performed at one location, an integrated processing facility (IPF) . It is optimal to use large integrated facilities to minimize costs, such as operational costs. For example, heat generated at one place, such as a distillation column, could be used to heat the feedstock. Energy usage is thus also quite efficient in these IPFs (Hackl & Harvey, 2013).

For the complex and wet waste valorisation, however, decentralisation of the pretreatment might be beneficial as the pretreatment changes the composition of the waste significantly (How et al., 2018). Decentralised pretreatment facilities are able to separate different types of waste of each other in fractions or intermediate products, such as metals, water and organic waste. These fractions could then be send to the right conversion centre (Robles et al., 2020). Due to the closer separation at the waste source, transportation costs can be decreased as large volumes of unsorted waste are not transported to central facilities (Moretti et al., 2021). Furthermore, the weight of the transported intermediate can be reduced in the case of a dewatering pretreatment, reducing the transportation costs further (Moretti et al., 2021). This process also decreases the greenhouse gas (GHG) emissions by transportation (Liu et al., 2017).

Nevertheless, centralisation and decentralisation both have certain economic and environmental advantages and disadvantages. Economically, a more centralised system including more IPFs has lower operational costs due to more efficient systems within the facilities, but the transportation costs are likely to be higher compared to the decentralised system (Lam et al., 2021). Also, investment costs are higher for decentralised systems due to increased equipment and building costs (Lam et al., 2021). The internal environmental trade-offs consist of the earlier mentioned energy usage and GHG emissions; The first being more efficient in a more centralised system, while the latter in a more decentralized system. Thus, the second key feature of the model should be the ability to choose between IPFs and decentralised pretreatment facilities and examine the performance.

The complexities due to multi-feedstock valorisation and decentralisation, are beyond the internal economic and environmental trade-offs (Raschke et al., 2021). Environmental considerations, such as resource recovery, emissions and energy usage, should be weighed against economic factors such as investment and operational costs and selling price. The final key feature of the model is to handle all these different objectives of the supply chain.

So, the general supply should be adjusted to contain the three features to i) include multi-feedstock valorisation, ii) have the option to decentralise the pretreatment and iii) examine multiple objectives. Therefore, an overview of the supply chain that contains these features is given in Figure 2. It shows the supply chain with an emphasis on the three features. Multiple waste from collectors undergoes pretreatment in either IPFs (centralised) or pretreatment facilities (decentralised), producing fractions. These fractions are then processed in the same IPF (centralised) or in a conversion facility (decentralised). The performance of the supply chain is then measured through economic and environmental indicators.

In an extensive literature review, Espinoza Pérez & Vásquez (2023) discussed the economic and environmental objective functions used to examine the chain performance. Of the 17 economic indicators, profitability is chosen as it is relatively easy to obtain data on and provides a relative complete view. Three environmental indicators were chosen of the 15 mentioned. The goal of valorisation is to reduce waste for incineration or landfilling. Therefore, the resource recovery will be a suitable indicator. Furthermore, as the conversions, mainly gasification and pyrolysis, are energy intensive techniques, energy usage is a convenient indicator as well. Lastly, GHG emissions would handle the environmental impact for implementing the pretreatment facility options.

So, to overcome technical and logistical challenges of the complex and wet waste stream, a supply chain network design model has to be developed with the three key features. The next subsection discusses what has been done in literature to tackle the multi-feedstock valorisation for complex and wet waste with optional decentralised pretreatment facilities.

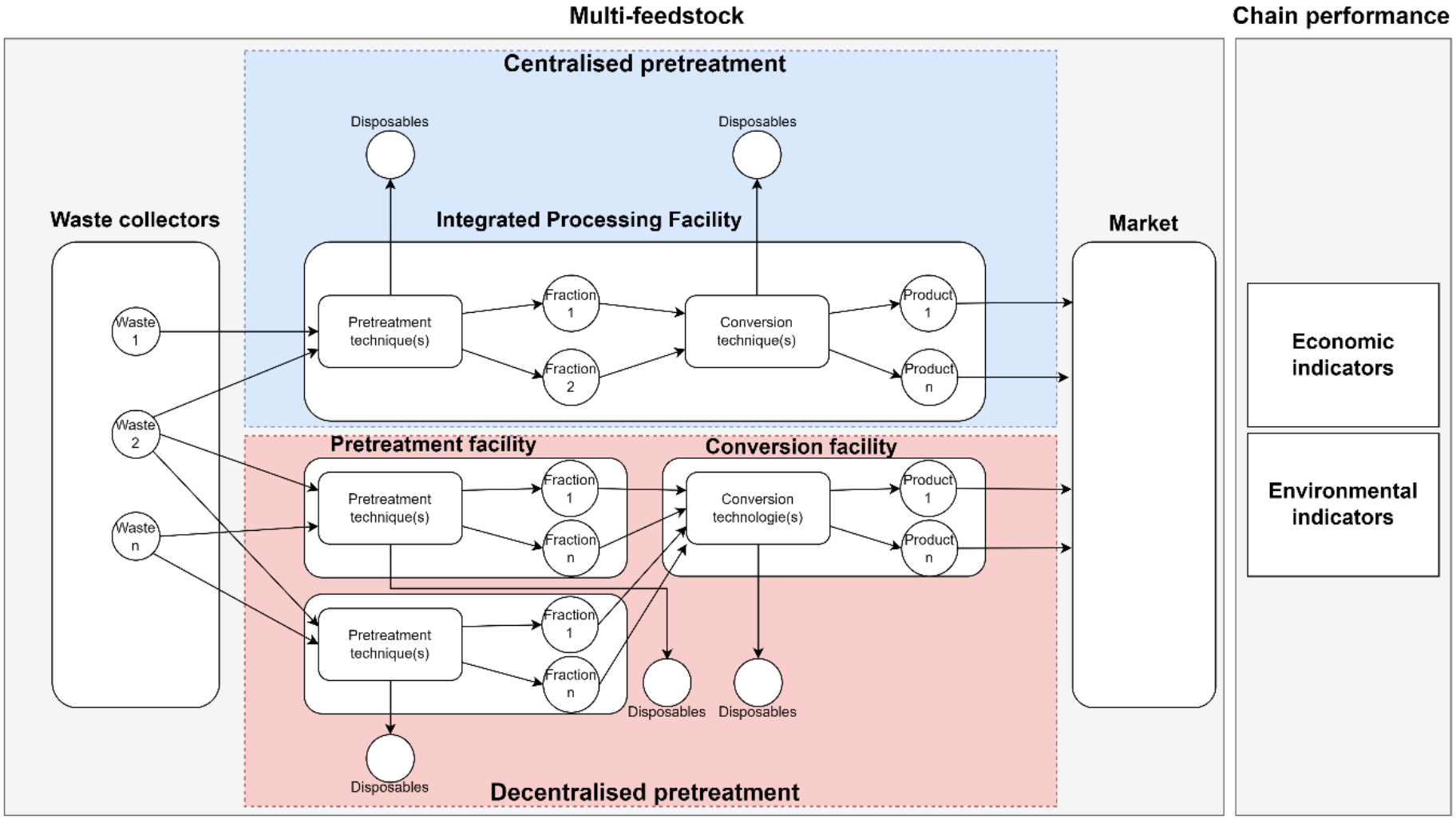

Figure 2. Overview of the proposed multi-feedstock supply chain for complex and wet waste including decentralisation of the pretreatment from the conversion and multi objective optimisation.

2.3. Systematic literature review on multi-feedstock complex and wet waste supply chain network design models

In this subsection, the results of the systematic literature review on supply chain network design models with multi-feedstock valorisation of complex and wet waste streams. Here, the features of these models to tackle the decentralisation and the multi-feedstock valorisation are discussed. The review aims to identify what has already been researched and highlight the gaps to tackle the problems sketched in the previous subsection.

State of current literature

To find out what has been performed to model the supply chain described in Figure 2, a systematic literature review was performed on Scopus. The queries used are given in A-1 Systematic literature review queries. The first query was tried to find papers that tackled the whole problem. However, no papers were found that describe the exact supply chain as presented in section 2. Afterwards, queries 2 and 3 were performed to find papers that either closely resemble the supply chain or describe parts of the supply chain, such as the multi-feedstock conversion or the choice to separate the pretreatment centres. The publication year was set after 2020 for relevance. Note that the publication year is before 2024, as this review was performed in December 2023.

Of each query, one paper was chosen to give a concise overview of the known literature. First, all the abstracts were read. After this, a selection of papers was made. These papers were the ones that actually contained the features that this works model needs. Then, the introduction and conclusion of those papers were read. The papers that contained the most information about i) multi-feedstock, ii) decentralisation, iii) complex and wet waste were chosen. The model developed in this work is based on the models of these chosen papers. Therefore, these two papers will be briefly discussed in query order.

One final paper is discussed, which was found by Google Scholar before the systematic literature review. The paper was regarded as relevant to this study. The focus of this paper did, similar to the other papers, not fully align with this study. However, the information provided regarding the general decentralisation and multi-feedstock valorisation was giving insights into what has been done to tackle the proposed supply chain.

Robles et al. (2020) designed a MILP model, combining spatial, chemical and technoeconomic aspects for optimization of a waste-to-resource value chain. Here, complex organic waste is converted by AD into several products. One of the products is the digestate of the organisms. Usually, this is used as a land fertilizer. However, posttreatment is possible in this system, such as pyrolysis, to generate bio-oil. They perform a single-objective optimization in terms of profit. In this work, organic waste can undergo several different AD pathways, optimizing the technologies at each facility based on the expected waste quality. The model has existing conversion and posttreatment plants. The posttreatment is optional for the products to undergo. This differs from the system in this work, where no existing plants are yet implemented and pretreatment is optional. Besides, they do not account for multi-objective optimisation.

Moretti et al. (2021) designed a MILP model for the optimization of advanced biofuel supply chains. Here, biomass is converted into biofuel. They minimized one economic objective: the annualized investment costs and annual operating costs, while accounting for the revenue from methanol selling. In their work, they proposed a superstructure in with an intermediate depot/preprocessing facility and a conversion facility. In their work, biomass can undergo preprocessing or go directly to the conversion

facility. Furthermore, inventory management is taken into account. However, the model in this work is lacking a way to handle with multiple technologies. Pretreatment is specifically based on drying, and conversion of the biomass only yields one product. Besides, conversion yields are only based on predetermined moisture thresholds, not taking into account other feedstock qualities.

López-Molina et al. (2020) developed a model to support decision making of centralized and decentralized biorefineries with environmental and economic objectives. In their work, biorefineries convert feedstock with a yield based on feedstock characteristics and the conversion technology. Afterwards, depending on the quality and technology, the product is sold based on its qualities. The facility locations are based on demand and source locations. The biorefineries are, however, only integrated processing facilities, without the separation of pretreatment.

3. Model description

This section describes the developed decision support model. First, the conceptual model is described, showing the structure and the main decisions. Second, the assumptions made for the model are presented. Finally, the mathematical formulation of the model is given and explained.

3.1. Conceptual model

Based on the supply chain overview of Figure 2, the conceptual model is presented in Figure 3. The waste with certain qualities *w* can be obtained from a waste collector at location *l* in a time period *t*. Depending on these qualities, the waste can be processed in a product of type *p* right away, or needs to be pretreated. The waste ready for processing is transported to a conversion facility at a location *n* and converted with a conversion pathway *j* into a product *p*, shown in the figure with material flow *D*. However, waste, especially wet waste, often needs to be pretreated with for example a drying technique before valorisation. For the to-be-pretreated waste, there are two pretreatment options. The first is undergoing a pretreatment with pretreatment pathway *i* at location *m* into intermediate *c*, shown with flow *A*. This intermediate is then transported to a conversion facility for processing into the final product *p*, represented in Figure 3 with flow *B*. The second option for waste *w* is to be transported to an IPF at location *n*, where waste is processed with a pathway *j*, which contains both the pretreatment and the conversion technique, into a product *p*. Note that this is also shown with flow *D*, just as the waste that can be converted directly. The products *p* from location *n* that are made are given with flow *C*.

During pretreatment and conversion, some waste cannot be processed. This disposable of type *d* needs to be disposed. Therefore, it is transported from either the pretreatment facility, flow *E*, or the conversion facility/IPF, both flow *F*, to a disposal facility at location *q*. The performance of this supply chain is assessed on both economic and environmental indicators.

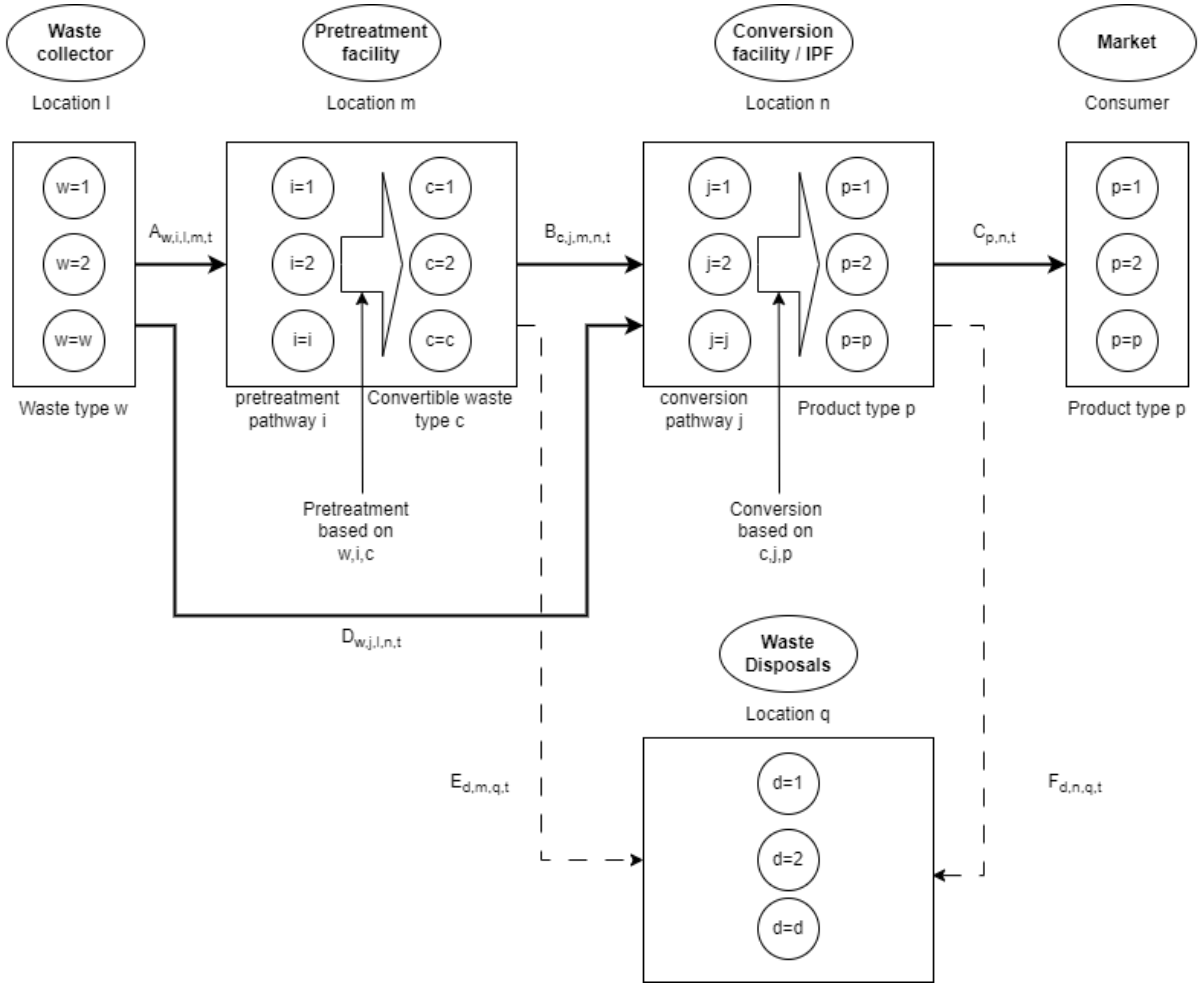

Figure 3. Main flows and decision variables of the multi-objective location-allocation model of the complex and wet waste supply chain.

3.2. Mathematical model

In this subsection, the mathematical formulation of the model is presented. Table 2, Table 3, and Table 4 give an overview of the set of indices, parameters and decision variables, respectively.

Table 2. Set of indices of the model.

Index	Set	Definition
w	$\in W$	Set of different types of waste
c	$\in C$	Set of intermediate products (after pretreatment)
p	$\in P$	Set of final valorised products
d	$\in D$	Set of disposable types
i	$\in I$	Set of pretreatment pathways
j	$\in J$	Set of conversion pathways, with a subset of pretreatment and conversion pathways together
l	$\in L$	Set of locations of waste collectors
m	$\in M$	Set of locations for pretreatment facility
n	$\in N$	Set of locations for conversion facility or IPF (integrated processing facility)
q	$\in Q$	Set of locations to dispose waste
k	$\in K$	Set of capacity constraints
t	$\in T$	Set of time periods

Table 3. Set of parameters of the model.

Parameters	Definition	Units
aw_{wlt}	Amount of available waste of type *w* from location *l* in time period *t*	kg
b_{wci}	Convertible waste production of convertible waste *c* of pathway *i* on waste *w*	kg convertible waste/kg waste
c_{cpj}	Product production of product *p* of pathway *j* on convertible waste *c*	kg product/kg convertible waste
e_{wdi}	Disposable waste production of disposable waste *d* of pathway *i* on waste *w*	kg disposable waste/kg waste
f_{cdj}	Disposable waste production of disposable waste *d* of pathway *j* on convertible waste *c*	kg disposable waste/kg convertible waste
wf_w	Waste valorisation fee of waste type *w*	€/kg
pp_p	Selling price of product *p*	€/kg
icx_m	Investment costs of pretreatment facility at location *m*	€
icy_n	Investment costs of conversion facility at location *n*	€
ici_i	Investment costs of pretreatment pathway *i*	€
icj_j	Investment costs of conversion pathway *j* and IPF building with pathway *j*	€
tca_{wlm}	Transportation cost of waste *w* from location *l* to location *m*	€/kg
tcb_{cmn}	Transportation cost of waste *c* from location *m* to location *n*	€/kg
tcd_{wln}	Transportation cost of waste *w* from location *l* to location *n*	€/kg
tce_{dmq}	Transportation cost of disposable waste *p* from location *m* to location *q*	€/kg
tcf_{dnq}	Transportation cost of disposable waste *p* from location *n* to location *q*	€/kg
pcp_{wi}	Production costs for pretreatment *i* of waste *w*	€/hours
pcc_{cj}	Production costs for conversion *j* of waste *w*	€/hours
dcp_d	Disposal cost of disposable waste *d*	€/kg
eni_{wi}	Energy usage of pre-treating waste *w* with pretreatment pathway *i*	J/kg
enj_{cj}	Energy usage of converting intermediate *c* with conversion pathway *j*	J/kg
$ghga_{wilm}$	GHG emission of transporting waste *w* from location *l* to location *m*	CO_2 eq./kg
$ghgb_{cjmn}$	GHG emission of transporting intermediate *c* from location *m* to location *n*	CO_2 eq./kg
$ghgd_{wjln}$	GHG emission of transporting waste *w* from location *l* to location *n*	CO_2 eq./kg
$ghge_{dmq}$	GHG emission of transporting disposable waste *d* from location *m* to location *q*	CO_2 eq./kg
$ghgf_{dnq}$	GHG emission of transporting disposable waste *d* from location *n* to location *q*	CO_2 eq./kg
$ghgia_{wi}$	GHG emission to pretreat waste *w* with pretreatment pathway *i*	CO_2 eq./kg

$ghgjb_{cj}$	GHG emission to convert intermediate *c* with conversion pathway *j*	CO_2 eq./kg
$ghgjd_{wj}$	GHG emission to convert waste *w* with conversion pathway *j*	CO_2 eq./kg
$capp_{mkt}$	Capacity limit of capacity constraint *k* at pretreatment facility *m* in time period *t*	Capacity unit
$capc_{nkt}$	Capacity limit of capacity constraint *k* at conversion facility/IPF location *n* in time period *t*	Capacity unit
cpu_{wik}	Capacity factor per unit for a pretreatment facility based on the pretreatment of waste *w* with pathway *i* for capacity constraint *k*	Capacity unit / kg waste
ccu_{cjk}	Capacity factor per unit for a conversion facility/IPF based on the conversion of waste *c* with pathway *j* for capacity constraint *k*	Capacity unit / kg waste
$mind_p$	Minimum demand of product *p*	kg
$maxd_p$	Maximum demand of product *p*	kg
plp_m	Pathway limit at pretreatment facility *m*	-
plc_n	Pathway limit at conversion facility *n*	-
g_j	Binary parameter whether a pathway is a IPF pathway (1) or not (0)	-
s_m	Amount of pretreatment pathways possible at location *m*	-
u_n	Amount of conversion pathways possible at location *n*	-

Table 4. Set of variables of the model.

Variables	Definition	Units
A_{wilmt}	Quantity of waste *w* from location *l* to be pretreated with pathway *i* at location *m* in time period *t*	kg
B_{cjmnt}	Quantity of convertible waste *c* from location *m* to be processed by pathway *j* at location *n* in time period *t*	kg
C_{pnt}	Quantity of product *p* produced at location *n* in time period *t*	kg
D_{wjlnt}	Quantity of waste *w* from location *l* to be processed with pathway *j* at location *n* in time period *t*	kg
E_{dmqt}	Quantity of disposable waste *d* produced at location *m* to be brought to waste disposer at location *q* in time period *t*	kg
F_{dnqt}	Quantity of disposable waste *d* produced at location *n* to be brought to waste disposer at location *q* in time period *t*	kg
O_m	Binary value whether a pretreatment facility is opened (1) or not (0) at location *m*	
R_n	Binary value whether a conversion facility is opened (1) or an IPF (0) or nothing (0) at location *n*	
X_{im}	Binary value whether a pretreatment facility with pathway *i* should be opened at location *m*	-
Y_{jn}	Binary value whether a conversion facility or IPF with pathway *j* should be opened at location *n*	-
$SALES$	Total sales of products	€
$FEES$	Total fees for valorising waste	€
$INVCOST$	Total investment costs for the opened facilities	€

$TRANSCOST$	Total transportation costs from waste location to pretreatment or conversion facility or IPF	€
$PRODCOST$	Total production costs at all the facilities	€
$DISCOST$	Total disposal costs for all the remaining waste	€
$NETWASTE$	The net amount of waste handled	kg
$ENERGY$	The total amount of energy used	J
GHG	The total amount of GHG emitted	CO_2 eq.

As discussed before, the performance of the supply chain is assessed by objective functions: the economic and the environmental ones. The economic objective function is the maximisation of the profit of the supply chain to make sure that investments are accounted for. The environmental objective functions are the maximisation of the net waste handled and the minimisation of energy usage and GHG emissions.

Economic objective: maximisation of profit

$$\max(PROFIT = SALES\ (1) + FEES\ (2) - INVCOST(3) - TRANSCOST(4) - PRODCOST(5) - DISCOST\ (6))$$

$$SALES = \sum_{p,n,t} pp_p C_{pnt} \quad (1)$$

$$FEES = \sum_{w,i,l,m,t} wf_w A_{wilmt} + \sum_{w,j,l,n,t} wi_w D_{wjlnt} \quad (2)$$

$$INVCOST = \sum_{m} icx_m O_m + \sum_{n} icy_n R_n + \sum_{i,m} ici_i X_{im} + \sum_{j,n} icj_j Y_{jn} \quad (3)$$

$$TRANSCOST = \sum_{w,i,l,m,t} tca_{wlm} A_{wilmt} + \sum_{c,j,m,n,t} tcb_{cmn} B_{cjmnt} + \sum_{w,j,l,n,t} tcd_{wln} D_{wjlnt} + \sum_{d,m,q,t} tce_{dmq} E_{dmqt} + \sum_{d,n,q,t} tcf_{dnq} F_{dnqt} \quad (4)$$

$$PRODCOST = \sum_{w,i,l,m,t} pcp_{wi} A_{wilmt} + \sum_{c,j,m,n,t} pcc_{cj} B_{cjmnt} + \sum_{w,c,j,l,n,t} pcc_{cj} D_{wjlnt} \quad (5)$$

$$DISCOST = \sum_{d,m,q,t} dcp_d E_{dmqt} + \sum_{d,n,q,t} dcp_d F_{dnqt} \quad (6)$$

Environmental (1): maximisation of net waste processed

$$\max\ (NETWASTE\ (7))$$

$$NETWASTE = \sum_{w,i,l,m,t} A_{wilmt} + \sum_{w,c,j,l,n,t} D_{wjlnt} - \sum_{d,m,q,t} E_{dmqt} - \sum_{d,n,q,t} F_{dnqt} \quad (7)$$

Environmental (2): minimisation of energy usage

$$\min\ (ENERGY\ (8))$$

$$ENERGY = \sum_{w,i,l,m,t} eni_{wi} A_{wilmt} + \sum_{c,j,m,n,t} enj_{cj} B_{cjmnt} + \sum_{w,j,l,n,t} enj_{cj} D_{wjlnt} \quad \textbf{(8)}$$

Environmental (3): minimisation of GHG emission

min (GHG (9))

$$GHG = \sum_{w,i,l,m,t} ghgta_{wlm} A_{wilmt} + \sum_{w,i,l,m,t} ghgia_{wi} A_{wilmt} + \sum_{c,j,m,n,t} ghgtb_{cmn} B_{cjmnt} + \sum_{c,j,m,n,t} ghgjb_{cj} B_{cjmnt} + \sum_{w,j,l,n,t} ghgtd_{wln} D_{wjlnt} + \sum_{w,j,l,n,t} ghgjd_{wj} D_{wjlnt} + \sum_{d,m,q,t} ghgte_{dmq} E_{dmqt} + \sum_{d,n,q,t} ghgtf_{dnq} F_{dnqt} \quad \textbf{(9)}$$

Maximising the profit results into the economic objective function. The profit is the total costs subtracted from the total income. The income is the sum of the revenue from selling the products (1) and the valorisation fees for handling waste from another company (2). Note that the valorisation fees can change in the purchasing costs for the starting materials by making wi_i negative if the valorising company has to pay for the waste. The total costs include investment costs (3), transportation costs (4), processing costs (5) and disposal costs (6).

There are three objective functions presented. The first is the maximisation of the net waste that is handled by the supply chain. It is calculated by adding the waste streams that are converted into products together. Then, the waste produced is subtracted to result into the net waste handled (7). The second environmental objective function is the minimisation of the energy used. The total energy usage is calculated by adding the energy usage of every separate process together (8). The third objective is the minimisation of the GHG emissions. This is calculated by adding the GHG emission of every transport together with the GHG emissions of all the processes in the facilities (9).

$$\sum_{i,m} A_{wilmt} + \sum_{j,n} D_{wjlnt} \leq aw_{wlt} \qquad \forall\, w,l,t \qquad \textbf{(10)}$$

$$\sum_{j,n} B_{cjmnt} = \sum_{w,i,l} b_{wci} A_{wilmt} \qquad \forall\, c,m,t | b_{wci} > 0 \qquad \textbf{(11)}$$

$$C_{pnt} = \sum_{c,j,m} c_{cpj} B_{cjmnt} + \sum_{w,c,j,l|w=c} c_{cpj} D_{wjlnt} \qquad \forall\, p,n,t | c_{cpj} > 0 \qquad \textbf{(12)}$$

$$\sum_{q} E_{dmqt} = \sum_{w,i,l} e_{wdi} A_{wilmt} \qquad \forall\, d,m,t | e_{wdi} > 0 \qquad \textbf{(13)}$$

$$\sum_{q} F_{dnqt} = \sum_{c,j,m} f_{cdj} B_{cjmnt} + \sum_{w,c,j,l|w=c} f_{cdj} D_{wjlnt} \qquad \forall\, d,n,t | f_{cdj} > 0 \qquad \textbf{(14)}$$

$$\sum_{w,i,l} cpu_{wik} A_{wilmt} \leq capp_{mkt} \qquad \forall\, m,k,t \qquad \textbf{(15)}$$

$$\sum_{c,j,m} ccu_{cjk} B_{cjmnt} + \sum_{w,c,j,l|w=c} ccu_{cjk} D_{wjlnt} \leq capc_{nkt} \qquad \forall\, n,k,t \qquad \textbf{(16)}$$

$$\sum_{w,l} cpu_{wik} A_{wilmt} \leq capp_{mkt} X_{im} \qquad \forall\, i,m,k,t \qquad \textbf{(17)}$$

$$\sum_{c,m} ccu_{cjk} B_{cjmnt} + \sum_{w,c,l|w=c} ccu_{cjk} D_{wjlnt} \leq capc_{nkt} Y_{jn} \qquad \forall\, j,n,k,t \qquad \textbf{(18)}$$

$$mind_p \leq \sum_{n,t} C_{pnt} \qquad \forall\, p \qquad \textbf{(19)}$$

$$\sum_{n,t} C_{pnt} \leq maxd_p \qquad \forall\, p \qquad \textbf{(20)}$$

$$\sum_{i} X_{im} \leq s_m O_m \qquad \forall\, m \qquad \textbf{(21)}$$

$$\sum_{j|g_j=0} Y_{jn} \leq u_n R_n \qquad \forall\, n \qquad \textbf{(22)}$$

$$\sum_{j|g_j=1} Y_{jn} \leq 1 - R_n \qquad \forall\, n \qquad \textbf{(23)}$$

$$O_m + R_n + \sum_{j|g_j=1} Y_{jn} \leq 1 \qquad \forall\, m,n|m=n \qquad \textbf{(24)}$$

$$\sum_{w,i,l,m,t|\sum_c a_{w,c,i}\leq 0} A_{wilmt} + \sum_{c,j,m,n,t|\sum_{w,i} a_{w,c,i}\leq 0} B_{cjmnt} + \sum_{c,j,m,n,t|\sum_p b_{c,p,j}\leq 0} B_{cjmnt} + \sum_{w,j,l,n,t|\sum_{c,p} b_{c,p,j}\leq 0} D_{wjlnt} + \sum_{p,n,t|\sum_{c,j} b_{c,p,j}\leq 0} C_{p,n,t} + \sum_{w,j,l,n,t|w\notin C} D_{wjlnt} = 0 \qquad \textbf{(25)}$$

$$A_{wilmt}, B_{cjmnt}, C_{pnt}, D_{wjlnt}, E_{dmqt}, F_{dnqt} \geq 0 \qquad \forall\, w,c,p,i,j,l,m,n,q,t \qquad \textbf{(26)}$$

$$X_{im}, Y_{jn}, O_m, R_n \in \{0,1\} \qquad \forall\, i,j,m,n \qquad \textbf{(27)}$$

Constraint (10) makes sure that the quantity of a waste type going to the facilities is not more than the waste made available by the waste suppliers in a time period. Constraint (11) till constraint (14) are the material balance constraints. Constraint (11) ensures that the quantity of pretreated waste from a pretreatment facility is equal to the sum of all the intermediates times their matching conversion factor. According to constraint (12), the final products produced at a conversion facility or an IPF is equal to the incoming waste streams and intermediates times the corresponding conversion factor resulting into that product. Constraint (13) makes sure that the amount of disposable waste produced is equal to the conversion factor multiplied by the amount of waste at pretreatment centres. Constraint (14) does the same for conversion facilities/IPFs by multiplying the conversion factor with the quantity of waste and intermediates.

Next are the capacity constraints for all the facilities. The amount of waste handled at a facility multiplied with the amount of a constrained capacity necessary for 1 unit of waste handled with a certain pathway, should be less than the capacity limit of that location for that constrained capacity. For the pretreatment facilities, this is ensured by constraint (15), while constraint (16) handles the conversion facilities/IPFs. Then, to know which technology is used at which location constraints (17) and (18) are created for the pretreatment facilities and conversion facilities/IPFs, respectively. Constraint (19) makes sure that the minimum demand is met, while constraint (20) ensures that the maximum demand is not exceeded.

Constraint (21) limits the amount of pathways that can be installed at a pretreatment facility. Besides, it notes when a pretreatment facility is opened with a binary variable. The next two constraints have two similar functions. The first is to limit the amount of pathways installed at conversion facilities, constraint (22), and at IPFs, constraint (23). The second is to keep track if either a conversion facility is opened or an IPF is opened/nothing is opened with the binary variable. The difference between a conversion facility and IPF is made with the parameter g_j. Conversion facilities are able to contain multiple conversion technologies. IPFs on the other hand are complicated integrated processes, where only one technology is possible due to the synergy of the different processes, hence, the different constraints. Constraint (24) ensures that only one type of facility is maximally opened at a location.

Constraint (25) ensures that incoming and outgoing flows from facilities are 0, when the conversion factor is 0. Note, the last term of constraint (25) makes sure that the flow is 0 when the a waste type is not yet convertible. Then, constraint (26) is the non-negativity constraint for the flows. Lastly, are the binary constraints stated in constraint (27) .

4. Illustrative example

An illustrative example was used to illustrate how the model can be used to optimize decisions of a multi-waste valorisation system. Moreover, the aim is to reveal important model results that can be useful for managers in the waste valorisation chain. For this example, we assume that maximisation of the profit and maximisation of the net waste handled are the main objectives. We do not account for energy usage and GHG emissions due to limited time and data availability. The net handled waste was chosen as environmental performance because it aligns the best with the general objective of waste valorisation facilities to reduce the quantity of waste incinerated or landfilled.

The supply chains of corn stover and paper sludge valorisation are used in this example. An overview is given in Figure 4. Multiple assumptions were made. Firstly, we assumed the state Illinois in the United States of America as a region with three suppliers for corn stover (Templeton et al., 2009) and three for paper sludge, assumed by paper manufacturing companies (Aeroleads, n.d.), and six locations for valorisation. All these possible facilities have a processing capacity of 0.73 Mt (megatonne) a year, which is the only capacity constraint in this example (Anex et al., 2010). Furthermore, the supply of waste is constant over time, with the quantities given in Table 5.

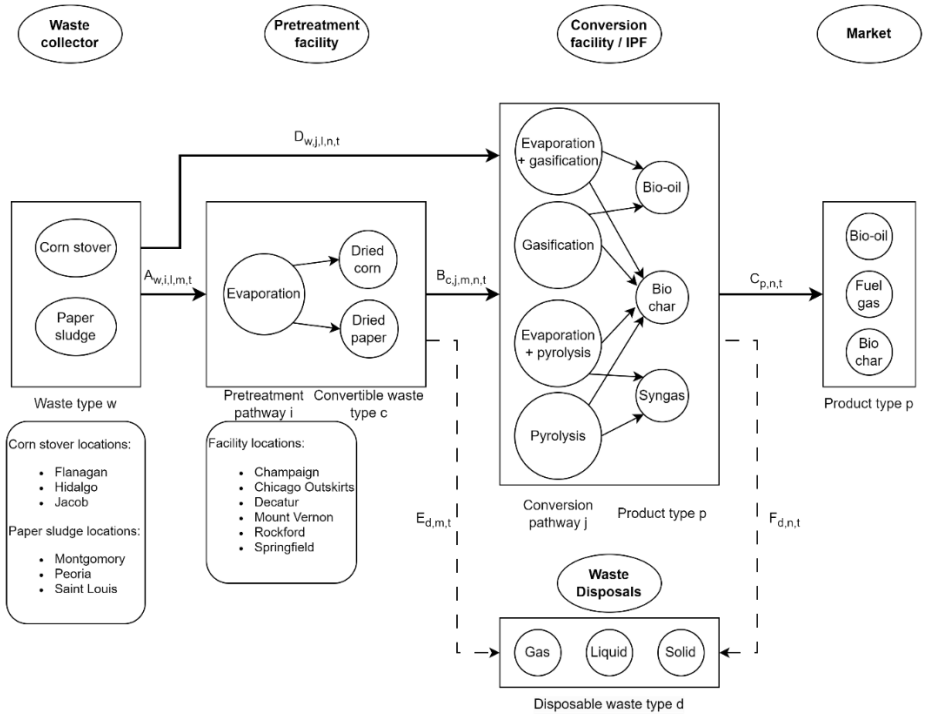

Figure 4. Overview of the supply chain in the illustrative example.

Two valorisation options are assumed for the supply chains: pyrolysis and gasification. The pretreatment, evaporation, can be done at a pretreatment facility or valorisation facility, making it an IPF. Evaporation yields dried corn and dried paper. When they undergo pyrolysis, bio char and bio-oil are the products, while their gasification yields bio char and syngas. It is assumed that the paper sludge and the corn stover have similar enough chemical composition for yielding products with the same qualities. However, the water content between corn stover and paper sludge differs quite, being 25% and 50% respectively (Anex et al., 2010; Assis & Chirwa, 2021). The valorisation also yields disposable waste, which is categorized by physical state: solids, liquids and gasses. It is assumed that the disposal costs are only dependent on this physical state. Transport costs for disposing waste are not considered as no information for disposal locations was found. Lastly, it was assumed that valorisation fees were obtained for handling the waste of the supplier.

Table 5. Overview of estimated available waste per location.

Waste type	Location	Estimated quantity (Mt)	Source
Corn Stover	Flanagan	0.25	(Graham et al., 2007; Templeton et al., 2009)
	Hidalgo	0.25	(Graham et al., 2007; Templeton et al., 2009)
	Jacob	0.25	(Graham et al., 2007; Templeton et al., 2009)
Paper sludge	Montgomery	0.21	(Aeroleads, n.d.; Glinska et al., 2019)
	Peoria	0.14	(Aeroleads, n.d.; Glinska et al., 2019)
	Saint Louis	0.05	(Aeroleads, n.d.; Glinska et al., 2019)

4.1. Set and parameter initialisations

The locations of the paper sludge are chosen by simple random sampling three locations in a list of in total eleven large paper manufacturers as seen in Appendix A-2 Random sampling of paper manufacturers. The processing locations are chosen by simple random sampling six cities in Illinois of

fifteen chosen cities all over the state as seen in Appendix A-3 Random sampling of processing cities. As no information is found easily on the changes of parameters over time and Swanson et al. (2010) and Wright et al. (2010) provide their data in annual units, the time period set contains two entries of 1 year. The parameter values used in the illustration can be found in Appendix A-4 Parameter overview.

4.2. Scenarios illustrative example

To demonstrate the managerial insights of the model, three scenarios were created to show how the challenges of section 2.2 can be handled by the developed model. The conditions are assumed to be mainly the same for both the scenarios, such as available facility ground and waste, and equal waste quality. The differences between the scenarios are given in an overview in Table 6 . As all the products are in high demand, the demand constraints are disregarded.

Table 6. Overview of the different scenarios.

Scenario	Multi-feedstock	Pretreatment location possible
1: Integrated SC with pretreatment facilities	✓	✓
2: Integrated SC with only IPFs	✓	
3: Separated SC with pretreatment facilities		✓

The mathematical model was implemented into Xpress IVE version 1.26.00 and solved with Xpress Optimizer version 42.01.04 as stated in Appendix A-5 Model script. The scenarios are first evaluated by a single-objective optimalisation, followed by the trade-offs between economic and environmental performance. The ε-constraint method was used to solve the multi-objective optimalisation as explained by Mavrotas (2009). In the computational model, the nadir and ideal values were first calculated for normalisation. Next, the environmental objective is written as a constraint, incorporating the slack variable. After optimizing the economic objective and using the result as a constraint, the normalised slack was optimized for 11 runs with 11 different values of ε. These values were determined as stated in equation (28). Where, ϵ_v is the epsilon constraint for iteration v, v is the iteration index ranging from 0 to 10, f^{nd} is the nadir value and f^{id} is the ideal value.

$$\epsilon_v = f^{nd} + 0.1v(f^{id} - f^{nd}) \quad \textbf{(28)}$$

In the first scenario, the supply chains of paper sludge and corn stover are integrated and regarded as one. The pretreatment step, evaporation, can be performed at a separate location of the remaining valorisation. The model used is the one as presented in section 3. An overview of the system is given in Figure 4.

In the second scenario, the supply chains are still integrated. However, the system contains only integrated valorisation processes. An overview of this system is given in Figure 5. Pretreatment facilities are not possible anymore and therefore the material stream coming to and going from them are also impossible. To ensure this, constraint (29) is added to the model for this scenario.

$$\sum_{i,m} X_{im} = 0 \quad \textbf{(29)}$$

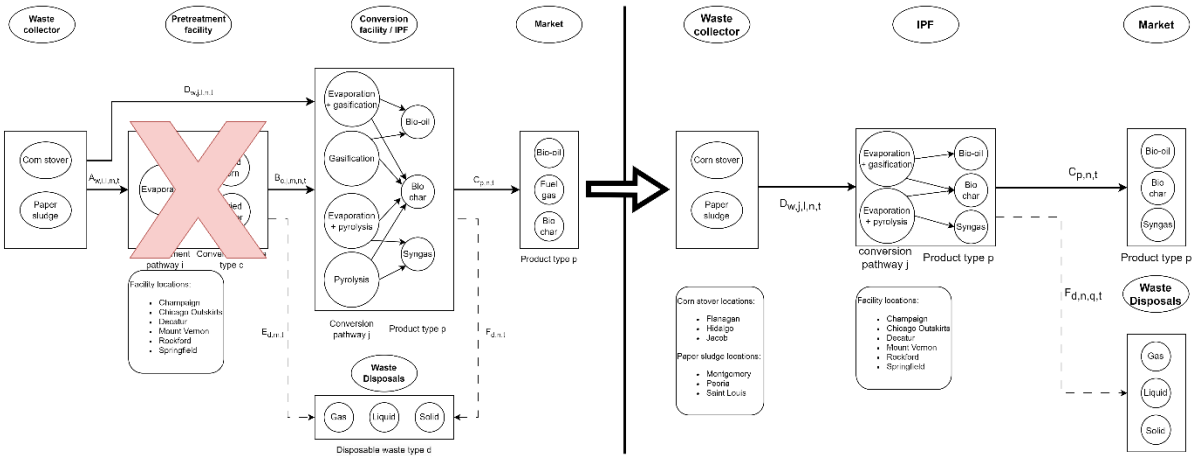

Figure 5. Overview of the changed supply chain for scenario 2. Left the proposed model of this work, with the pretreatment facilities deleted. Right the result for scenario 2.

The last scenario is an evaluation of the paper pulp and corn stover valorisation as separate supply chains, while it is possible to have pretreatment facilities. An overview is given in Figure 6. In this single-feedstock scenario, still six locations are available for facilities. These locations can facilitate a facility for only corn stover or paper pulp. Therefore, the decision variables for the pretreatment facilities (X_{im} and O_m) and conversion facilities/IPF (Y_{jn} and R_n) will be dependent on the incoming waste (set W and C, respectively), gaining those subscripts. The existing constraints containing these binary variables are adapted, being free in w and c. Furthermore, constraints (30) and (31) are added to this scenario to ensure the one-type-facilities for pretreatment and valorisation, respectively.

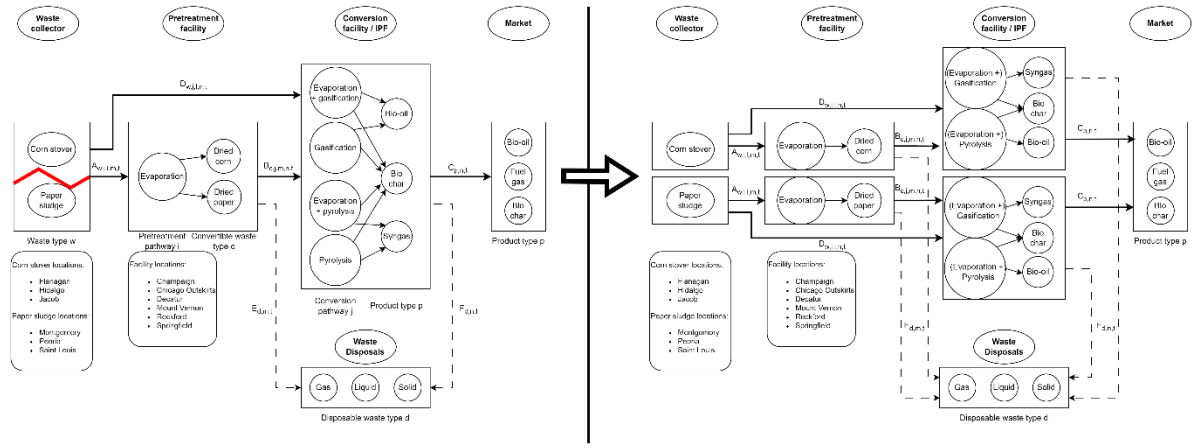

Figure 6. Overview of the supply chain in scenario 3. Facilities are only able to handle one kind of waste (single-feedstock).

$$\sum_{w} O_{wm} \leq 1 \qquad \forall\, m \qquad \textbf{(30)}$$

$$\sum_{c} R_{cn} \leq 1 \qquad \forall\, n \qquad \textbf{(31)}$$

5. Results

In this section, first, the results of the single objective optimisation are given in terms of optimal economic and environmental performance, followed by the breakdown of the location-allocation problem. Next, the profit breakdown is shown. Lastly, the trade-offs are given by multi-objective optimisation.

5.1. Single objective optimisation

5.1.1. Optimal solutions

The solutions of profit and net waste processed optimisation for all three scenarios are given in Table 7 and Table 8, respectively. For scenario 1, the maximum possible profit is $38.0 million with a net processed waste quantity of 1.52 Mt. Net processed waste maximisation results into a profit of $30.9 million, while 1.85 Mt waste is net processed. Maximising the net waste processing decreases the profit by 19%, although the net waste processed is increased by 22%. This indicates a trade-off between the two objectives in this scenario.

In the second scenario, where only IPFs are used, profit maximisations results into a profit of $36.7 million and a net waste processing of 1.77 Mt. Here, net waste processing maximisation yields $12.0 million, a decrease of 67%, and a net waste processing of 1.85 Mt, an increase of 5%. Just as scenario 1, this indicates there is a trade-off between profit and net waste processing maximisation. The large decrease compared to the relative small increase in waste valorisation is discussed in more depth in the profit breakdown.

The option with evaporation facilities, scenario 1, results in a higher profit for both optimisations; 3.8% for profit and 158% for waste processing. However, this is not the case for the waste processing. Profit optimisation results in 14% less waste processed by the integrated supply chain. When the net waste processed is optimised, both scenarios yield the same quantity of 1.85 Mt. When all the waste is processed, scenario 1 has a bit higher profit. This difference is explained by less costs that are made, as discussed in Section 5.1.2.

The third scenario has optima of $12.9 million and 1.19 Mt waste processed for profit optimisation, which is the worst solution of the three scenarios. This can be explained by the more efficient supply chain of the first two scenarios due to the multi-feedstock valorisation. The supply chain of just paper sludge does not seem to be profitable in this scenario. Waste optimisation results in a decrease in profit of $0.56 million by handling more net waste, 1.85 Mt. Comparable with scenario 1 and 2, there seems to be a trade-off between the economic and environmental objectives. Although all the waste can be processed in all the scenarios, the profit is significantly higher for scenario 1 and 2 compared to scenario 3. Again, this can be explained by the multi-feedstock valorisation in scenario 1 and 2. The valorisation of paper sludge is not as profitable as corn stover.

Table 7. Optima solutions for three scenarios by optimizing profit.

Profit optimisation				
Variable		Scenario 1 Integrated supply chain	Scenario 2 Only IPF	Scenario 3 Separated supply chain
Profit	$MM	38.0	36.7	12.9
Net waste processed	Mt	1.52	1.77	1.19
Waste processed	%	82	95	65
Technologies		Evaporation, Pyrolysis	Evap. + pyrolysis (IPF)	Evaporation, Pyrolysis
Valorised waste		Corn stover Paper sludge	Corn stover Paper sludge	Corn stover

Table 8: Optimal environmental solutions for three scenarios by optimizing net waste processing.

Waste processed optimisation				
Variable		Scenario 1 Integrated supply chain	Scenario 2 Only IPF	Scenario 3 Separated supply chain
Profit	$MM	30.9	12.0	0.56
Net waste processed	Mt	1.85	1.85	1.85
Waste processed	%	100	100	100
Technologies		Evaporation, Pyrolysis, Evap. + pyrolysis (IPF)	Evap. + pyrolysis (IPF)	Evaporation, Pyrolysis
Valorised waste		Corn stover Paper sludge	Corn stover Paper sludge	Corn stover, Paper sludge

5.1.2. Profit breakdown

In Figure 7, the profit is broken down for each scenario for both optimisations. When profit is optimised, scenario 2 has the highest revenue and total costs, followed by scenario 1. The lowest revenue and costs is obtained when the supply chains are single-feedstock. This order is explained by the amount of waste valorised. More valorisation results in higher valorisation fees as well as sales income. Therefore, the revenue order is the same as the quantity of waste valorised order. Notably, scenario 3 has a s Besides, scenario 1 and 2 have almost the same valorisation fees income, but a large difference in sales. Significant more waste is valorised into valuable products, increasing the sales. However, these products are mainly made of corn stover. Having a lower valorisation fee of 2 cent, corn stover does not influence the fee income as much as the paper sludge already did with a valorisation fee of 6 cent.

The costs are largely influenced by the production costs as the chosen valorisation options are energy intensive. The impact of the production costs on the IPF only scenario is slightly lower, as the productions costs are less for IPF systems. However, the production costs remain higher because of the increased utilization of starting materials. In terms of investment costs, IPF is the most expensive as more complete technologies have to be installed. Transportation costs are moderately higher for scenario 1 and 3 as more tonne-kilometres are required.

When waste processing is optimised, all scenarios handle all the waste, resulting in the same sales and valorisation fees and thus revenue. The cost breakdown shows the difference between the different scenarios. The IPF only scenario has the lowest production costs due to the high energy efficiency of the IPFs. The integrated supply chains production costs is somewhat lower than scenario 3 due to the addition of one IPF compared to two pretreatment and one valorisation facility. The investment costs stay the highest for scenario 2. The separated supply chain and integrated one are almost the same as only one extra evaporator location is necessary. The transportation costs are the lowest for scenario 2 as less tonne-kilometres are required. Here, due to the limitation in available locations, the separated supply chain has significant higher transportation costs.

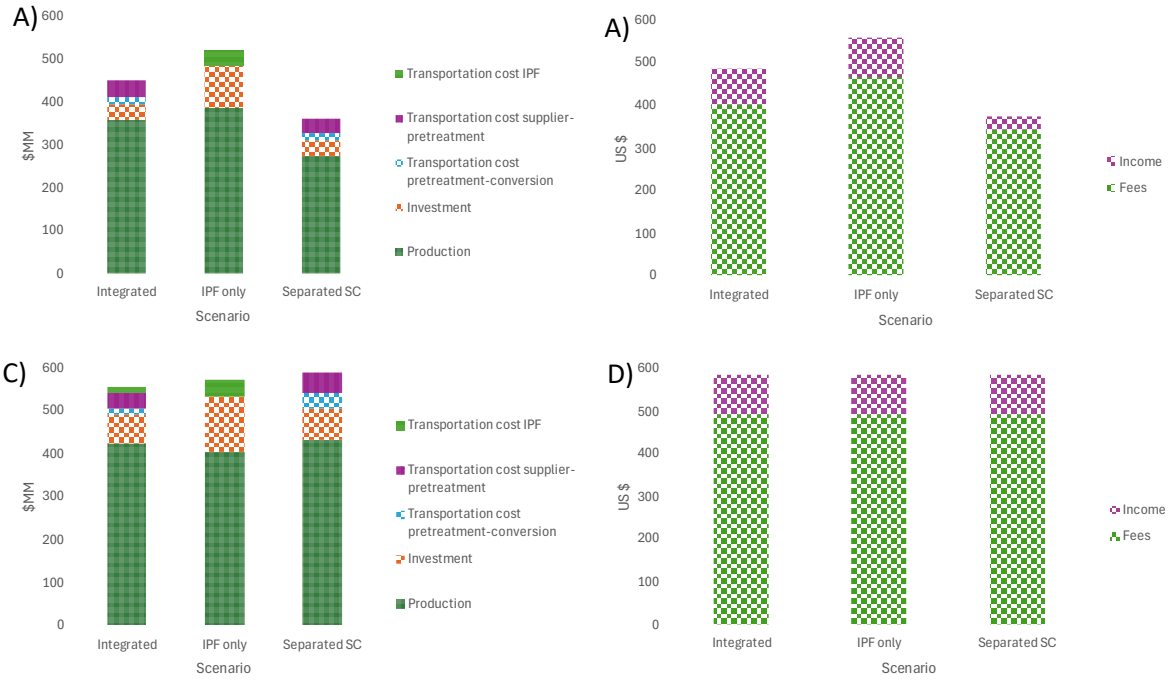

Figure 7. Profit breakdown of the three scenarios for both optimisations. The profit breakdown of profit optimisation is given at the top with the cost breakdown (A) and the revenue breakdown (B). The profit breakdown of waste handling optimisation is shown at the bottom with the cost breakdown (C) and revenue breakdown (D) as well.

5.1.3. Location-allocation

The optimal location-allocation solutions for the different scenarios and different objective functions are given in Figure 8. In all the cases, only pyrolysis is chosen as an valorisation option. When IPF was chosen, the technology was always evaporation with pyrolysis as well. This is due to the better parameters for pyrolysis; lower operational costs; lower investment costs; and lower disposable waste costs.

Figure 8 shows that three locations are necessary for an optimal solution when profit is optimised. Here, the limitations of the scenario 2 and 3 become visible. In scenario 1 and 3 there are no IPFs present indicating that a pretreatment facility, impossible in scenario 2, might be more favourable. A presumable explanation is that pretreatment lowers the weight of the waste before arriving at the valorisation location. Dried corn has a better efficiency than corn stover at the valorisation location, so the capacity of the valorisation location is used for a more efficient feedstock. The limitation in scenario 3 is the exclusion of a multi-feedstock supply chain. Maximising profit results in one supply chain for only corn stover. Corn stover is preferred over paper sludge as corn stover is more profitable. Paper sludge has a higher water content, so evaporation costs and transport costs per kg product are higher.

Waste optimisation in scenario 1 and 2 needs four locations, while scenario 3 needs six locations. When profit is optimised, scenario 1 and scenario 2 are using its full capacity without valorising all the available waste. Hence, more facilities are unavoidable in these scenarios for full waste valorisation. Scenario 1 specifically gains an IPF instead of a pretreatment and valorisation facility. A possible explanation for this is that the remaining waste to be valorised from profit maximisation is less than the capacity, so building one IPF is cheaper than a pretreatment and valorisation facility. Besides, using two locations from the three left is likely to result in higher transport costs as well.

In scenario 3, a new supply chain had to be made for valorising paper sludge as it was limited to single-feedstock valorisation, increasing the total facilities to six. The same reasoning for the separation of the pretreatment and valorisation is probably applicable as for the supply chain of corn stover.

Scenario 1 has the freedom to have separation of pretreatment and valorisation facilities and to have multi-feedstock technology. As it uses both the options in both the optimisations, these options have a possible influence on the objective functions.

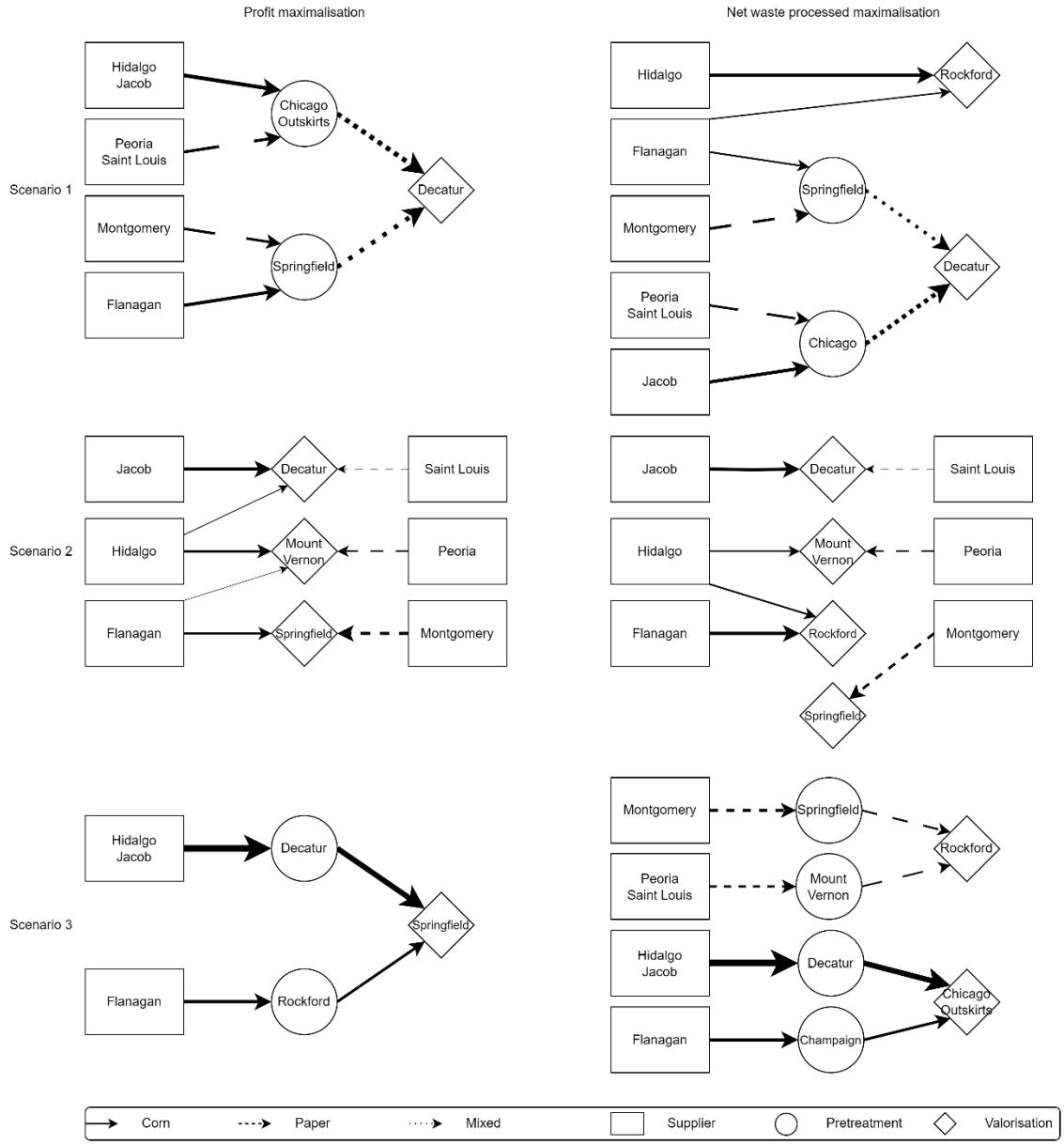

Figure 8. Overview of the location-allocation solutions. Each row contains one scenario. The first column contains the solutions for economic optimisation; The right column for net waste processed optimisation. The thickness of the arrow indicates the quantity of the stream.

5.2. Trade-offs

Single-objective optimisation showed conflict between the objective in all scenarios. Therefore, the trade-offs were calculated by multi-objective optimisation as seen in Figure 9. In total 11 model runs were performed with 11 different epsilon per scenario. Multiple points overlap as quite some slack is

present for the calculated points. This can be attributed to the branch-and-breaching as a result of the binary variables.

This visualisation of the trade-offs emphasises the benefits of a multi-feedstock supply chain. Scenario 3 underperforms significantly compared to the other scenarios in this illustrative example, being caused by the single-feedstock limitation. Furthermore, an interesting point in this trade-off graph is the profit optimisation of scenario 2, only IPF. This point overlaps with a pareto-optimum point of scenario 1, the integrated supply chain. This provides the insight that a full IPF system can be an optimal point for the integrated supply chain, even when a pretreatment facility is an option.

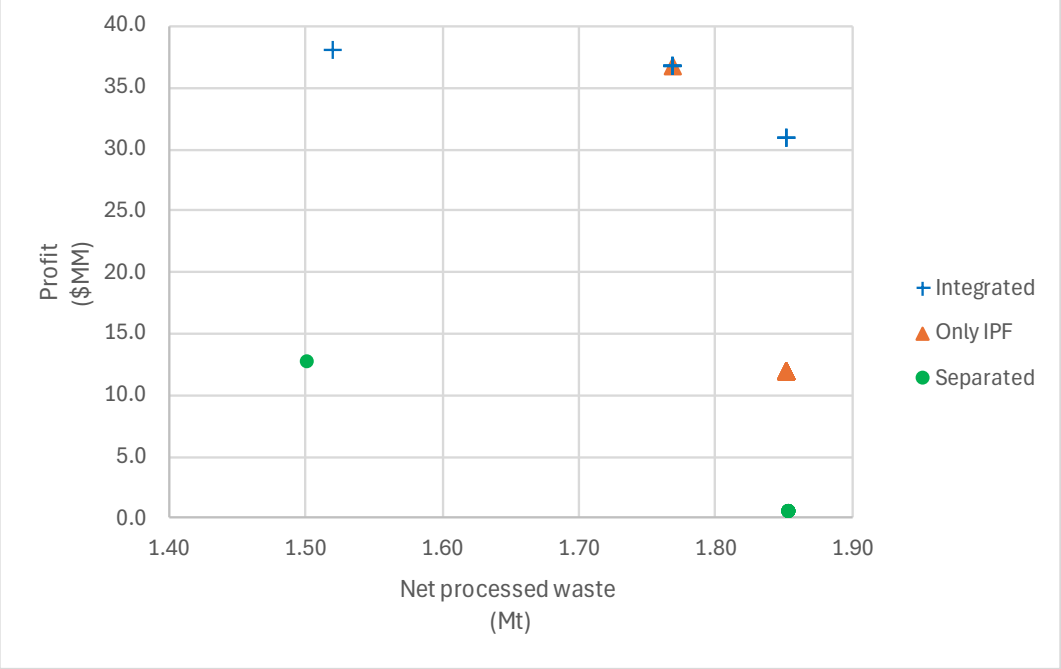

Figure 9. The trade-offs between profit and net processed waste of the three scenarios.

6. Discussion

In this MSc thesis a decision support model for the location-allocation of complex and wet waste streams supply chain was developed. The developed model is able to optimise decisions for complex and wet supply chains regarding facility locations, material flows, and the valorisation techniques. Decision support can be given considering multi-feedstock valorisation and decentralisation of the pretreatment taking multiple objectives into consideration. Besides, the model is capable of showing the trade-offs between these objectives. The objective optimisations are valuable for designing multi-feedstock valorisation chains and reduce landfilling and incineration.

The model's usage is broader than presented in the illustrative example. The indices can be used to be more specific. For example, waste quality *w* can include mineral or metal content or the age of certain biowaste. These qualities can influence the product *p* and therefore the selling price.

To improve the varying quality of the feedstock, uncertainty might be considered in the model. Uncertainty can be tested by a scenario analysis or by a probability analysis (Bairamzadeh et al., 2018; Seifbarghy & Alhoseini, 2019). The latter would help the decision maker with risk-analysis regarding the variation of feedstock and product quality. An important note on this is the difficulty to predict this uncertainty. It should only be implemented if one has expertise about uncertainty (Koh & Tan, 2006).

Including scaling into the model might enhance the performance of the supply chain by using different operational sizes. Currently, one scale is used in the model, which is mid to large-scale (Wright et al., 2010). Centralised benefit from larger-scale facilities, using economies of scale reducing the costs per unit. On the other hand, decentralised supply chains operate more efficient with smaller-scale facilities. These adapt the scale to the local resource availability. Incorporating this scaling would capture the problem more accurately, which improves strategic decision making (Robles et al., 2020).

The results of the illustrative example gave some compelling findings. To start, integration of supply chains to a multi-feedstock supply chain seems economically and environmental advantageous. Scenario 1 and 2, when the corn stover and paper sludge supply chains are integrated, score significantly better on both objectives than scenario 3, without integration. These results show the potential benefits of combining resources and optimizing processes through different supply chains.

However, in practice this integration would involve multiple companies, which have to collaborate with each other. This collaboration could be including sharing logistical information, such as collection schedules. Even joint investments in pretreatment facilities or infrastructure might have to be made. In other words, to ensure the optimal performance of the supply chain, trust between these companies would be crucial. Also, agreements have to be made regarding for example profit distribution. So, these practical challenges, which are not captured by the model, are essential for implementing an integrated supply chain in the real-world (Erhun & Keskinocak, 2011).

The results show higher investment costs and lower transport costs when IPF is used, which is different than the findings in literature (López-Molina et al., 2020). This is likely due to how the capacity constraint was used. It was assumed that the capacity of a conversion facility or IPF would always be 0.73 Mt a year. However, in these works found in literature, the capacity was based on dry weight feedstock instead of wet weight (Swanson et al., 2010). This means that the capacity would be increased in the case of an IPF to compensate for the wet waste arriving. The model, however, is able to perform this compensation with the variable ccu_{cjk} (capacity necessary per unit waste). Compensating with this variable changed the profit breakdown to comply with the conclusion of López-Molina et al. (2020)

A point of interest in the results is the overlapping Pareto optimum solution of scenarios 1 and 2. As the points overlap, it shows that a full IPF system might still be optimal. The option for splitting pretreatment and conversion, along with the option for IPFs, is a reliable feature of the model as it increases the decision space.

Calculating the trade-offs, pareto optimum solutions could be expected close to the optimal points found due to the presence of the continuous variables (Velázquez Martínez & Fransoo, 2017). However, these points were not observed. In their work, Pareto Robust Optimisation (PRO) was used to handle uncertainty. In this MSc thesis, uncertainty is unaccounted for, so a Robust Optimisation was not used. If uncertainty would be included in future research, PRO might be considerable as an framework to handle the uncertainty.

In this study, the available locations were limiting. Nevertheless, it still provided valuable insights. The results suggest that decentralised facilities could be advantageous at least when locations are limiting. Scenario 1 had the same performance or equal to scenario 2, where decentralisation was not an option. Furthermore, scenario 3 had the option for centralised and decentralised supply chains of which decentralised was more favourable. For future research, the model should be tested with more locations to verify the effect of decentralisation. Local dewatering at the waste supplier might decrease the transport costs even more, despite increasing the operational and investment costs.

In the illustrative example, net waste processed was taken as the environmental objective. However, the optimal solutions would likely be different when other indicators were used. Minimising energy usage would probably prefer IPFs due to the energy efficient process, while minimising the GHG emissions might favour pretreatment facilities according to literature (Shehabi et al., 2012). Therefore, a limitation of this illustrative example is the use of one indicator. It is advised to use multiple indicators in future research.

7. Conclusion and recommendations

To answer the main question, all the sub-questions were first handled. In this section, a summarised answer is given to all the sub-questions. Right after, the main question is answered. Lastly, the recommendations for future research are stated.

What are the challenges and decision problems of the complex and wet waste valorisation supply chain?

This question is answered in section 2. While several bottlenecks are mentioned concerning economic, environmental and social dimensions, two of the most important challenges for the complex and wet waste valorisation supply chain are i) the high logistic costs due to high moisture content and ii) high investment costs as low quantities of waste require expensive valorisation options. To tackle these problems, this work proposes to i) set up delocalized pretreatment centres to decrease logistic costs and ii) make an integral system with multi-feedstock instead of single-feedstock.

What models are currently available in literature for optimising the degree of centralisation for the multi-feedstock complex and wet supply chains?

The second sub-question was answered in section 2.3. A systematic literature review was performed. After the literature research, it was concluded that a new supply chain network model had to be developed. Multi-feedstock models are available, where the conversion factor is dependent on the quality of the incoming stream. Besides, some of these models are able to choose the optimal valorisation option for the different feedstocks or have separate pretreatment. However, no models were found which could handle multi-feedstock valorisation and pretreatment decentralisation.

What are the components and the mathematical formulation of a model to support the decision making to which the degree of centralisation should be applied for the supply chain design of the multi-feedstock complex and wet waste supply chain?

The developed model, its components and formulation are found in section 3. The model integrates the choice for separation of pretreatment and conversion facilities or IPFs, and multi-feedstock, where waste quality, pretreatment and conversion technologies are the most important factors. To optimise the performance of the supply chain, multiple objectives were chosen. The economic objective is profit maximalisation. Net waste processing maximisation, energy usage minimisation and GHG emission minimisation were chosen as environmental objectives.

What are the type of managerial insights that could be obtained from such a model?

The final sub-question was answered by performing an illustrative example, explained in section 4. The results and discussion were explained in section 5 and 6, respectively. Multiple managerial insights were obtained. The model is able to provide an optimized location-allocation supply chain according to the given decision variables and objectives. This includes multi-feedstock integration and the option

for pretreatment facilities and conversion facilities or IPFs or a combination. The model is able to quantify the effect of separating pretreatment and valorisation by the determined economic and environmental objectives. By calculating the set of pareto optimum solutions, the model can provide information for managers regarding the economic and environmental trade-offs. The illustrative example showed that multi-feedstock and decentralisation of the pretreatment could improve the economic and environmental performances. The scenarios with integrated chains show better optimisations. Decentralisation seems advantageous when location options are limited.

Main question: How to develop a decision support model and demonstrate its usage for the centralisation and multi-feedstock approach of the complex and wet waste valorisation supply chains?

A model is developed to support decision making for the complex and wet waste stream supply chains. This model aids decision making by optimising the location-allocation according to the given decision variables and set objectives. The model includes multi-feedstock input and decentralisation of the pretreatment technology. Besides, the model can calculate the trade-offs of the economic and environmental objectives. The results can help decision-makers in choosing the best fit solution according to their wishes.

The limitations of the model were discussed according to the methodology and the results of the illustrative example. To start, while the model shows the effectiveness for the performance of an integrated supply chain, practical challenges regarding collaboration between companies should be noted. Besides, quality of the feedstock is not constant and uncertainty could be included by probability analysis. Furthermore, to capture the problem more accurately, facility scaling could be included. Also, the model could be tested with more locations to explore the effectiveness of decentralisation. Lastly, using multiple environmental indicators could be considered to gain a more complete analysis of the environmental impact in the real world.

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Appendix

A-1 Systematic literature review queries

Table 9. The queries used to perform the systematic literature review for the model features.

Number	Query	Papers found	Papers after abstract
1.	TITLE-ABS-KEY((("MILP") OR ("mixed integer linear programming")) AND ("multi-feedstock" OR "multi feedstock") AND ("centralised" OR "centralized" OR "centralization" OR "centralisation")) AND ("waste supply chain" OR "waste valorisation")))	0	-
2.	TITLE-ABS-KEY((("MILP") OR ("mixed integer linear programming")) AND ("waste supply chain" OR "waste valorisation")) AND PUBYEAR > 2019 AND PUBYEAR < 2024	9	2
3.	TITLE-ABS-KEY(("supply chain design") AND (("MILP") OR ("mixed integer linear programming"))) AND ("multi-feedstock" OR "multi feedstock") AND PUBYEAR > 2019 AND PUBYEAR < 2024	5	1

A-2 Random sampling of paper manufacturers

Table 10. Random sampling results for choosing paper manufacturers based on (Aeroleads, n.d.).

Manufacturer	Random sampling value
International Paper Co.	0.814990537
Kimberly-Clark	0.64427689
WestRock	0.624156222
United Container	0.606277357
IPSC	0.583418956
Gorilla paper	0.42735274
Midland paper	0.319853844
Nd paper	0.224410729
Lewis paper	0.103614403
Murnane companies	0.048192164
Ecoplant bamboo	0.003578782

A-3 Random sampling of processing cities

Table 11. Random sampling results for choosing facility cities.

Cities	Random sampling value
Decatur	0.992196328
Mount vernon	0.858624706
Champaign	0.843208971
Springfield	0.792114263
Chicago outskirts	0.750547035
Rockford	0.684172352
Aurora	0.639863072

Naperville	0.631525716
Joliet	0.587692392
Elgin	0.506340072
Waukegan	0.443851123
Moline	0.400153412
Carbondale	0.388335718
Quincy	0.188117394
Effingham	0.035844594

A-4 Parameter overview

Table 12. IPF technology or not.

Parameter	Description	Value	Source
$g_{Evaporation+pyrolysis}$	IPF technology	1	-
$g_{Evaporation+gasification}$	IPF technology	1	-
$g_{Evaporation}$	Not an IPF technology	0	-
$g_{pyrolysis}$	Not an IPF technology	0	-
$g_{gasification}$	Not an IPF technology	0	-

Table 13. Overview of conversion parameters.

Parameter	Feed	Technology	Product	Conversion factor (kg/kg)	Source
$b_{w,c,i}$	Corn stover	Evaporation	Dried corn	0.83	(Swanson et al., 2010)(Swanson et al., 2010)
	Paper sludge	Evaporation	Dried paper	0.7	(Swanson et al., 2010)(Swanson et al., 2010)
$c_{c,p,j}$	Dried corn	Pyrolysis	Bio char	0.38	(Swanson et al., 2010)(Swanson et al., 2010)
	Dried corn	Pyrolysis	Bio-oil	0.14	(Swanson et al., 2010)(Swanson et al., 2010)
	Dried corn	Gasification	Bio char	0.25	(Wright et al., 2010)(Wright et al., 2010)
	Dried corn	Gasification	Syngas	0.1	(Wright et al., 2010)(Wright et al., 2010)
	Dried paper	Pyrolysis	Bio char	0.38	(Swanson et al., 2010)(Swanson et al., 2010)
	Dried paper	Pyrolysis	Bio-oil	0.14	(Swanson et al., 2010)(Swanson et al., 2010)
	Dried paper	Gasification	Bio char	0.25	(Wright et al., 2010)(Wright et al., 2010)

	Dried paper	Gasification	Syngas	0.1	(Wright et al., 2010)(Wright et al., 2010)
	Corn stover	Evaporation + Pyrolysis	Bio char	0.315	(Swanson et al., 2010)(Swanson et al., 2010)
	Corn stover	Evaporation + Pyrolysis	Bio-oil	0.11	(Swanson et al., 2010)(Swanson et al., 2010)
	Corn stover	Evaporation + Gasification	Bio char	0.21	(Wright et al., 2010)(Wright et al., 2010)
	Corn stover	Evaporation + Gasification	Syngas	0.083	(Wright et al., 2010)(Wright et al., 2010)
	Paper sludge	Evaporation + Pyrolysis	Bio char	0.266	(Swanson et al., 2010)(Swanson et al., 2010)
	Paper sludge	Evaporation + Pyrolysis	Bio-oil	0.1	(Swanson et al., 2010)(Swanson et al., 2010)
	Paper sludge	Evaporation + Gasification	Bio char	0.18	(Wright et al., 2010)(Wright et al., 2010)
	Paper sludge	Evaporation + Gasification	Syngas	0.07	(Wright et al., 2010)(Wright et al., 2010)
$f_{c,d,j}$	Dried corn	Pyrolysis	Gas waste	0.286	(Swanson et al., 2010)(Swanson et al., 2010)
	Dried corn	Gasification	Liquid waste	0.62	(Wright et al., 2010)(Wright et al., 2010)
	Dried corn	Gasification	Solid waste	0.0054	(Wright et al., 2010)(Wright et al., 2010)
	Dried paper	Pyrolysis	Gas waste	0.257	(Swanson et al., 2010)(Swanson et al., 2010)
	Dried paper	Gasification	Liquid waste	0.62	(Wright et al., 2010)(Wright et al., 2010)
	Dried paper	Gasification	Solid waste	0.0054	(Wright et al., 2010)(Wright et al., 2010)
	Corn stover	Evaporation + Pyrolysis	Gas waste	0.2	(Swanson et al., 2010)(Swanson et al., 2010)
	Corn stover	Evaporation + Gasification	Liquid waste	0.5	(Wright et al., 2010)(Wright et al., 2010)

Corn stover	Evaporation + Gasification	Solid waste	0.04	(Wright et al., 2010)(Wright et al., 2010)
Paper sludge	Evaporation + Pyrolysis	Gas waste	0.18	(Swanson et al., 2010)(Swanson et al., 2010)
Paper sludge	Evaporation + Gasification	Liquid waste	0.43	(Wright et al., 2010)(Wright et al., 2010)
Paper sludge	Evaporation + Gasification	Solid waste	0.035	(Wright et al., 2010)(Wright et al., 2010)

Table 14. Overview of the capacity parameters.

Parameter	Value	Source
$cpu_{wi,production}$	1	-
$ccu_{cj,production}$	1	-
$capp_{m,production,t}$	879000000	(Swanson et al., 2010)(Swanson et al., 2010)
$capc_{n,production,t}$	730000000	(Swanson et al., 2010)(Swanson et al., 2010)

Table 15. Overview of the compound prices in US$ per kg.

Parameter	Value ($)	Source
$wf_{corn\ stover}$	0.02	-
$wf_{paper\ sludge}$	0.08	-
$pp_{bio\ char}$	0.45	(Pokharel & Comer, 2021)
$pp_{bio-oil}$	0.75	(The Oil Market Journal, 2022)
pp_{syngas}	0.56	(Swanson et al., 2010)
$dcp_{liquid\ waste}$	0.00117	(Swanson et al., 2010)(Swanson et al., 2010)
$dcp_{solid\ waste}$	0.0259	(Swanson et al., 2010)(Swanson et al., 2010)

Table 16. Overview of the transport costs for tca_{wlm} and tcd_{wln} in US$ per kg based on (van der Meulen et al., 2023)(van der Meulen et al., 2023).

Waste type	Source location	Processing location					
		Decatur	Rockford	Chicago outskirts	Springfield	Champaign	Mount Vernon
Corn stover	Montgomery	0.039928	0.01932	0.005313	0.044758	0.031717	0.068425
Corn stover	Peoria	0.020447	0.035259	0.037513	0.018998	0.023184	0.055867
Corn stover	Saint Louis	0.029785	0.07567	0.070357	0.02415	0.046529	0.019481

Corn stover	Flanagan	0.022057	0.029785	0.02254	0.027048	0.020286	0.060053
Corn stover	Hidalgo	0.020769	0.067942	0.055062	0.030429	0.020608	0.025921
Corn stover	Jacob	0.044114	0.091931	0.086779	0.040572	0.055867	0.018354
Paper	Montgomery	0.0372	0.018	0.00495	0.0417	0.02955	0.06375
Paper	Peoria	0.01905	0.03285	0.03495	0.0177	0.0216	0.05205
Paper	Saint Louis	0.02775	0.0705	0.06555	0.0225	0.04335	0.01815
Paper	Flanagan	0.02055	0.02775	0.021	0.0252	0.0189	0.05595
Paper	Hidalgo	0.01935	0.0633	0.0513	0.02835	0.0192	0.02415
Paper	Jacob	0.0411	0.08565	0.08085	0.0378	0.05205	0.0171

Table 17. Overview of the transport costs in US$ per kg based on (van der Meulen et al., 2023)(van der Meulen et al., 2023).

Waste types	**Locations *m/n***	**Transport costs**
$tcb_{dried\ corn,mn}/tcb_{dried\ paper,mn}$	Decatur/Rockford	0.046851
	Decatur/Chicago Outskirts	0.012558
	Decatur/Springfield	0.010465
	Decatur/Champaign	0.041699
	Decatur/Mount Vernon	0.046851
	Rockford/Chicago Outskirts	0.038157
	Rockford/Springfield	0.022379
	Rockford/Champaign	0.046368
	Rockford/Mount Vernon	0.022862
	Chicago Outskirts/Springfield	0.03703
	Chicago Outskirts/Champaign	0.03542
	Chicago Outskirts/Mount Vernon	0.051198
	Springfield/Champaign	0.072772
	Springfield/Mount Vernon	0.047978
	Champaign/Mount Vernon	0.084364

Table 18. Overview of the production costs in US$ per kg.

Parameter	**Value**	**Source**
$pcp_{corn\ stover,evaporation}$	0.1	(Swanson et al., 2010)(Swanson et al., 2010)
$pcp_{paper\ sludge,evaporation}$	0.13	(Swanson et al., 2010)(Swanson et al., 2010)
$pcc_{dried\ corn,pyrolysis}$	0.1	(Swanson et al., 2010)(Swanson et al., 2010)
$pcc_{dried\ corn,gasification}$	0.17	(Wright et al., 2010)(Wright et al., 2010)
$pcc_{dried\ paper,pyrolysis}$	0.1	(Swanson et al., 2010)(Swanson et al., 2010)

$pcc_{dried\ paper,gasification}$	0.17	(Wright et al., 2010)(Wright et al., 2010)
$pcp_{corn\ stover,evaporation+pryolysis}$	0.17	(Swanson et al., 2010)(Swanson et al., 2010)
$pcp_{corn\ stover,evaporation+gasificaiton}$	0.25	(Wright et al., 2010)(Wright et al., 2010)
$pcp_{paper\ sludge,evaporation+pyrolysis}$	0.19	(Swanson et al., 2010)(Swanson et al., 2010)
$pcp_{paper\ sludge,evaporation+gasification}$	0.28	(Wright et al., 2010)(Wright et al., 2010)

Table 19. Overview of the investment costs in US$.

Parameter	Value	Source
icx_m	2,500,000	(Swanson et al., 2010)(Swanson et al., 2010)
icy_n	13,000,000	(Wright et al., 2010)(Wright et al., 2010)
$icj_{pyrolysis}$	18,000,000	(Swanson et al., 2010)(Swanson et al., 2010)
$icj_{gasification}$	60,000,000	(Wright et al., 2010)(Wright et al., 2010)
$icj_{evaporation+pyrolysis}$	32,000,000	(Swanson et al., 2010)(Swanson et al., 2010)
$icj_{evaporation+gasification}$	74,000,000	(Wright et al., 2010)(Wright et al., 2010)

A-5 Model script

```
(!*****************************************************************************
*
 Try out for the model
 =====================

 file model_tryout.mos
 ``````````````````````
 TYPE: MOMILP/location-allocation
 FEATURES: simple try out model of the SCND
                max 2 entries
 DESCRIPTION: A set of technologies are assigned to a certain location
                Besides, the material flows are determined. This all is
                based with the obejctive to maximize the profit, while
                minimizing the waste, GHG emissions and the energy usage.
 Author: H. H. Sol, 2024
****
!)

model "Tryout"
uses "mmxprs";   ! Gain access to Xpress-optimizer solver
uses "mmsheet";   ! Gain access to ExCel work sheets for data

 declarations
  ! Sets
   W : set of string   ! Set of waste types qualities
   C : set of string   ! Set of convertible intermediates qualities
   CA: set of string   ! Set of capacity constraints
   D : set of string   ! Set of disposable waste types
   P : set of string   ! Set of products
   I : set of string   ! Set of pretreatment pathways
   J : set of string   ! Set of conversion pathways
   L : set of string   ! Set of locations of waste collectors
   M : set of string   ! Set of locations for pretreatment
   N : set of string   ! Set of locations for conversion
   T : set of string   ! Set of time periods
   S = {"PROFIT", "SALES", "INCOME", "TRANS_COST_WST", "TRANS_COST_CONWST",
"TRANS_COST_DIRWST","PROD_COST", "DIS_COST", "INV_COST", "WST_STREAM",
"DIR_STREAM", "CON_STREAM", "PROD_STREAM", "DIS_PRE_STREAM",
"DIS_CON_STREAM", "WASTEHANDLED", "SLACK"}

  ! Parameters
   avail_wst   :array(W,L,T) of real   ! The available waste from a location in a time
period in kg waste
   cap_con   :array(N,CA,T) of real   ! Maximum value a certain capacity can have in
different units
```
```

```
cap_con_per_unit :array(C,J,CA)   of real ! A certain capacity constraint in kg per unit
                                  capacity (e.g. kg of convertible waste which results in
                                  one kg N2 emmission)
cap_pre :array(M,CA,T)            of real ! Maximum value a certain capacity can have in
                                  different units
cap_pre_per_unit :array(W,I,CA)   of real ! A certain capacity constraint in kg per unit
                                  capacity
conv_cost :array(C,J)             of real ! Production costs of the conversion of
                                  intermediate products per kg intermediate
conwst :array(W,C,I)              of real ! Amount of convertible waste produced from
                                  one kg waste
disp_cost :array(D)               of real ! Cost of disposing of disposable waste per kg
                                  dispoable waste
diswst_con :array(C,D,J)          of real ! Amount of disposable waste produced from
                                  one kg of convertible waste
diswst_pre :array(W,D,I)          of real ! Amount of disposable waste produced from
                                  one kg waste
inv_cost_con :array(J)            of real ! Investment cost for the conversion technology,
                                  normalized for the chosen time period
inv_cost_pre :array(I)            of real  ! Investment cost for the pretreatment facility,
                                  normalized for the chosen time period
inv_cost_y = 13000000             ! Investment cost for the conversion building
ipftech :array(J)                 of real ! Binary variable whether a technology is either
                                  an IPF (1) or not (0)
maxdemand :array(P)               of real ! Maximum demand of a product p on market
mindemand  :array(P)              of real ! Minimum demand of a product p on market
pretre_cost :array(W,I)           of real ! Production costs of the pretreatment of waste
                                  per kg waste
produ :array(C,P,J)               of real ! Amount of product produced from one kg
                                  convertible waste
prod_price :array(P)              of real ! Selling price of the products per kg product
tc_conwst :array(C,M,N)           of real ! Transportation costs of conv. waste from
                                  location m to location n per kg conv. waste
tc_dirwst :array(W,L,N)           of real ! Transportation costs of waste from location l
                                  to location n per kg waste
tc_wst :array(W,L,M)              of real ! Transportation costs of waste from location l
                                  to location m per kg waste
techlimcon :array(N)              of real ! Maximum amount of technologies j that are
                                  allowed at location n
techlimpre :array(M)              of real ! Maximum amount of technologies i that are
                                  allowed at location m
wst_inc :array(W)                 of real ! Income from processing waste per kg waste

  ! Variables
WST :array(W,I,L,M,T)             of mpvar ! Waste stream with quality w from location l
                                  to location m at period t in kg waste
CON_WST :array(C,J,M,N,T)         of mpvar        ! Convertible waste stream with quality
```

```
                                c from location m to location n at period in kg conv.
                                waste
RODU :array(P,N,T)              of mpvar ! Product stream with quality p from location
                                n to location o at period t in kg product
DIR_WST :array(W,J,L,N,T)       of mpvar ! Direct waste stream ready for conversion
                                with qualities w from location l to coation n with
                                pathway j in time period t
DIS_WST_PRE :array(D,M,T)       of mpvar ! Disposable waste stream from pretreatment
                                with quality d from location m to location q at period t
                                in kg disp. waste
DIS_WST_CON :array(D,N,T)       of mpvar ! Disposable waste stream from conversion
                                with quality d from location m to location q at period t
                                in kg disp. waste
Rm :array(M)                    of mpvar ! Whether a location m has a pretreatment
                                centre
Rn :array(N)                    of mpvar ! Whether a lcoation n has a conversion
                                centre or not
X :array(I,M)                   of mpvar ! Whether a location m has technology i (1) or
                                not (0)
Y :array(J,N)                   of mpvar ! Whether a location n has technology j (1) or
                                not (0)
PROFIT :mpvar                   ! Profit of the supply chain design
SALES :mpvar                    ! Sales of products
INCOME :mpvar                   ! Income for handling the waste of the waste collector
TRANS_COST_WST :mpvar           ! Transportation cost of the supply chain
TRANS_COST_CONWST :mpvar        ! Transportation cost of the supply chain
TRANS_COST_DIRWST :mpvar        ! Transportation cost of the supply chain
TRANS_COST_DISWST  :mpvar       ! Transportation cost of the supply chain
PROD_COST :mpvar                ! Production cost of the supply chain
DIS_COST :mpvar                 ! Cost for disposing the remeaning waste
INV_COST :mpvar                 ! Investment cost for the supply chain
WST_STREAM :mpvar               ! Total waste stream
DIR_STREAM :mpvar               ! Total direct stream
CON_STREAM :mpvar               ! Total convertible waste stream
PROD_STREAM :mpvar              ! Total product stream
DIS_PRE_STREAM :mpvar           ! Total disposable waste stream from the pretreatment
DIS_CON_STREAM :mpvar           ! Total disposable waste stream from the conversion
WASTEHANDLED :mpvar             ! Waste left from the supply chain * -1
SLACK :mpvar                    ! Slack variable
RESULT :array(S) of real        ! Results array to contain the results
 end-declarations

 initializations from "mmsheet.excel:Data.xlsx"
  ! Parameters
   W as "[Index overview$B2:B3]"
   C as "[Index overview$E2:E5]"
   D as "[Index overview$H2:H4]"
```

```
 P as "[Index overview$K2:K4]"
 L as "[Index overview$B8:B13]"
 M as "[Index overview$E8:E13]"
 N as "[Index overview$H8:H13]"
 I as "[Index overview$B16]"
 J as "[Index overview$E16:E19]"
 CA as "[Index overview$H16]"
 T as "[Index overview$K16:K17]"

 avail_wst          as "partindex;skiph;[avail_wst$A:D]"
 cap_con            as "skiph;[cap_con$A:D]"
 cap_con_per_unit   as "skiph;[cap_con_per_unit$A:D]"
 cap_pre            as "partindex;skiph;[cap_pre$A:D]"
 cap_pre_per_unit   as "skiph;[cap_pre_per_unit$A:D]"
 conv_cost          as "skiph;[conv_cost$A:C]"
 conwst             as "skiph;[conwst$A:D]"
 disp_cost          as "skiph;[disp_cost$A:B]"
 diswst_con         as "skiph;[diswst_con$A:D]"
 diswst_pre         as "skiph;[diswst_pre$A:D]"
 inv_cost_con       as "skiph;[inv_cost_con$A:B]"
 inv_cost_pre       as "skiph;[inv_cost_pre$A:B]"
 ipftech            as "skiph;[ipftech$A:B]"
 !maxdemand         as "skiph;[maxdemand$A:B]"
 mindemand          as "skiph;[mindemand$A:B]"
 pretre_cost        as "skiph;[pretre_cost$A:C]"
 produ              as "skiph;[produ$A:D]"
 prod_price         as "skiph;[prod_price$A:B]"
 tc_conwst          as "skiph;[tc_conwst$A:D]"
 tc_dirwst          as "partindex;skiph;[tc_dirwst$A:H]"
 tc_wst             as "partindex;skiph;[tc_wst$A:H]"
 techlimcon         as "skiph;[techlimcon$A:B]"
 techlimpre         as "skiph;[techlimpre$A:B]"
 wst_inc            as "skiph;[wst_inc$A:B]"
end-initializations

 SALES =                 sum(p in P, n in N, t in T) prod_price(p) * PRODU(p,n,t)
 INCOME =                sum(w in W, i in I, l in L, m in M, t in T) wst_inc(w) *
                         WST(w,i,l,m,t) + sum(w in W, j in J, l in L, n in N, t in T)
                         wst_inc(w) * DIR_WST(w,j,l,n,t)
 TRANS_COST_WST =        sum(w in W, i in I, l in L, m in M, t in T) tc_wst(w,l,m) *
                         WST(w,i,l,m,t)
 TRANS_COST_CONWST =     sum(c in C, j in J, m in M, n in N, t in T) tc_conwst(c,m,n) *
                         CON_WST(c,j,m,n,t)
 TRANS_COST_DIRWST =     sum(w in W, j in J, l in L, n in N, t in T) tc_dirwst(w,l,n) *
                         DIR_WST(w,j,l,n,t)
 PROD_COST =              sum(w in W, i in I, l in L, m in M, t in T) pretre_cost(w,i) *
```

```
                        WST(w,i,l,m,t) + sum(c in C, j in J, m in M, n in N, t in T)
                        conv_cost(c,j) * CON_WST(c,j,m,n,t) + sum(w in W, c in C, j in J,
                        l in L, n in N, t in T|w = c) conv_cost(c,j) * DIR_WST(w,j,l,n,t)
DIS_COST =              sum(d in D, m in M, t in T) disp_cost(d) * DIS_WST_PRE(d,m,t)
                        + sum(d in D, n in N, t in T) disp_cost(d) * DIS_WST_CON(d,n,t)
INV_COST =              sum(i in I, m in M) inv_cost_pre(i) * X(i,m) + sum(j in J, n in N)
                        inv_cost_con(j) * Y(j,n) + sum(n in N) Rn(n) * inv_cost_y

PROFIT =                SALES + INCOME - TRANS_COST_WST - TRANS_COST_CONWST
                        - TRANS_COST_DIRWST - PROD_COST - DIS_COST - INV_COST


WST_STREAM =            sum(w in W, i in I, l in L, m in M, t in T) WST(w,i,l,m,t)
DIR_STREAM =            sum(w in W, j in J, l in L, n in N, t in T) DIR_WST(w,j,l,n,t)
CON_STREAM =            sum(c in C, j in J, m in M, n in N, t in T) CON_WST(c,j,m,n,t)
PROD_STREAM =           sum(p in P, n in N, t in T) PRODU(p,n,t)
DIS_PRE_STREAM =        sum(d in D, m in M, t in T) DIS_WST_PRE(d,m,t)
DIS_CON_STREAM =        sum(d in D, n in N, t in T) DIS_WST_CON(d,n,t)

WASTEHANDLED =          WST_STREAM + DIR_STREAM - DIS_PRE_STREAM –
                        DIS_CON_STREAM

! Constraints
 ! Waste stream to facilities is max the available waste
 forall(w in W, l in L, t in T)
        sum(i in I, m in M) WST(w,i,l,m,t) + sum(j in J, n in N) DIR_WST(w,j,l,n,t) <=
        avail_wst(w,l,t)

 ! Flow balancing for pretreatment to conv. waste
 forall(c in C, m in M, t in T|sum(w in W, i in I) conwst(w,c,i) > 0)
        sum(j in J, n in N) CON_WST(c,j,m,n,t) = sum(w in W, i in I, l in L) conwst(w,c,i) *
        WST(w,i,l,m,t)

sum(c in C, m in M, t in T, j in J, n in N|sum(i in I, w in W)conwst(w,c,i) = 0)
CON_WST(c,j,m,n,t)=0
sum(w in W, i in I, l in L, m in M, t in T|sum(c in C) conwst(w,c,i) = 0) WST(w,i,l,m,t)=0

 ! Flow balancing for conversion to product
 forall(p in P, n in N, t in T|sum(w in W, c in C, j in J|w = c)produ(c,p,j) > 0)
   PRODU(p,n,t) = sum(c in C, j in J, m in M) produ(c,p,j) * CON_WST(c,j,m,n,t) +
                  sum(w in W, c in C, j in J, l in L|w = c) produ(c,p,j) * DIR_WST(w,j,l,n,t)

 forall(w in W, c in C|w not in C)
         sum(j in J, l in L, n in N, t in T) DIR_WST(w,j,l,n,t) = 0

 sum(c in C, j in J, m in M, n in N, t in T|sum(p in P) produ(c,p,j) <= 0) CON_WST(c,j,m,n,t) =
 0
```

```
sum(w in W, j in J, l in L, n in N, t in T|sum(c in C, p in P|w = c) produ(c,p,j) <= 0)
DIR_WST(w,j,l,n,t) = 0
sum(p in P, n in N, t in T|sum(c in C, j in J)produ(c,p,j) <= 0) PRODU(p,n,t) = 0

 ! Flow balancing for pretreatment to disp. waste
 forall(d in D, m in M, t in T|sum(w in W, i in I)diswst_pre(w,d,i) > 0)
   DIS_WST_PRE(d,m,t) = sum(w in W, i in I, l in L) diswst_pre(w,d,i) * WST(w,i,l,m,t)

 sum(d in D, m in M, t in T|sum(w in W, i in I) diswst_pre(w,d,i) <= 0) DIS_WST_PRE(d,m,t) =
 0

 ! Flow balancing for conversion to disp. waste
 forall(d in D, n in N, t in T|sum(c in C, j in J) diswst_con(c,d,j) > 0)
   DIS_WST_CON(d,n,t) = sum(c in C, j in J, m in M) diswst_con(c,d,j) * CON_WST(c,j,m,n,t)
   + sum(w in W, c in C, j in J, l in L|w = c) diswst_con(c,d,j) * DIR_WST(w,j,l,n,t)

 sum(d in D, n in N, t in T|sum(c in C, j in J) diswst_con(c,d,j) <= 0) DIS_WST_CON(d,n,t) = 0

 ! Capacity of the pretreatment centres
 forall(m in M, t in T, ca in CA)
   sum(w in W, i in I, l in L) WST(w,i,l,m,t) * cap_pre_per_unit(w,i,ca) <= cap_pre(m,ca,t)

 ! Technology installed or not
 forall(i in I, m in M, t in T, ca in CA)
   sum(w in W, l in L) WST(w,i,l,m,t) * cap_pre_per_unit(w,i,ca) <= cap_pre(m,ca,t) * X(i,m)

 ! Capacity of the conversion centres
 forall(n in N, t in T, ca in CA)
   sum(c in C, j in J, m in M) CON_WST(c,j,m,n,t) * cap_con_per_unit(c,j,ca) +
   sum(w in W, c in C, j in J, l in L|w in C) DIR_WST(w,j,l,n,t) * cap_con_per_unit(c,j,ca) <=
   cap_con(n,ca,t)

 ! Technology installed or not
 forall(j in J, n in N, t in T, ca in CA)
   sum(c in C, m in M) CON_WST(c,j,m,n,t) * cap_con_per_unit(c,j,ca) +
   sum(w in W, c in C, l in L|w in C) DIR_WST(w,j,l,n,t) * cap_con_per_unit(c,j,ca) <=
   cap_con(n,ca,t) * Y(j,n)

 ! Meet minimun demand
 !forall(p in P)
   !sum(n in N, t in T) PRODU(p,n,t) >= mindemand(p)

 ! Not exceeding maximum demand
 !forall(p in P)
  !  sum(n in N, t in T) PRODU(p,n,t) <= maxdemand(p)

 ! Not exceeding maximum techniques per factory
```

```
  forall(m in M) sum(i in I) X(i,m) <= techlimpre(m) * Rm(m)
  forall(n in N) sum(j in J|ipftech(j)=0) Y(j,n) <= techlimcon(n) * Rn(n)
  forall(n in N) sum(j in J|ipftech(j)=1) Y(j,n) <= 1 - Rn(n)
  forall(m in M, n in N|m = n)
    Rm(m) + Rn(n) + sum(j in J|ipftech(j) = 1) Y(j,n) <= 1

  ! Binary constraints
  forall(i in I, m in M) X(i,m) is_binary
  forall(j in J, n in N) Y(j,n) is_binary
  forall(m in M) Rm(m) is_binary
  forall(n in N) Rn(n) is_binary

! Ending mathematical formulation

! Optimalization
maximize(PROFIT)
FidPROFIT              := getsol(PROFIT)
FndWASTEHANDLED  := getsol(WASTEHANDLED)

maximize(WASTEHANDLED)
FndPROFIT              := getsol(PROFIT)
FidWASTEHANDLED   := getsol(WASTEHANDLED)

WASTEHANDLED - SLACK = FndWASTEHANDLED + 0.5 * (FidWASTEHANDLED -
FndWASTEHANDLED)
maximize(PROFIT)
PROFIT_star            := getsol(PROFIT)
PROFIT >= PROFIT_star
maximise(SLACK/(FidWASTEHANDLED - FndWASTEHANDLED))

RESULT("PROFIT")                    := getsol(PROFIT)
RESULT("SALES")                     := getsol(SALES)
RESULT("INCOME")                    := getsol(INCOME)
RESULT("TRANS_COST_WST")            := getsol(TRANS_COST_WST)
RESULT("TRANS_COST_CONWST")         := getsol(TRANS_COST_CONWST)
RESULT("TRANS_COST_DIRWST")         := getsol(TRANS_COST_DIRWST)
RESULT("PROD_COST")                 := getsol(PROD_COST)
RESULT("DIS_COST")                  := getsol(DIS_COST)
RESULT("INV_COST")                  := getsol(INV_COST)
RESULT("WST_STREAM")                := getsol(WST_STREAM)
RESULT("DIR_STREAM")                := getsol(DIR_STREAM)
RESULT("CON_STREAM")                := getsol(CON_STREAM)
RESULT("PROD_STREAM")               := getsol(PROD_STREAM)
RESULT("DIS_PRE_STREAM")            := getsol(DIS_PRE_STREAM)
RESULT("DIS_CON_STREAM")            := getsol(DIS_CON_STREAM)
RESULT("WASTEHANDLED")              := getsol(WASTEHANDLED)
RESULT("SLACK")                     := getsol(SLACK)
```

```
!maximize(SLACK / (FidWASTEHANDLED - FndWASTEHANDLED))
!sum(p in P, n in N, t in T) PRODU(p,n,t)>=getsol(sum(p in P, n in N, t in T) PRODU(p,n,t))
!minimize( sum(m in M) X(m))

! Report output and input
if(getprobstat=XPRS_OPT)
  then  writeln("Profit =", getsol(PROFIT))
       writeln("Waste handeled =", getsol(WASTEHANDLED))
       writeln("     ")
       writeln("Total revenue =", getsol(SALES + INCOME))
       writeln("Total cost = ", getsol(TRANS_COST_WST + TRANS_COST_CONWST +
TRANS_COST_DISWST +
                              TRANS_COST_DIRWST + PROD_COST + DIS_COST + INV_COST))
       writeln("     ")
       writeln("Sales =", getsol(SALES))
       writeln("Income = ", getsol(INCOME))
       writeln("     ")
       writeln("Transportation cost = ", getsol(TRANS_COST_WST + TRANS_COST_CONWST +
TRANS_COST_DISWST + TRANS_COST_DIRWST))
       writeln("Production cost = ", getsol(PROD_COST))
       writeln("Disposing waste cost = ", getsol(DIS_COST))
       writeln("Investment cost = ", getsol(INV_COST))
       writeln("     ")
       writeln("     ")
       writeln("Waste stream =", getsol(WST_STREAM))
       writeln("Direct stream =", getsol(DIR_STREAM))
       writeln("Constream =", getsol(CON_STREAM))
       writeln("Product stream =", getsol(PROD_STREAM))
       writeln("     ")
       writeln("     ")
       forall(w in W, i in I, l in L, m in M, t in T|getsol(WST(w,i,l,m,t))>0)
          writeln("Waste(w",w,",i",i,",l",l,",m",m,",t",t,")= ",getsol(WST(w,i,l,m,t)))
       writeln("     ")
       writeln("     ")
       forall(w in W, j in J, l in L, n in N, t in T|getsol(DIR_WST(w,j,l,n,t))>0)
         writeln("Direct stream (w",w,", j",j,", l",l,", n",n,", t",t,") = ", getsol(DIR_WST(w,j,l,n,t)))
       writeln("     ")
       writeln("     ")
       forall(c in C, j in J, m in M, n in N, t in T|getsol(CON_WST(c,j,m,n,t))>0) do
         writeln("Con waste(c",c,", j",j,", m",m,", n",n,", t",t,") = ",getsol(CON_WST(c,j,m,n,t)))
       end-do
       writeln("     ")
       writeln("     ")
       forall(p in P, n in N, t in T|getsol(PRODU(p,n,t))>0)
         writeln("Product stream (p",p,", n",n,", t",t,") = ", getsol(PRODU(p,n,t)))
       writeln("     ")
       writeln("     ")
```

```
    forall(d in D, m in M, t in T|getsol(DIS_WST_PRE(d,m,t))>0)
      writeln("Dis wst Pretreatment (d",d,", m",m,", t",t,") = ",getsol(DIS_WST_PRE(d,m,t)))
    writeln("     ")
    writeln("     ")
    forall(d in D, n in N, t in T|getsol(DIS_WST_CON(d,n,t))>0)
      writeln("Dis wst Conversion (d",d,", n",n,", t",t,") = ",getsol(DIS_WST_CON(d,n,t)))

else
    if(getprobstat = XPRS_UNB)
      then writeln("Problem is unbounded")

end-if
    if(getprobstat = XPRS_INF)
      then writeln("Problem is infeasible")

end-if
end-if

end-model
```