Evaluation of the energy potential of organic waste in Havenstad : From a systems modelling and behavioural perspective

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Evaluation of the energy potential of organic waste in Havenstad : From a systems modelling and behavioural perspective

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Complex Systems Engineering and Management**

Faculty of Technology, Policy and Management

by

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To be defended in public on 29th April 2020

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Acknowledgement

This thesis concludes my Master's in Complex Systems Engineering and Management and my journey at TU Delft. Writing this thesis has been one of the most challenging tasks that I have ever experienced. I encountered a fair bit of struggle during the process but I have also learnt a lot through it. My time in TU Delft has been challenging, but highly rewarding. For the last two and half years I have grown a lot as a person and this is partially due to my experiences in TU Delft. I always wanted to study in a foreign country, learn a new field of study, experience a different culture and work with culturally diverse students. I thoroughly enjoyed all of that in TU Delft and the Netherlands. I shall never forgot this time.

As a CoSEM student I was introduced to Agent-Based Modelling, something that I found really interesting. The systems thinking approach & Agent-Based Modelling motivated the choice for my thesis. Also, I wanted to do something in the field of waste recycling, so I am glad I was given a chance to pursue this thesis topic.

My journey at TU Delft would not have been possible without the constant support of my family. I would like to thank my dad, Gagan, for always pushing me and providing me with constructive feedback. My mom, Reema, for supporting me in the decisions I make. Lastly, my brother, Shiv, thank you for taking on my responsibilities and looking after the family. I am blessed to have a family like ours. I love you all!

I would like to thank my graduation committee as well. Thank you Laurens for having faith in me and providing me the opportunity to pursue this thesis. I am really grateful to have your support during my thesis, even when things weren't working out. Your feedback and critical comments helped me structure my thoughts and improve my understanding. Next I would like to thank Els. Your comments and feedback on my report helped me a lot during the process. Especially your suggestion to take a coaching session to improve my writing skills. Last, but not the least, my daily supervisor, Kasper. Thank you Kasper for our weekly meetings. I enjoyed our long discussions on how to model. I remember when I doubted myself on something, you were always there push me. I am grateful for your supervision during my thesis.

Lastly, I would like to thank my housemates from house number 8. Your constant support, chai pe charcha, awesome cooking skills and company never let me feel far from home. Also, I would like to thank the DISS board I shared during the years 2018-2019. We organized some great events and enjoyed along with other international students. My time in DISS helped me grow more confident of my abilities, so I am grateful to be associated with it.

I look forward to what lies ahead. Although this might be the end of my student life, but I am still curious to learn something new, as I have always been. Anyways, hope you enjoy the read! Until next time !

Executive summary

Waste-to-Energy (WtE) serves as an important source to meet the growing energy demands of the world in a sustainable manner. It can help in the reduction of Greenhouse Gases (GHG) emissions, lower the risk of environmental pollution and contribute towards the establishment of a circular economy. By generating steam or electrical energy, WtE helps avoid the CO_2 emissions from fossil-fuel based electrical generation. According to the European Commission, WtE can play a key role in the transition to a circular economy. But it requires further improvements within the area of waste management.

Waste management mainly involves the collection, treatment and transportation of Municipal Solid Waste (MSW) to WtE infrastructures. One of its key objectives is to improve the source separation of Organic Fraction of Municipal Solid Waste (OFMSW) generated by households and Small-Medium Enterprises (SMEs). Source separation of waste helps in maximizing the energy recovery from waste, reduces the cost of waste treatment & increasing the sustainability of the waste management process . Source separation of OFMSW results in a more efficient treatment of organic waste by diverting it to the appropriate WtE technology, which is Anaerobic Digestion (AD). It also reduces the instances of incineration & landfilling of OFMSW, which are not as sustainable as Anaerobic Digestion (AD). The increase in source separation of OFMSW depends upon two factors: *Internal & External factors.* Internal factors are intrinsic to individuals participating in the waste separation scheme. They involve an individual's attitude, motivation, intention or behaviour. External factors are extrinsic to these individuals. They include the availability of waste collection infrastructures and the convenience of using them. Together the internal & external factors influence an individual's participation in the waste separation scheme.

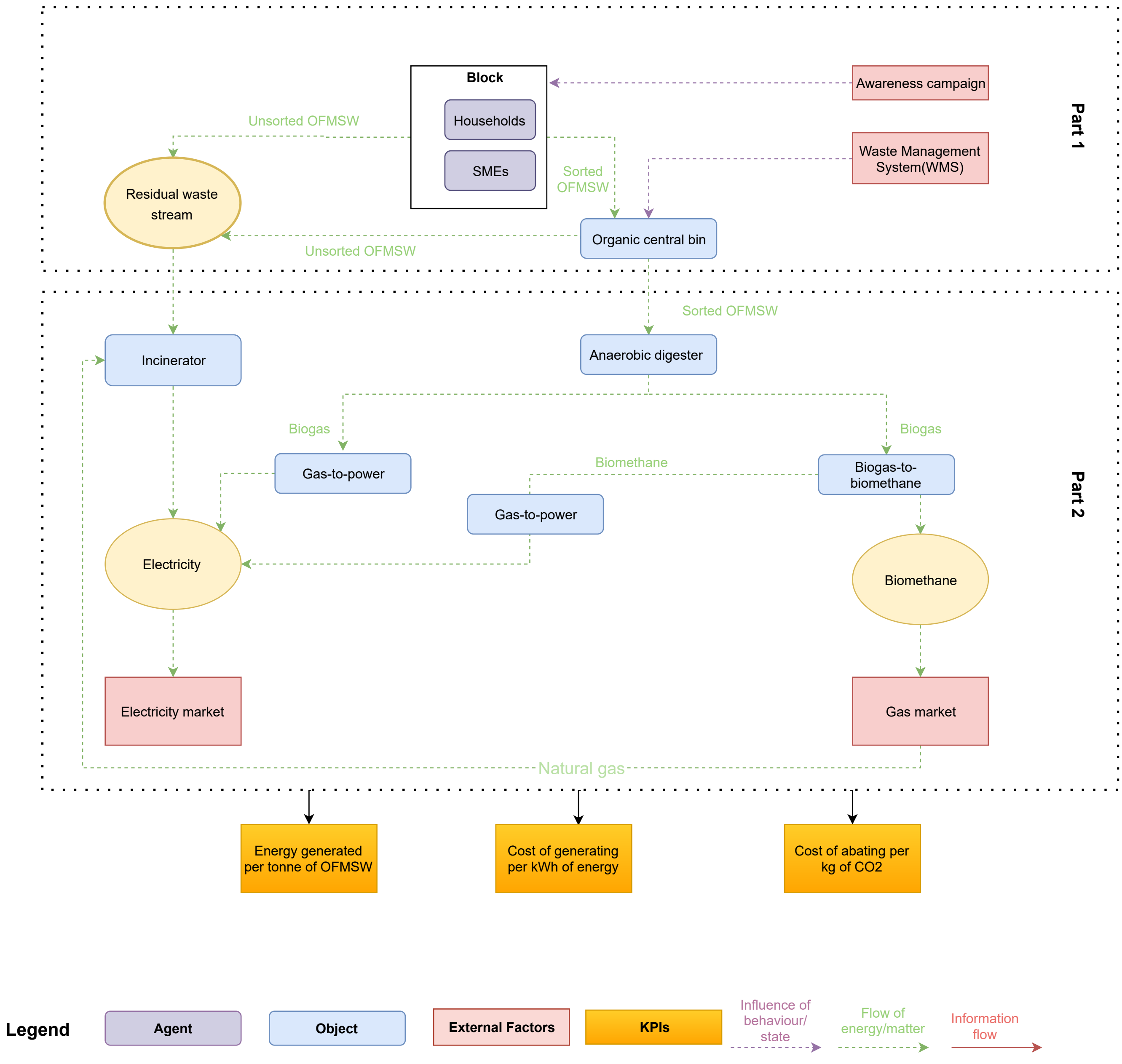
Although the influence of these factors on the waste separation rate is documented, but their influence on the potential of energy obtained from increased waste separation of OFMSW is not fully known. Furthermore, the influence of these factors on the environmental benefits and economics of WtE generation from OFMSW is not fully documented as well. Therefore, based on this knowledge gap, the research question for this thesis is formulated as follows:

What is the potential of energy generation, its net operating costs and CO2 abated from per tonne Organic Fraction of Municipal Solid Waste(OFMSW) generated by households and Small-Medium Enterprises(SMEs) ?

To answer this research question an Agent-Based Model (ABM) is constructed based on the case study of Havenstad- which is planned city in Amsterdam region. The ABM simulates waste separation activity of Havenstad & calculates the energy obtained from OFMSW generated for a period of 7 months. The ABM captures the internal & external factors pertaining to the participation of households & SMEs in the waste separation scheme. The waste separation behaviour or Pro-environmental behaviour is the internal factor that is examined in the ABM. To predict and capture the waste separation behaviour, the Value-Belief Norm (VBN) theory is employed and quantified in the ABM. The four behaviour values of the VBN theory help in its

quantification and serve as input to determine the waste separation behaviour of an individual household or SME via the variables of the VBN theory .

Furthermore, the ABM helps study the influence of these factors on the waste separation rate and subsequently the energy generated (in kWh) from one tonne of OFMSW, the cost of generating 1 kWh of energy & cost of abating 1 kg of CO_2 . Apart from these two factors, the ABM also examines the role of urban planning & different WtE technologies on the model outputs.



The conceptualization of the ABM can be split into two parts. The first part simulates the waste generation & waste separation activity of households and SMEs. The source sorted OFMSW ends up in the organic central bin while the unsorted OFMSW ends up in the residual waste stream. Together these entities (or agents) are represented in the form of a block or neighbourhood. It also includes external factors, such the awareness campaign & the Waste Management System (WMS), that influence the waste separation activity of the entities. They are modelled as informational intervention & structural interventions respectively.

The second part of the model calculates the model Key-Performance Indicators (KPIs) based on the WtE technological route. The unsorted OFMSW ends up in the incinerator, which converts it into electricity and sells it in the electricity market. The sorted OFMSW goes to anaerobic digester, which is produced biogas out of it. This biogas is converted into electricity and sold in the electricity market. Or it ends up being upgraded to biomethane, which is either converted into electricity or sold in the gas market.

The ABM offers a high degree of flexibility to study the influence of factors pertaining to the waste separation scheme, choice of technological route and distribution of entities within a block, on the model KPIs. To study these aspects a set of experiments are performed on the model, the results of these experiments help to answer the research question of this thesis.

Before carrying out the experiments, a baseline scenario is simulated in the model.The baseline scenario replicates the current set up of Havenstad in the model. The KPIs and the waste separation obtained from the simulation of this scenario are compared with the experiments carried out in the model. Furthermore, in each experiment a particular parameter from the baseline scenario is varied.

In the first experiment the distribution of households & SMEs in a block is examined. The results show that the waste separation rate increased when there is a high proportion of households in a block. In the second experiment the informational and structural interventions are studied. The results show that structural interventions are more effective in increasing the waste separation rate. Furthermore, within the structural intervention, increasing the organic central bin size is more economical in terms of power generation and CO_2 abatement, compared to increasing the frequency of waste collection. In the third experiment the influence of behaviour values and waste separation behaviour on the separation rate is examined. It is observed that the high egoistic & hedonic values reduce the waste separation rate as compared to the baseline scenario. Additionally, the increase in waste separation rate in case of high pro-environmental behaviour is limited by organic central bin size. On basis of additional experiments, it is observed that, to increase the waste separation rate due to the presence of high pro-environmental behaviour, the capacity of the central organic bin has to be increased.

The last experiment examines the three different WtE technological routes to treat source separated OFMSW: *Biogas to electricity, Biogas to biomethane and Biomethane to electricity.* In the baseline scenario, the route *Biogas to electricity* is employed. On the basis of the results it is observed that the route *Biomethane to electricity* gave the highest energy from the OFMSW generated by the entities within a block. Also, it the most economical and environmental compared to the other technological routes. Furthermore, additional experiments are carried out to examine the choice of the WtE technological route on the influence of structural interventions and behaviour values. The results show that increased waste separation results in higher energy from the OFMSW, only if biomethane, instead of biogas, is used to generate electrical power.

Based on the results of these experiments, it is concluded that waste separation rate is influenced by a the combined state of the internal and external factors. In other words, individualistic influence of either of the two factors on the waste separation rate is limited due the constant state of the other factor. For example, high pro-environmental behaviour did not increase the waste separation rate due to the unchanged central bin size of the baseline scenario. By increasing the capacity of the central bin, the state of the external factor is changed , which increases the waste separation rate due to the presence of Pro-environmental behaviour. Furthermore, to increase the energy obtained from OFMSW, a high waste separation is not sufficient. But the presence of a highly efficient technological route to process source separated OFMSW is required as well. Therefore, it is the combined state of the internal factor, external factor & WtE technological route that determine the potential of energy obtained from OFMSW.

The research question posed can be answered from a qualitative & quantitative point of view.From a qualitative research point of view, the combination of the internal and external factors shown in the figure below, gives a higher amount of source separated OFMSW. This source separated waste when processed into biomethane and then into electricity results in a higher energy obtained from OFMSW, compared to the baseline scenario.

A system is proposed by using the above mentioned factors as design principles and is based on the WtE technology route of *Biomethane to electricity*. The model KPIs along with waste separation rate for the system proposed are compared with that of the baseline scenario in the table below

Output	Baseline	System proposed	% change
Waste separation rate	6.9%	53.43%	+ 674.34%
Energy generated per tonne OFMSW	277 kWh	322 kWh	+ 16.24%
Cost of generating per kWh of energy	0.386 €	0.352 €	- 8.80%
Cost of abating per kg of CO_2	1.34 €	1.13 €	- 15.67%

The system proposed results in 322 kWh of (electrical) energy from one tonne of OFMSW, at a rate of 0.352 € per kWh and abates 100 kg of CO_2 per tonne of OFMSW processed.

Compared to the baseline scenario, the waste separation rate increases by nearly 7 times. The energy generated per tonne of OFMSW incrased by 16.24%. Furthermore, the cost of generating per kWh of energy decreased by 8.80% and the amount of CO_2 abated increases by 25.32%.

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Abbreviations

AC	Awareness of Consequences
AR	Ascription of Responsibility
CCGT	Combined Cycle Gas Turbine
MSW	Municipal Solid Waste
NEP	New Ecological Paradigm
OFMSW	Organic Fraction of Municipal Solid Waste
PEB	Pro-environmental Behaviour
PN	Personal Norm
SMEs	Small-Medium Enterprises
SOI	System of Interest
TPB	Theory of Planned Behaviour
VBN	Value-Belief Norm
WMS	Waste Management System
WtE	Waste-to-Energy

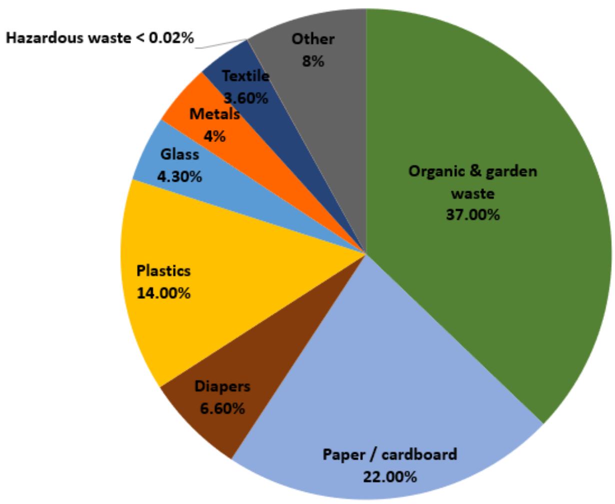
1. Introduction

The chapter begins by introducing the main theme of this thesis and the research problem. Based on which the knowledge gaps are presented in Section 1.3 . Section 1.4 lists out the sub research questions and main research. Lastly, in section 1.5 the structure of the whole report is explained.

1.1 Waste to Energy

Waste-to-Energy (WtE) can play an important role in fulfilling the growing energy demands of the world in a sustainable way. WtE is the process in wherein Municipal Solid Waste (MSW) is utilized to generate useful energy in the form of electricity, heat, or transport fuels (Barik, 2019; Cleveland & Morris, 2005). MSW is the waste generated by households, institutions and Small-Medium Enterprises (SMEs). Most of the WtE processes result in zero net emissions of CO_2 . Furthermore, WtE can help in the reduction of Greenhouse Gases (GHG) from conventional fossil fuel based power plants such coal power plants and Combined Cycle Gas Turbine (CCGT) plants. It can do so by generating electrical power or steam, instead of fossil fuel based electrical generation that emits CO_2 (Johnke, 1996; Michael, 2013).

Figure 1.1: Composition of residual household waste in the Netherlands (Goorhuis et al., 2012)



The typical composition of the MSW in the Netherlands is depicted with help of Figure 1.1. The 'Organic & garden waste' or Organic Fraction of Municipal Solid Waste (OFMSW) constitutes more than one-third of the total MSW in the Netherlands. The OFMSW is mostly composed of vegetables & fruits, garden cuttings, food, bread and organic residues (CREM, 2013). Given its large proportion, OFMSW[1], can serve as potential fuel source to generate heat, electricity or fuel (Rousta & Bolton, 2019; Wilken et al., 2019).

The most commonly used WtE technologies to process OFMSW are: *Incineration* & *Anaerobic digestion*. Incineration involves the combustion of waste to release heat energy, which can be used to generated electricity. Incineration is carried out for the residual waste streams, that cannot be recycled. The unsorted OFMSW forms a part of this residual waste stream. Anaeobic digestion is a microbial process of generating biogas from OFMSW. It is the most promising technology for intensive bio-degradation of organic matter (Saadabadi et al., 2019). Furthermore, the biogas obtained can be used to generate electricity or can be upgraded to biomethane. In comparison to biogas, which is compared of 55% methane, carbon dioxide and other trace gases, biomethane has a methane content of over 90%. Thus, biomethane has a higher energy output than biogas.

The electricity obtained from OFMSW can be sold in the electricity market and potentially replace the electricity generated by fossil-fuel based coal and natural gas plants. Alternatively, biomethane obtained from OFMSW can substitute natural gas in gas grid (GasTerra, 2009; German Biogas Association, 2016).

Of the two technologies, anaerobic digestion is more sustainable & environmental friendly. It can result in lower emissions compared to waste incineration. Also, apart from generating biogas, it gives compost as a by-product which can be used as a fertilizer. But route taken by the OFMSW generated depends on its separation into the correct collection infrastructures.

1.2 Source separation

The source separation of OFMSW can play a role in determining the WtE technological route employed to extract energy out of OFMSW. Source separation is the segregation of different types of MSW at its point of generation. The waste is segregated by households and SMEs in kerbside collection bins allocated to a particular waste type. If the waste cannot be classified for any of the bins, then in that case the waste ends up in residual bin.

For example,organic waste segregated correctly in the organic waste bin meant for it, mostly ends up in the anaerobic digester. But, if for some reason, an individual does not identify the organic waste or cannot separate it correctly, then it ends up in the residual waste bin. The organic waste, along with other types of waste (glass, plastic) ends up in the incinerator.

Source separation of organic waste is beneficial for the setup and working of an anaerobic digester . Source separation of organic waste maximizes the energy recovery from organic waste by providing high quality OFMSW for anaerobic digestion (Al Seadi, Owen, Hellström, & Kang, 2013). Although it is possible to separate the organic waste from the residual waste stream using costly machinery in a Material Recovery Facility (MRF). But currently there is no available equipment that sorts all fractions in a commingled waste stream (Rousta & Bolton, 2019). Furthermore, the source separation of organic waste is better as compared to the material recovery from the commingled residual waste stream because separation at the source results in cleaner, higher-quality materials (Bennagen, Nepomuceno, Covar, et al., 2002). Also, it means the presence of contaminants in the organic waste is decreased, thus making sure the efficiency of waste treatment processes like anaerobic digestion is not decreased (Rousta & Bolton, 2019).

To summarise, source separation aids in providing a high quantity & high quality feedstock for anaerobic digestion, which is the preferred technology over waste incineration.Also, it is

[1]In some parts of the report the terms ‘organic waste’ & ‘biowaste’ are used interchangeably instead of OFMSW

proven to beneficial for the environment and human & animal health (Al Seadi et al., 2013). Given its benefits, the increase in source separation of waste is high on the European & worldwide agenda (European Commission, 2018; Polprasert, 2017; Scalco et al., 2017). It is said to play a key role in setting up a Circular economy in Europe (European Commission, 2018).

In order to achieve high source separation it important to understand the factors that determine it. Rousta and Bolton (2019) state that there are three factors that influence an individual participation in source separation: *Socio-demographic, Internal & External factors.* Together these factors influence the waste separation rate at source.

Socio-demographic factors are variables such as culture, age, gender, level of education and income. Although socio-demographic factors play a role in determining the waste separation rate, but it is still unclear how they affect the waste separation behavior (Meng et al., 2019).

Internal factors are intrinsic to each individual, who carry out the waste separation activity. They effect an individual's participation in the waste separation scheme.These factors include the individual's values, knowledge about organic waste, attitude and personal beliefs & norms towards recycling or waste separation(Meng et al., 2019; Minelgaitė & Liobikienė, 2019; Rousta & Bolton, 2019). Values (or Behaviour values) of an individual can determine the norm held by it towards source separation of waste. The presence of this norm increases an individual's participation in the waste separation scheme. The relationship between the behaviour values and personal norms can be determined with the help of the Value-Belief Norm (VBN) theory. According to the theory, there are four behaviour values: *Altruistic, Biospheric, Egoistic & Hedonic*. Between them, Altruistic & Biospheric values are shown to be more strongly associated with pro-environemntal or waste separation behaviour (Steg, Dreijerink, & Abrahamse, 2005).

External factors include the state of waste collection infrastructures and presence feedback mechanisms. Waste collection infrastructures can be defined by their proximity to a household or SME, size, convenience and hygiene. These variables together affect the interaction of the individual within a household or SME with the infrastructure (Meng et al., 2019). While feedback mechanisms can be in the form of social norms or a medium that transmits relevant information, like an awareness campaign. Setting up a awareness campaign is known as an *Informational intervention* and on the other hand, altering the state of the waste collection infrastructures is known as a *Structural intervention.* Another form of structural intervention can be varying the allocation of households and SMEs to the waste collection bin.

To summarise, the behaviour values of individuals determine the influence of internal factors on the waste separation behaviour. In a similar manner, interventions determine the role of external factors on the waste separation behaviour.

Although, the role of these factors in increasing the source separation of waste is documented, but their influence on the energy generated from OFMSW, due to increased separation, is not fully known. On the basis of the preliminary research presented in this chapter, the following *research problem* is formulated:

WtE is claimed to be a sustainable alternative to meet the growing energy demands from OFMSW. To increase the efficiency of this process, there is a need for increased source separation of OFMSW by households & SMEs. The presence of certain behaviour values and the implementation of interventions plays a role in the increased source separation of OFMSW. However, the influence of these factors and the choice of WtE technology, on the increase in the energy generated from OFMSW, due to increased source separation, is still not known yet. Furthermore, the reduction in cost of energy generation & increase of the environmental benefit bought by a combination of behaviour values, interventions & choice of

WtE technologies is not examined as well.

1.3 Knowledge gaps

Based on the preliminary research, research problem and literature review in Chapter 3, a list of knowledge gaps are presented in this section.

Firstly, from literature it is observed that a comparison between the influence of internal and external factors on waste separation is not analysed well enough.

Secondly, the influence of behaviour values & interventions on the energy obtained from OFMSW, its net operating costs and the economic efficiency of CO_2 abatement is not thoroughly examined.

Thirdly, the economic & environmental benefit from a combination of behaviour values, interventions & choice of WtE to treat source separated OFMSW, is not thoroughly examined.

1.4 Research questions

Based on the knowledge gaps, literature review (Chapter 3) and Interviews (Appendix C) the main research question along with its sub-questions is formulated below:

What is the potential of energy generation, its net operating costs and CO2 abated from per tonne Organic Fraction of Municipal Solid Waste(OFMSW) generated by households and Small-Medium Enterprises(SMEs) ?

SQ1 What are the characteristics of the commonly used WtE technologies to treat OFMSW ?

SQ2 How does distribution of households and SMEs in a neighbourhood influence the energy generated from their OFMSW, its economics of energy generation and the economic efficiency of CO_2 abatement ?

SQ3 What is the influence of different types of interventions on the energy generated from OFMSW, its economics of energy generation and the economic efficiency of CO_2 abatement?

SQ4 What is the influence of different behaviour values on the energy generated from the OFMSW,its economics of energy generation and the economic efficiency of CO_2 abatement ?

SQ5 How do different WtE technologies, that treat source separated OFMSW, influence the contribution of interventions and behaviour values on economics of energy generation & economic efficiency of CO_2 abatement ?

The research approach employed to answer the main research question and its sub-questions is discussed in Chapter 2.

1.5 Report structure

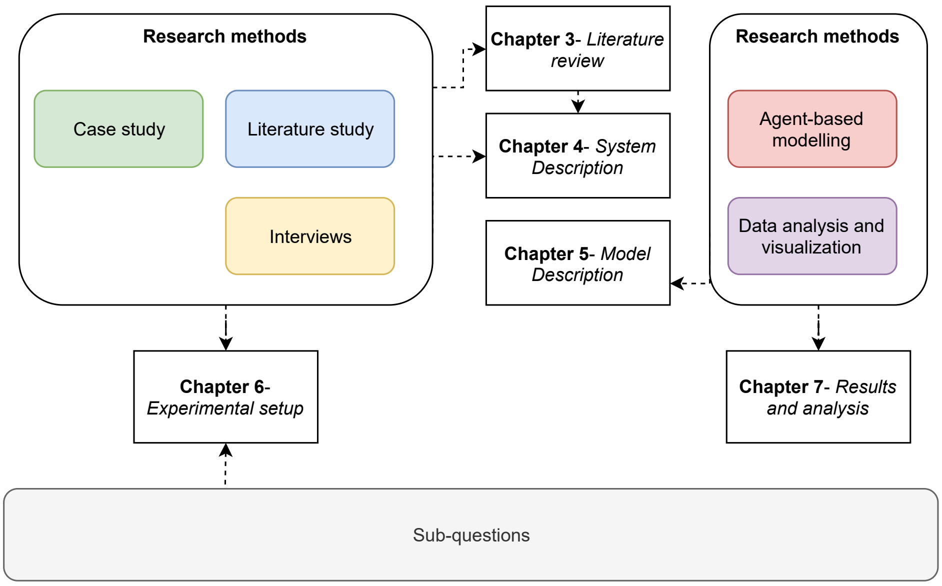
The thesis report is divided into nine chapters (including this one). The initial chapters describe the research, followed by the results and conclusion. Chapter 2 describes the research approach and its link to the Master's programme. In Chapter 3 , a literature review is presented to comprehend this research and its concepts. Chapter 4 describes the system to-be-modelled with the help of literature and databases. In Chapter 5 , the model and its logic are described. Chapter 6 describes the experiments carried out in the model to answer sub-questions and subsequently the main research question. Chapter 7 presents the results of these experiments along with the analysis of these results. The results obtained are discussed in Chapter 8. The report concludes in Chapter 9, which includes the answer to the main research question, academic & societal relevance, limitations of the research and recommendations for future research.

2. Research Approach

The chapter presents the research approach for addressing the research questions. The chapter begins by describing the research approach and identifies the research methods used. The research methods are described and discussed from Section 2.1 to 2.5. The chapter ends by discussing the link of this thesis with the CoSEM Master's programme.

The main research question and the subsequent sub-questions introduced in the previous chapter are addressed in Chapters 3 to 7. To answer these sub-questions, certain research methods are employed. These research methods are specific to each chapter and this can be elaborated with help of Figure 2.1.

Figure 2.1: Research approach



In the research approach , as seen from Figure 2.1, first the system of interest is described (Chapter 4) to gather the necessary information & data required to model it. This is accomplished by carrying out a study of the relevant literature (Chapter 3), studying case study reports and gathering expert opinion.

The next step is capturing this system in a simulation model and describing this model (Chapter 5), which is accomplished based on steps given by Van Dam, Nikolic, and Lukszo (2013) on constructing an Agent-Based Model (ABM).

Once the ABM is created, experiments are carried out on it. The experimental setup (Chapter 6) is based on the sub-questions and is represented by varying the parametric values of the model. Also, the interviews conducted provide input for the experimental setup.

Subsequently, the results of these experiments and their analysis (Chapter 7) help provide answer to the sub-questions with the help of the ABM and data analysis & visualization.

In the following sections the five research methods are described and role in this research is discussed.

2.1 Literature study

A literature study involves the investigation of scientific literature for a certain theme. Literature study plays an important role as a foundation for all types of research (Snyder, 2019).

In this thesis research, it serves as a basis for knowledge development, fostering new ideas, provide evidence of an effect and gathering empirical data. Also, it highlights the past research conducted, which helps in narrowing down and identifying the knowledge gap.

This research method is mainly used to describe the system in Chapter 4. The empirical data obtained from literature is mainly about the characteristics of different WtE technologies, energy conversion values, potential of abating CO_2 by processing organic waste into energy, energy prices and behaviour values of Dutch households.

The relevant concepts & theories that are identified through the literature study are: waste separation behaviour , social theories (particularly VBN theory), interventions to increase waste separation, and environmental benefits of using WtE technologies to process organic waste. All these concepts and insights from literature are discussed in Chapter 3.

2.2 Case study

Case study,helps study complex phenomena under certain contexts. It facilitates the exploration of a certain phenomenon using a range of data sources (Baxter, Jack, et al., 2008).

In the case of this research, the purpose of using a case study based approach, is to examine the energy potential of the OFMSW generated in the planned city of Havenstad.

Havenstad is a large developing area with twelve sub-areas to the west and northwest of the Amsterdam center. The area is as large as the center of Amsterdam (Gemeente Amsterdam, 2017a). It would consist of households, business, shops and services. The plan is to have 40,000 to 70,000 houses along with the creation of 45000 to 58000 jobs. The houses & SMEs would be built in phases until 2060 (Gemeente Amsterdam, 2019a). The area plans to be one of the most prominent urban transformation areas in the Netherlands. Also, it aims to address the issues of energy, water and waste in a sustainable manner by renovating the built environment. It aims to have 75% reduction in CO2 emissions as compared to 2016, emission free mobility by 2029 , 65% separation of household waste and development of a circular economy (Gemeente Amsterdam, 2017a).

The municipality of Amsterdam, one of the stakeholders of Havenstad, is interested to develop a circular economy in Havenstad and to examine the contribution of the Municipal Solid Waste(MSW) towards it. Given that the area would be developed in phases, there is room for certain flexibility present on how the area is planned to meet its sustainable goals.

One of the objectives of this research is to also contribute towards the establishment of a circular economy, involving the energy processing of MSW. Therefore, based on common objectives, the city of Havenstad is used in this case study based approach.

Furthermore, the documents available from the Municipality of Amsterdam help define the define the case for Havenstad. The documents provide empirical data about the distribution of households & SMEs and organic waste generation of these entities. This data is then used to describe the system in Chapter 4.

2.3 Agent-Based Modelling

Agent-Based Models are a type of simulation models (Macal & North, 2005). Simulation models help explore and determine the how a system will work in the future (Edmonds, 2017). While an optimisation model focuses on finding the optimal solution (Lund et al., 2017).

Another difference is that optimisation models are more quantitative in nature, while simulation models can have both qualitative & quantitative aspects (Fleiter et al., 2018; Lund et al., 2017).

Agent-Based Models can help capture the complex interactions and behaviors (Macal & North, 2005), especially in case of a Waste-to-Energy (WtE) system. In other words, they can help investigate complex socio-technical systems . A WtE system comprises of individuals that carry out the waste separation activity. This activity may influence the output of the system. The decision making of individuals based on their properties (such as behaviour) and interaction with artefacts can be captured in an Agent-Based Model (Bonabeau, 2002; Jennings, Sycara, & Wooldridge, 1998). Additionally, these individuals or agents have the ability to act autonomously (Macal & North, 2005).

The advantages of using Agent-Based Models is that they help show emergent behaviour, are cost-effective, offer flexibility to analyse different scenarios and can provide a natural description of systems (Bazghandi, 2012; Bonabeau, 2002).

Emergent behaviour occurs due to interactions of individual entities. It is something that is not programmed in a model, but rather emerges from it. Emergent behaviours cannot be easily predicted or observed, but through Agent-Based Models they can be observed and explained. In this research it helps study the waste separation activity of households & SMEs for different scenarios. These scenarios are represented by the experiments in Chapter 6.

Another approach that can be used to study complex systems is System dynamics (SD). The difference between System dynamics (SD) and Agent-Based Modelling (ABM) is that ABM uses a bottom-up approach that involves spatial or social interactions between entities. By simulating these interactions it is able to determine the macro behaviour of a system (Ding, Gong, Li, & Wu, 2018).

On the other hand, SD is a top-down modelling method that analyses problems from a macro and holistic-thinking perspective (Ding et al., 2018).

But in this research, ABM is preferred over SD because it can capture the micro-phenomenon of waste separation activity of individual agents and their spatial interactions. By doing so, it can investigate the influence of this bottom-up phenomenon on the performance of WtE systems.

The nine steps provided by (Van Dam et al., 2013) for Agent-Based Modelling of Socio-technical systems are used as instructions to construct the model. These steps are addressed in the various chapters of this report. Table 2.1 describes the steps along with the reference to chapter they can be found in.

In this research *Netlogo* is used for the software implementation of the Agent-Based Model. Netlogo is a "multi-agent programming language and modelling environment for simulating natural and social phenomena" (Tisue & Wilensky, 2004, pp. 1) .It is useful because it is a freely available software that is capable of simulating highly complex human behaviour (Macal & North, 2005). Furthermore, Netlogo has a big community and contribution in the Agent-Based Modelling domain.

Table 2.1: Modelling steps

Step	Description	Addressed in
Problem formulation	Identifying the problem or research question to be investigated	Chapter 1
System Decomposition	Deciding system composition, its internal structure and the boundaries	Chapter 4
Concept Formlisation	Generalising system description to a model domain	Chapter 5
Model Formalisation	Agent narrative & model logic	Chapter 5
Software Implementation	Implementing the model concept in a programming language	Chapter 5 & Appendix F
Model verification	Verifying the translation of conceptual model to computational model	Chapter 5 & Appendix F
Experimentation	Design of experiments or scenarios	Chapter 6
Data analysis	Exploring, Interpreting and Visualising the data obtained from model	Chapter 7
Model validation	Validating model results with of literature & expert opinion	Chapter 8

2.4 Interview and personal communication

Interview and personal communication with experts or stakeholders of Havenstad is used to collect empirical data needed to describe the system in Chapter 4 and to validate the results of the model in Chapter 8.

A semi-structured interview is conducted with a Urban Planner in the Municipality of Amsterdam, who is also a stakeholder for the case of Havenstad. The transcript of the interview is provided in Appendix C. The interview provided some necessary data and information needed for the system description. But most importantly it aids in the experimental design, by discussing the stakeholder's perspective on this thesis research.

Apart from an interview, emails were exchanged with the experts in the field of waste management, mostly from the Municipaity of Amsterdam. In this case communication over email is preferred over an interview because the questions posed were specific and did not require discussion. Also, it is more time efficient and practical than conducting a face to face interview. The transcripts of the email conversations are given in Appendix C. From these emails, empirical data needed to describe a system is obtained and the necessary information needed for the model validation.

2.5 Data analysis visualization

The number of experiments, described in Chapter 6, are carried out in the Agent-Based Model created on Netlogo. The output generated by the model are in the form of big numerical-based datasets and by glancing through these datasets, a reader cannot gather insights or necessary information (Kelleher & Wagener, 2011).

To gain insights from these large sets of datavalues it is more practical to explore, analyse and visualize these datavalues by synthesizing them into effective graphics (Kelleher & Wagener, 2011). Furthermore, visualization of datasets could make it more effective to analyze and communicate the information, which is necessary to answer the research questions.

The datasets are visualised with help of certain libraries in *Python*- which is freely available & popular data visualisation software. This software is preferred over Microsoft Excel because it can sort and visualise data in a more time efficient & neat manner.

2.6 Link with the Master's programme

This thesis research is conducted as part of the Complex Systems Engineering and Management (CoSEM) Master's programme. The programme focuses on exploration of 'innovations in a complex socio-technical environments' [1]. As the name suggests, the programme is about the field of systems engineering and analysis, which is taught with the help of courses and tools within the programme. One of them being Agent-Based Modelling (ABM), which is used as a research method in this thesis.

The thesis is of relevance to the CoSEM Master's programme and has a link to it due to the following reasons: Firstly, the research conducted as part of this thesis examines a complex socio-technical system of *Waste Management and Energy System*, which consists of concepts like waste management ,human behaviour and energy systems. Furthermore, it examines the link between these two concepts, something that would have expected out of a CoSEM student.

Secondly, it uses the field of systems engineering to examine and analyse the Waste-to-Energy system. It examines the Waste-to-Energy system as a *system-of-systems (SoS)*. In the SoS examined in this thesis, there are two systems : Waste Management System (WMS) and the WtE technologies, which are analysed together. The aim of this research is to examine the collective influence of these two systems on the WtE system.

Thirdly, to examine a socio-technical system such as WtE system an Agent-Based Modelling approach is employed, which is also part of the CoSEM Master's programme. This approach helps examine the influence of 'socio' part (i.e. waste separation behaviour) on the technical WtE system. Thereby, studying the WtE system from a socio-technical perspective.

[1] https://www.tudelft.nl/onderwijs/opleidingen/masters/cosem/msc-complex-systems-engineering-and-management/

3. Literature review

In this chapter a literature review is presented on the topics introduced in Chapter 1. At beginning of the chapter the search plan of the literature review is discussed. This is followed by a paragraph that address the structure of this literature review.

The literature search is carried out on scientific databases such as *Google scholar*, *Science direct* , *TU Delft library* and *TU Delft repository*. Also, the technique of backward snowballing is employed to identify new research papers based on the literature that is examined.

Table 3.1: Keywords for literature search

Keywords
"anaerobic digestion" , "Organic Fraction of Municipal Solid Waste" ,"Waste-to-energy technologies ", "Waste incineration", "waste separation behaviour", "social theories", "Value-Belief Norm", "awareness campaigns", "informational campaigns", "waste management system", "the Netherlands", "biomethane"

The keywords used are presented in Table 3.1.Also, the search for the literature can be composed of a combination of these keywords.

The choice of the keywords is motivated by the aspects discussed in Chapter 1. They are : *Waste-to-energy technologies*, *Waste separation* and *Internal and external factors*.Although the three aspects address the general waste fraction, but while searching for literature emphasis is given on the OFMSW.

Section 3.1 examines the literature about the internal factors, which can be considered equivalent to the waste separation behaviour shown by individuals. The external factors are examined in Section 3.2 and presented in the form of interventions. This is because elements of these factors can be tweaked around to increase the source separation of organic waste. In the last section literature about the technologies employed to extract energy from OFMSW is discussed.

3.1 Waste separation behavior

Intention and ability are two important aspects that determine behavior. Intentions are influenced by attitudes, social norms and personal beliefs. Together they build motivation for the behavior (I. Ajzen & Fishbein, 1980; Ølander & Thøgersen, 1994; Rousta & Bolton, 2019). A target behavior cannot be solely be achieved based on motivation, the entity should have the ability to perform the behavior (Rousta & Bolton, 2019). Ability is based on the personal knowledge, physical ability and availability of convenient sorting facilities, the latter of which are discussed in Section 3.2.

Similarly, internal factors influencing waste separation are intrinsic to each individual and affect an individual's participation in the waste separation scheme.These factors include the individual's values, knowledge about organic waste, attitude and personal beliefs & norms towards recycling or waste separation(Meng et al., 2019; Minelgaitė & Liobikienė, 2019; Rousta & Bolton, 2019).

Values are defined as "underlying orientations held by individuals towards the physical environment" (Barr, 2007) and are responsible for determining pro-environmental behavior such as waste separation(Barr, 2007; P. C. Stern, Dietz, Abel, Guagnano, & Kalof, 1999)

Environmental attitudes are about willingness to participate in waste separation and recycling and awareness about the environmental importance of recycling(Koerkamp, 2019; Meng et al., 2019).

Personal norm is defined as the degree to which an individual feels morally obliged to engage in a certain behavior and is highly representative of recycling behavior (Barr, 2007). Personal norms are said to be linked to beliefs about the consequences of their behavior(P. C. Stern et al., 1999), or their waste separation behavior (Van der Werff, Vrieling, Van Zuijlen, & Worrell, 2019). According to Barr (2007, p. 435) recycling behavior can be described as "highly normative" (Barr, 2007, pp. 435).

Most of these internal factors (except knowledge) shape the intention of an individual, which is an important aspect to determine waste separation behaviour. In order to describe and analyse the role of these factors on the waste separation behaviour, a social theory has to utilized.

Social theories can be described as analytical frameworks or paradigms that are employed to study and interpret individual behaviours or a social phenomena (Seidman et al, 2013; Yuriev, Dahmen, Paillé, Boiral, & Guillaumie, 2020).

Social theories such as Theory of Planned Behaviour (TPB), VBN and Norm activation theory can be used to describe pro-environmental or waste separation behavior (Barr, 2007; Ofstad, Tobolova, Nayum, & Klöckner, 2017; Scalco et al., 2017; Yuriev et al., 2020). TPB is one of the most commonly used and highly supported theory to explain recycling behavior (Strydom, 2018).

The central theme in the TPB is the individual's *intention* to perform a certain behaviour (Icek Ajzen, 1991). *Intention* is defined as "indications of how hard people are willing to try, to perform the behaviour" (Icek Ajzen, 1991, p. 181). The intention depends on three determinants or predictors: attitude, subjective norm and perceived behavioural control (PBC) (Icek Ajzen, 1991; Yuriev et al., 2020). The theory states that these predictors are influenced by indirect determinants: behavioural, normative and control beliefs. Behaviroual beliefs are concerned with the " perceived advantages and disadvantages of performing a certain behaviour " (Yuriev et al., 2020, p.1). Normative beliefs are concerned with the probability that individuals or groups approve or disapprove of carrying out a certain behaviour (Icek Ajzen, 1991).

TPB has its limitations that well documented as well.Boldero (1995) concluded that TPB is inadequate to account for attitudes and intentions that are responsible to predict recycling behavior. TPB tends to measure the intention to act environmentally rather than the behaviour (Yuriev et al., 2020), due to which TPB could find it difficult to predict pro-environmental behavior. Also, the factors influencing pro-environmental behaviour, such as knowledge, habits, required effort, self-identity & moral obligation, are not an integral part of the TPB (Meng et al., 2019; Yuriev et al., 2020).

Furthermore, TPB finds it difficult to predict behaviour that is not out of personal choice or preference or that requires resources and skills(Strydom, 2018). Specially in the case of waste separation behavior which majorly relies on knowledge and awareness (Meng et al., 2019).

Alternatively, VBN theory established by P. C. Stern et al. (1999) aims to explain and relate the influence of human values on the pro-environmental behavior. It provides a framework to examine the normative factors promoting sustainable attitudes and behaviour (Lind, Nordfjærn, Jørgensen, & Rundmo, 2015). According to P. C. Stern et al. (1999), the theory revolves around the individual's basic values and the fact that individuals believe that their actions would protect these values, which eventually translates to an obligation (or personal norm) to carry out certain actions.

Additionally, the support for the action is dependent on the individual's skills and limitations. The VBN theory presents a more exegetical explanation of the human- environment interaction and how these interactions can affect each other,by considering an ample number of variables responsible for cause and action (A. Akintunde, 2017).

Furthermore, individualistic or behaviour values are shown to be more predictive of environmentally relevant beliefs, preferences and recycling behaviour (Steg, De Groot, Dreijerink, Abrahamse, & Siero, 2011).

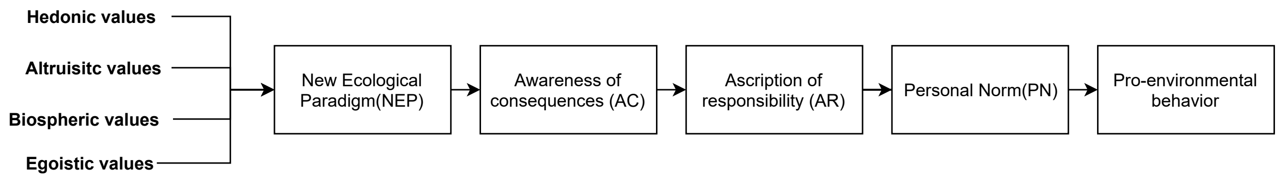
To conclude, it is shown from literature that values, beliefs and norms are predictive of waste separation behaviour. Therefore, in order to study the influence of these determinants the use of VBN theory is more appropriate than TPB. In the following paragraphs, determinant variables of the VBN theory are described and the relationship between these variables and the pro-environmental or waste separation behaviour is discussed.

3.1.1 Value-Belief Norm theory

The VBN theory links Value theory (Shalom H. Schwartz, 1992), New Envrionmental paradigm (R. Dunlap & Liere, 2008) and Schwartz's Norm activation theory(Shalom H. Schwartz, 1977). In doing so, it presents relationships between values, beliefs, norms and behaviors (Ghazali, Nguyen, Mutum, & Yap, 2019).

In Figure 3.1 the chain of predictor variables of the VBN theory are shown. All these variables are notably related to the next variable in the chain (Steg et al., 2005). The four values in the model are related to the pro-environmental behaviour through a set of variables. Although values can help determine the behavior, this relationship is enhanced in the presence of other predictor variables such as beliefs or personal norms(Ghazali et al., 2019).

Figure 3.1: Value-belief Norm (VBN) model (P. C. Stern, Dietz, Abel, Guagnano, & Kalof, 1999)



Shalom H. Schwartz (1992) defined values as "desirable transsituational goals varying in importance, which serve as a guiding principle in the life of a person or other social entity". There are usually four values (sometimes three) in the VBN model: *Altruistic, Biospheric, Egoistic and Hedonic.*

Altruistic values are concerned with welfare of other people or living species. *Biospheric values* focus on welfare of the ecosystem or biosphere. According to Steg et al. (2005), many studies have found that individuals with strong biospheric & altruistic values tend to engage in pro-environmental behaviour.

Egoistic values represent self-interests such as wealth and authority with regards to a society. *Hedonic values* are concerned with pleasure or enjoyment of oneself. According to some studies, egoistic values and hedonic values have a negative influence on environmental attitudes & behaviours (De Groot & Steg, 2009; Hiratsuka, Perlaviciute, & Steg, 2018; Steg, Perlaviciute, van der Werff, & Lurvink, 2014; Paul C Stern, 2000).

But human behavior cannot solely be represented by single values but rather a plurality of values(Cohen & Ben-Ari, 1993). According to (Pan et al., 2015, p. 416) entities in a community are made up of a "'spectrum of different viewpoints" and should be " treated as such instead of a collective whole". Steg et al. (2014, p. 163) suggested that the inclusion of the four values is " not only theoretically meaningful but also recognized by individuals ".

As seen in Figure 3.1, the four values of the VBN model are shown to serve as input for the New Ecological Paradigm (NEP). The NEP[1] offers a scale to measure environmental attitudes (R. E. Dunlap & Jones, 2002; P. C. Stern et al., 1999). The scale is universal in the manner it focuses on multiple environmental issues. It measures the board beliefs about the environment and the influence of human activities on it (P. C. Stern et al., 1999).Furthermore, the NEP scale help measure "awareness of very general consequences of environmental conditions" (P. C. Stern et al., 1999).

Next in the VBN model (Figure 3.1) are the beliefs. Beliefs are about one's thoughts about natural environment and human behavior. In the VBN model it is composed of two components; Awareness of Consequences (AC) and Ascription of Responsibility (AR). The former is refers to the belief that the environmental or societal circumstances will either improve or threaten the biosphere (Ghazali et al., 2019). The latter, which succeeds is the ascription of responsibility, a belief that an individual's actions can either prevent or promote potentially undesirable consequences. It also relates to one's own sense of responsibility to minimize negative environmental consequences (Ghazali et al., 2019).

The beliefs and values of the agents with regards to preserving the environment lead to the establishment of personal norms for such individuals(Ghazali et al., 2019). Also, individuals receive feedback from their peers as social norms, which in-turn can influence their personal norms.

Out of all the variables of the VBN model ,the Personal Norm (PN) established by individuals are shown to directly activate their pro-environmental behaviour (Davis, 2014; Mtutu & Thondhlana, 2016; P. C. Stern et al., 1999).

Overall, VBN model presents casual chain of five variables: values, NEP, Awareness of Consequences, Ascription of responsibility and Personal norm. On the basis of this relationship, the last variable of the model: 'Pro-environmental behaviour' , can be determined. Moreover, the theory and its variables provides a basis to predict waste separation behaviour with the help of the internal factors (such as behaviour values) that tend determine waste separation.

[1]Also known as 'New Environmental Paradigm'

3.2 Structural and informational interventions

Aside from internal factors, external factors also influence waste separation (Rousta & Dahlen, 2015). The external factors are introduced in Chapter 1 as *interventions* needed to promote behaviour change or this case, improve waste separation. This analogy is based on a article by Abrahamse and Matthies (2012).

In the article, Abrahamse and Matthies (2012) describe two types of interventions(or strategies): *Informational interventions* & *Structural interventions*.

Informational interventions are focused on altering knowledge, norms, awareness & attitudes and subsequently promoting sustainable behaviour (Van der Werff et al., 2019). For example, setting up of campaigns to increase awareness about recycling or reducing waste.

Informational interventions have shown to influence waste separation. Meng, Wen, and Qian (2018) studied the decision making mechanism of household's waste disposal behaviours using structural equation modelling(SEM) method. According to the study, provision of information and educating households about recycling is one of significant factors contributing towards recycling or waste separation.

Furthermore, some other studies conducted found that provision of information to individuals (or households) on how to recycle can promote recycling behaviour and increase recycling rates (Bowman, Goodwin, Jones, & Weaver, 1998; Hopper & Nielsen, 1991; Varotto & Spagnolli, 2017).

On the other had, *structural interventions* are focused on altering the conditions wherein behavioural decisions are made. For example, altering the state of bins that are meant to collect source separated organic waste.

Similar to informational interventions, structural interventions have shown to influence waste separation. Like the availability of waste collection infrastructure is shown to be crucial for the success of waste recycling (Barr, 2007; Bernstad, 2014; Gellynck, Jacobsen, & Verhelst, 2011; Meng et al., 2019). Proximity of waste collection bins, convenience and hygiene are shown to affect the interaction with these bins and subsequently influence the waste separation (Bernstad, 2014; Gilli, Nicolli, & Farinelli, 2018; Meng et al., 2019).

Moreover, Meng et al. (2019) concluded that the effect of external factors (or interventions) on household's waste separation is twice that of internal factors. Although Srun and Kurisu (2019) did not share the same conclusion for waste disposal behaviour. According to the study conducted by Srun and Kurisu (2019), internal factors such as personal & social norms had a more significant influence on waste disposal behaviour as compared to external factors.

In conclusion, this section discusses the importance of interventions or factors on determining waste separation. But between the two interventions, it is still not clear which one has a higher influence of the waste separation. Also, the effect of these interventions on the energy obtained from waste is not addressed in the literature. Lastly, more about these interventions is discussed in Chapter 4.

3.3 Energy generation from organic waste

The aim of this section is to discuss the commonly used WtE technologies or technological process to generate energy from organic waste. Also, to examine the link between the energy obtained from organic waste and the waste separation.In the following sub-sections these technologies are further elaborated.

3.3.1 Incineration

Incineration is the process of combustion of waste to release heat energy that can be utilized to generate steam for electricity production, district heating or other industrial purposes (Mutz, Hengevoss, Hugi, & Gross, 2017).

In developed nations, including some European countries, waste incineration is commonly used to recover energy from different waste fraction (Mubeen & Buekens, 2019). This waste fraction also includes organic waste.

The incineration process involves the burning of the waste fraction, followed by an oxidation reaction when the waste fraction reaches necessary ignition temperatures. The temperature could be between 850 and 1450 °C (Mutz et al., 2017).

But to enable this thermal reaction, a minimum calorific value of the waste is required (Mutz et al., 2017). The minimum calorific value or lower calorific value (LCV) should be 7 MJ/kg on average over an year (Rand, Haukohl, & Marxen, 2000).

As compared to other waste fractions organic waste has lower calorific value and high moisture content. Therefore, in order to incinerate the organic waste there is sometimes a need for additional energy sources such as natural gas (Di Maria & Micale, 2015; Mubeen & Buekens, 2019; Mutz et al., 2017).

Although incineration of waste helps avoid the methane gas emissions, it can contribute towards the generation of climate-relevant emissions such as CO_2 (carbon dioxide) and NO_x (oxides of nitrogen) (Johnke, 1996; Rand et al., 2000). But incase of organic waste, these emissions could be lesser.

The generation of emissions from the incineration process depends on the composition of the MSW and origin of carbon in the waste. The waste fraction generally consists of two types of carbon: *Biogenic* and *Fossil carbon* (Astrup, Møller, & Fruergaard, 2009; Johnke, 1996).

Biogenic carbon carbon has a global warming potential (GWP) of 0, while fossil based caron has a GWP of 1 (Astrup et al., 2009). This implies that climate relevant CO_2 emissions are determined by the content of fossil based carbon (Johnke, 1996).

Furthermore, the OFMSW, among other waste fractions, has shown to have one of the lowest content of fossil carbon per tonne (Astrup et al., 2009). Thus, the incineration of OFMSW could result in less CO_2 emissions as compared to the incineration of other fractions such as plastics or textiles.

3.3.2 Anaerobic Digestion

There are other existing waste-to-energy (WtE) technologies that can convert OFMSW to conventional form of energy such as gas and/or electricity. The OFMSW can be converted into biogas by carrying out the process of anaerobic digestion.

Anaerobic digestion is a microbial process carried in the absence of oxygen on the organic waste- which is converted into biogas and digestate with help of bacteria & archea (Saadabadi et al., 2019; Valijanian, Tabatabaei, & Aghbashlo, 2018).

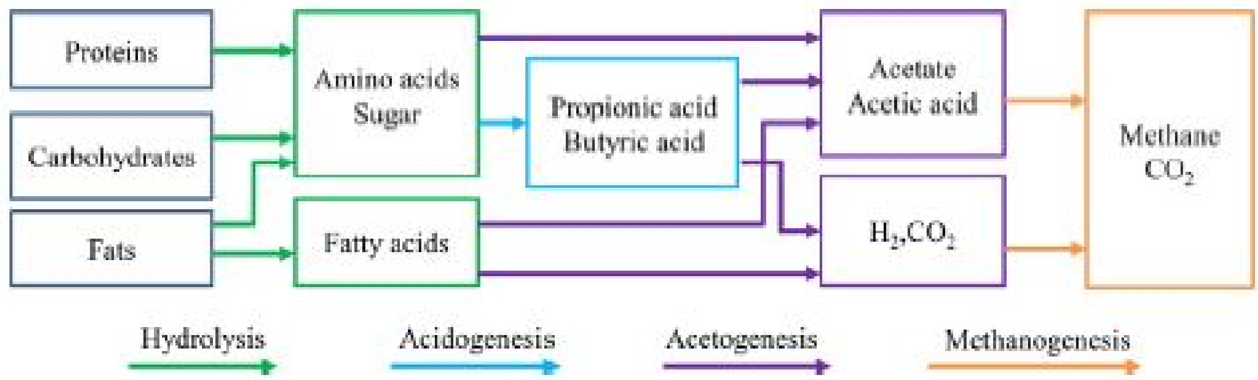
In this *sub-section* firstly, the process of anaerobic digestion is described, followed by the use of biogas as an energy source. Secondly, the environmental benefits of producing and using biogas as an energy source are discussed.

Anaerobic digestion is step-wise process consisting of Pre-treatment of waste, Hydrolysis, Acidogenesis, Acetogensis and Methanogenesis. Pre-treatment is conducted before feeding the organic waste into the anaerobic digester and improves the process of anaerobic digestion by reduction of particle size and removal of contaminants like plastics or metals (Ariunbaatar, Panico, Esposito, Pirozzi, & Lens, 2014).

The pre-treatment of waste can result in loss of organic material and is deemed expensive as well (Milios, 2013; WRAP, 2008). Also it could lower the production of biogas and increase operating costs.Although it can be avoided by the source separation of organic waste (Goossensen, 2017; Mubeen & Buekens, 2019; Wilken et al., 2019).

The rest of the process is presented in Figure 3.2. The process begins with hydrolysis, in which the organic matter primarily consisting of carbohydrates, fats & proteins is turned basically into smaller sugars that acted upon by bacteria in later stages (Ostrem, Millrath, & Themelis, 2004). In the second step bacteria transform products from hydrolysis into short chain volatile acids, alcohols, hydrogen and carbon dioxide. In the third step volatile acids and alcohols are transformed into hydrogen, carbon dioxide and acetic acids which would be the used in the last step of methanogenesis(Goossensen, 2017). The last step occurs under anaerobic conditions to convert hydrogen and acetic acids into biogas, which consists of methane gas and carbon dioxide (Curry & Pillay, 2012). These chain of processes are same in most of the anaerobic digesters.

Figure 3.2: Process of anaerobic digestion(Kaspar & Wuhrmann, 1978; Saadabadi et al., 2019)



Biogas obtained from anaerobic digestion typically consists of methane (50% to 80% by volume), carbon dioxide(20% to 50% by volume) and trace levels of nitrogen, hydrogen sulfide and waste (Tricase & Lombardi, 2012). The biogas can used to produce electricity or biomethane.

Bio-gas produced from anaerobic digestion has the potential to provide electricity at a uniform rate and has the potential to meet the flexibility needs in the electricity market by reduction of overall residual load function(Mubeen & Buekens, 2019; T. Persson et al., 2014; Purkus et al., 2018; Thrän, Dotzauer, Lenz, Liebetrau, & Ortwein, 2015). Energy conversion technologies can be used to convert biogas to electricity .Such as gas turbines, Otto cycle internal combustion engines, fuel cells and Combined Heat & Power (CHP) plants (Cohen & Ben-Ari, 1993; Saadabadi et al., 2019). The electricity generated from organic waste, similar to biogas generation, depends on its constituents. Also, it depends on the type and efficiency of energy conversion technologies (Achinas, Achinas, & Euverink, 2017; Saadabadi et al., 2019; Wilken et al., 2019).

Generation of electricity from solid biomass, biomethane and biogas is present in various European countries, with Germany having an high share of biogas generated. . Biogas and biomethane based plants accounted for 73.9% of the total bioelectricity generated in Germany

(Purkus et al., 2018). Also, the Netherlands is one of the top five producers of biogas in Europe (Achinas et al., 2017).

Another possible use of biogas could be its upgradation to biomethane with help of certain technologies. The technologies focus on the enrichment of methane content, which is done by 'scrubbing' off CO_2 (de Mes, Stams, Reith, & Zeeman, 2003; Ryckebosch, Drouillon, & Vervaeren, 2011).

The biomethane generated can be injected into the gas grid, used in gas pressure cylinders ,as a transportation fuel or to produce electricity (GasTerra, 2009; German Biogas Association, 2016).

Using biogas generated from OFMSW has environmental benefits.The combustion of biogas or biomethane produced by anaerobic digestion results in zero net production of CO_2 (European Compost Network, 2016; Jingura & Matengaifa, 2009).

Furthermore, energy generated from biogas (or its derived forms) can replace the energy generated by fossil-based conventional energy sources. Thus, more biogas production implies more CO_2 emissions can be prevented from conventional energy sources.

According to Ten Brummeler (2000) replacing the energy generated from fossil-based energy sources with that of biogas results in the reduction 1 kg CO_2 per ton of waste processed. In the case study based research carried out by Merchán (2009), the direct mitigation potential from using biogas generated from 14 Mt of OFMSW per year in Mexico ranges from 1.4 to 1.9 Mt CO_2-eq/year and the indirect potential being 11.7 Mt CO_2-eq/year. Furthermore, Greenhouse Gases (GHG) originating from waste can be reduced to 0.09 ton CO_2 eq/ton waste, if biogas generated from the waste is used for electricity generation instead of landfilling the waste(Mubeen & Buekens, 2019).

Compared to incineration , anaerobic digestion of OFMSW is preferred because incineration is not recommended for most part of OFMSW, whose low calorific value and high moisture content makes them an undesirable feedstock(Merchán, 2009).

But the costs associated with the energy generated and the CO_2 abated are not thoroughly compared for two technologies. Specially for the OFMSW. Although it may seem, based on the literature discussed, that anaerobic digestion of OFMSW is more environmentally friendly, but it might not be the case. For example, Di Maria and Micale (2015) concluded based on a Life-Cycle Assessment of an Italian district that incineration of organic waste leads to maximum environmental benefits compared to anaerobic digestion & composting.

4. System Description

In the chapter the system-of-interest is identified and described in Section 4.1. In the following sections (Section 4.2 onwards) the different phases and the elements of the system are described .Lastly, the chapter ends with a summary (Section 4.10) of all empirical data collected for the Waste-to-Energy technological routes.

As mentioned in the previous chapter, the System of Interest (SOI) has to described in order construct the model that is required to required to answer the research questions.

A system is defined as a combination of internal interacting elements organized to achieve certain stated purposes (Faulconbridge & Ryan, 2014). To identify the system that is of interest or the *System of Interest* , an external boundary is specified. The elements and their interconnections enclosed inside this boundary together constitute the *system of interest.*Together these elements within the external boundary interact to achieve the system's *mission*(Faulconbridge & Ryan, 2014).

4.1 System of Interest

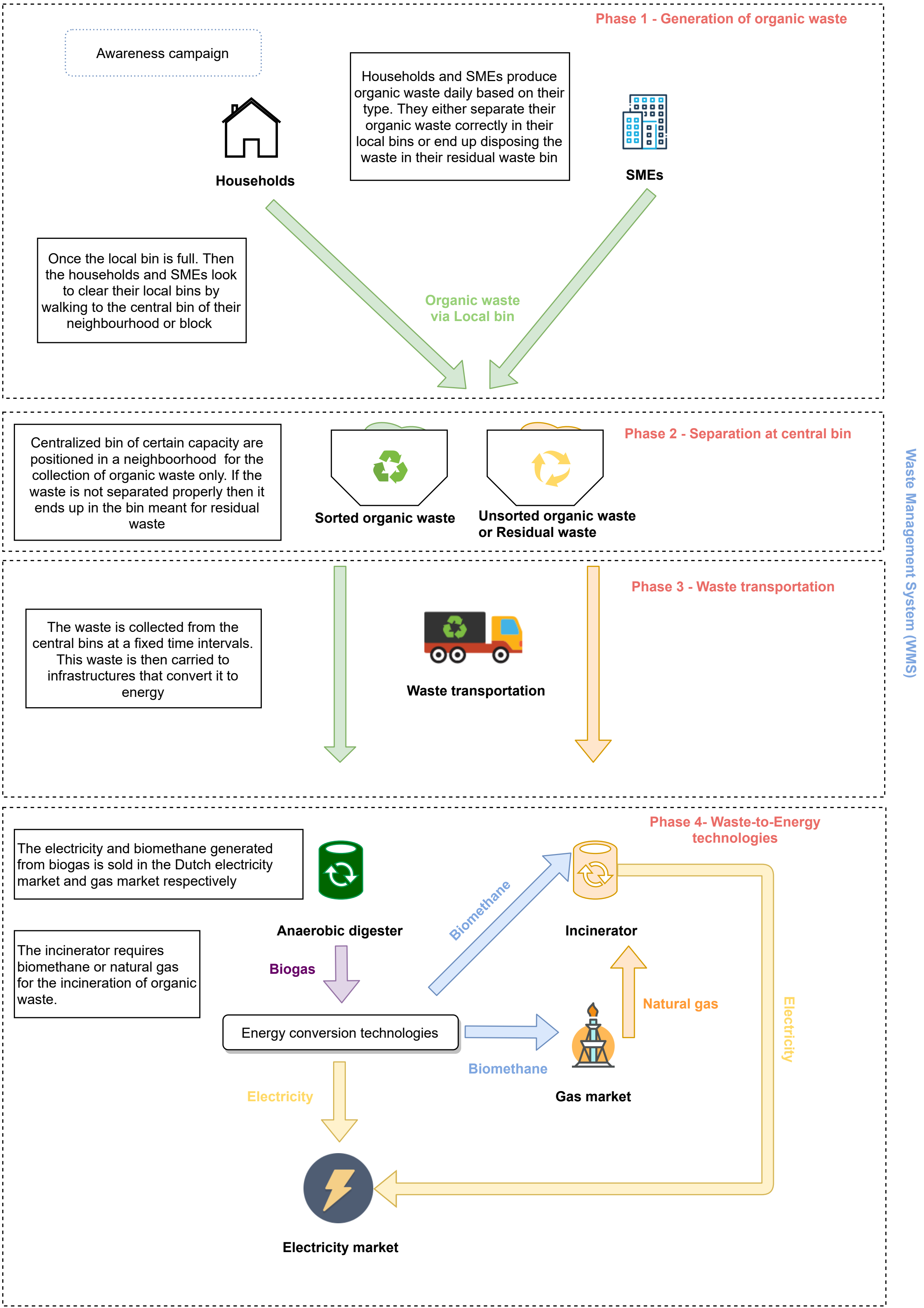
The SOI is presented with the help of Figure 4.1. The SOI consists of elements, relationships between them and the flow of energy/mass. All this enclosed within an external boundary, which is not specified in the figure.

The elements in the SOI are divided into four phases, according to the common characteristics that these elements share. The four phases are : *Phase 1- Production of organic waste* , *Phase 2- Separation at central bin* , *Phase 3- Waste transportation* , *Phase 4- Waste-to-Energy technologies* .

Before describing the phases, elements and the choice of its elements, the Figure 4.1 is explained along with its phases. Phase 1 is about the generation of organic waste by households & SMEs and the local separation/disposal of the generated waste. Local separation (or disposal) implies that households & SMEs will undergo a decision making process to separate their organic waste correctly in the their local-bin[1] or to dispose the organic waste in their local-residual-bin[2] respectively.

[1]Local bin is meant *only* for organic waste. Every household and SME can own one of a fixed capacity.
[2]Local residual bin is meant for all kinds of unsorted waste. Every household and SME can have one.

Figure 4.1: System of Interest



Once the local bin of a household or SME is full, then the agent (i.e. household or SME) proceeds to Phase 2- Separation at central bin. In Phase 2, the agents choose to separate their organic waste correctly at the centralized bin allocated for their block or neighbourhood. If the agent chooses not to separate its organic waste correctly, then it ends up in the residual waste bin.

Therefore, upto phase 2 the agents have to make certain decisions that is based on the their behaviour and external factors surrounding the central and local bins.

In Phase 3, the waste from the central bins (Organic & residual bins) is collected at fixed time intervals. Subsequently, this affects the characteristics of the organic central bin such as bin fullness.

The organic waste (sorted & unsorted) is further transported to infrastructures responsible for producing energy out of this waste. These infrastructures are addressed as WtE technological infrastructures in Phase 4.

There are two types of WtE technological infrastructures in in Phase 4: Anaerobic digester & Incinerator. The former is responsible for handling the sorted organic waste collected in the central bin. The latter handles the unsorted organic waste that ends up in the residual waste bin.

The anaerobic digester converts the sorted OFMSW into biogas, which when passed through Energy conversion technologies gives out electricity & biomethane. The electricity generated can be sold in the Dutch electricity market, while the biomethane is sold in the Dutch Gas market.

The incinerator converts unsorted OFMSW along with other waste streams into electricity. But in this thesis electricity from other is not included within the research scope. The electricity generated is subsequently sold to the Dutch electricity market.

Also, as seen from Figure 4.1, the incinerater requires natural gas or biomethane. This due to the fact that incineration of OFMSW requires certain amount of natural gas or biomethane.

This concludes the description of the SOI. In the following subsections the characteristics of the elements of SOI are discussed with the help of literature and interviews. Also, choice of data in these sub-sections is structured as per the case study of Havenstad or sometimes based on Amsterdam because Havenstad is a part of the Amsterdam region and secondly, data about the system elements is available and accessible for Amsterdam as compared to Havenstad.

In Figure 4.1 the system of interest that would be analysed is presented.The system is design and organized for the city of Havenstad. It depicts the system components and the flow of material and energy between these components. Starting from the top of the figure, the waste generating agent set of households and SMEs are shown to separate(or not) their organic fraction in the respective central bins

The central bin is responsible for the collection of its respective block's OFMSW along with other types of waste. Central waste collection bins in the Netherlands are mostly localized as per neighborhoods("Household waste in Amsterdam," 2019). The central bin is part of the waste management system which includes the collection and transportation of OFMSW to the anaerobic digester and the incinerator.The source sorted OFMSW is transported to the anaerobic digester where is it is converted to biogas, while the unsorted OFMSW is taken to the incinerator with the residual waste where it is converted into heat and electricity.Biogas as an energy source can be converted into electricity by supplying biogas to a power plant, via pipes

(Krich et al., 2005).This electricity generated and that from the incinerator is traded in the Dutch electricity market. Also, biogas can be upgraded to biomethane or natural gas, which can be supplied to the incinerator, used a source of power generation or sold in the Dutch the gas market.

The purpose of analysing this system and its elements is to assess the role of OFMSW in providing a sustainable form of energy for the city of Havenstad. Certain *Key-Performance Indicators(KPIs)* are employed to evaluate the system. The KPIs and their numerical representation depends on the functioning of the system components individually & collectively. The KPIs are elaborated in Chapter 6.

4.2 Organic waste generation

As shown in Figure 4.1, the organic waste in the SOI is generated by households & SMEs. In this section we discuss about data and information available about the organic waste or Organic Fraction of Muncipal Solid Waste (OFMSW) by these agents.

4.2.1 Households

The municipal solid waste(MSW) generated by Amsterdam households mainly consists of organic , paper , bulky , glass and plastic waste . Out of which organic waste makes up a quarter of the total waste generated (Gemeente Amsterdam, 2015).

On an average each inhabitant in an Amsterdam household generates about *92 kgs of OFMSW per year* (Gemeente Amsterdam, 2015). The OFMSW of these households is composed of fruits & vegetables, garden cuttings, bread, food leftovers and bread (CREM, 2013; Gemeente Amsterdam, 2015).According to the report by CREM (2013) the organic waste flow of Amsterdam households consists of 61% of fruits & vegetables, 26% garden waste, 9.5% food waste, 3% bread and 0.5% organic residues.Small-Medium Enterprises(SMEs) also have a similar composition of organic waste but their waste generation is generally higher(Gemeente Amsterdam, 2017b).

The OFMSW generated by households is based on their inhabitants or more specifically the type of household. The type of household and their distribution can help generalize the total number of inhabitants present.

The households types planned in Havenstad can be classified according to the following types:*Single bedroom apartment, Two-bedroom apartment, Three-bedroom apartment and Four-bedroom apartment* (Gemeente Amsterdam, 2019a).The number of inhabitants in each household type is determined by the space an inhabitant takes up on average.

In case of Havenstad the minimal living space or *gbo*[3] for a studio in Havenstad is 25 m^2 (Gemeente Amsterdam, 2019a). In other words, a single person in Havenstad would require a minimum living space of 25 m^2

Using this value as minimum space required for a single person, the number of inhabitants in each household type can be determined based on the living space allocated for the households types. Therefore, the total amount of organic waste generated by each household type (per

The term 'agent' in this chapter refers to households & SMEs

[3] gbo in Dutch is known as *gebruiksoppervlak*. It means the area that can used effectively. It is used as a measure to compare household sizes and prices

year) is given by Table 4.1. Also, the planned distribution of the household types in Havenstad, based on the report by Gemeente Amsterdam (2019a), is presented in the table below.

Table 4.1: Organic waste generated by households in Havenstad

Type	Distribution	No. of inhabitants	gbo	Waste generated (per year)
Studio	5 %	1	25 m^2	92 kg
Two-room, 1Bedroom	35 %	1- 2	41 m^2	92 to 184 kg
Three-room, 2Bedrooms	38 %	2- 3	60 m^2	184 to 276 kg
Four-room, 3Bedrooms	22 %	3- 4	90 m^2	276 to 368 kg

The waste generation numbers have arrived by considering the per captia organic waste generation of Amsterdam and multiplying this with the number of inhabitants for each household type in Table 4.1.

4.2.2 Small-Medium Enterprises

Based on the report by Gemeente Amsterdam (2017b), the Small-Medium Enterprises (SMEs)found in Amsterdam are given in Appendix A.2 along with their annual organic waste generation.

According to the report, there are seven types of SMEs found in Amsterdam: *Offices, Shops, Businessess, Horeca, Others, School, Sport Complex* .

According to the planning for Havenstad (Gemeente Amsterdam, 2019a), small offices, supermarkets, businesses (service), healthcare services and schools are planned to be constructed in the Sloterdijk Zuid region(a part of Havenstad). The ratio of offices to businesses offering services is 4:1(Gemeente Amsterdam, 2019b, pp.12). Information regarding the exact distribution of these SME types for Havenstad is not available. Also, the data about organic waste generated by these SME types is not available.

Thus, using the data for the organic waste generated by the SMEs in Amsterdam (See Appendix A.2) , the organic waste generated by the SMEs in Havenstad can be estimated. This is presented in the Table 4.2.

Table 4.2: Organic waste generated by SMEs in Amsterdam

Type	% of SMEs using central bin for households	Organic waste generated (per year)
Offices	44 %	730 kg
Shops	46 %	310 kg
Businesses	22 %	410 kg
Horeca	19 %	860 kg
Others	8 %	25 kg
School	2 %	1520 kg
Sport complex	1 %	6050 kg

The second columnn in Table 4.2 represents the % of SMEs of a particular type using the centralized bin for household waste collection (Gemeente Amsterdam, 2017b). SMEs that

Horeca is a Dutch abbreviation of the words '**ho**tels', '**re**staurants', '**ca**fes'. According to Google translate it means *catering industry* produce around the same quantity of waste as households are allowed to use this centralized bin. While those SMEs that produce large quantity of waste have to sign a waste collection contract with the municipality of Amsterdam or waste collection service (City of Amsterdam, n.d.-a; Gemeente Amsterdam, 2017b).

The data tells us that approximately 50% of Offices and Shops use the central bin meant for households. Considering a ratio of Offices to Business offering services(such as shops) in Havensatd (i.e. 4:1) , the total organic waste generated by an SME averages out to 646 kg per year.

In the previous two subsection the types of households and SMEs are discussed. But it is also important highlight the total number of households and SMEs that are going to be setup in Haventstad.

The city of Havenstad is setup phasewise. In each phase a fixed amount of households & SMEs are being set. This data is given in the planning report for Havenstad (Gemeente Amsterdam, 2019a). Also, based on the interview conducted of a stakeholder (See:Appendix C), the total number of households and SMEs planned are compared to the report and presented in Table 4.3.

Table 4.3: Phasewise planning of Havenstad

	Number of households	**Number of SMEs**
Phase 1	21,100	1000
Phase 2	40,000	3670
Phase 3	57,900	4840
Phase 4	73,300	5870

The value for the number of SMEs is arrived based on the fact that Offices and Businesses in Amsterdam employ about 5 employees on an average (Gemeente Amsterdam, 2017b).

4.3 Waste separation behaviour

The waste separation activity is carried out by each individual waste producing agent. As mentioned in Chapter 1, the waste separation depends on certain internal and externals factors. These factors together influence the decision making process of the agent to separate its waste.

The internal factors have a lot to do with the waste separation behaviour of the agent. which can be determined by the personal norms of these agents. Based on the VBN theory, the formation of personal norms is based on Schwartz behaviour values that an agent holds: Biospheric, Alturistic, Hedonic & Egoistic (Shalom H. Schwartz, 1992).

An agent can have a mixture of these four values and it could be some values are more prominient than the other. For example: An agent who is pro-envrionmental would have higher weightage of biospheric values than egoistic values.

In a survey conducted by Namazkhan, Albers, and Steg (2019) the Schwartz values of the persons living in Dutch households was carried. Namazkhan et al. (2019) employed a 9-point questionnaire to carry out such a survey among 1461 Dutch households. The respondents were told to identify themselves to certain statements made that were representative of Schwartz's four values- Hedonic, Altrusitic, Egoistic and Biospheric.They were told to answer based on a

9-point scale ranging from -1= "opposed to my values" to 7= "very important" . The results of the survey are presented in Table 4.4.

Table 4.4: Quantification of behaviour values of Dutch households

Behaviour value	Mean	Standard deviation	Maximum number	Range
Biospheric	5.17	1.27	7.00	7.75
Egoistic	1.94	1.23	6.40	7.40
Hedonic	4.62	1.38	7.00	7.00
Altruistic	5.14	1.18	7.00	7.00

The dataset presented in Table 4.4 presents the numerical mean of the four behaviour values (including other statistical parameters) held by Dutch households. As seen from the table, the households have high biospheric, altruistic and hedonic values.

Based on a literature search, this is the closest dataset available about the behaviour values of the Dutch households. This dataset can serve as an input towards determining the waste separation behaviour of the agents of Havenstad via their personal norm values. These values can be considered for SMEs as well because they are representative of the behaviour showcased by people- something that could be common between the households and SMEs. For example, a inhabitant in Havenstad could perhaps work in a office in Havenstad, thereby the behaviour values obtained for both the agents could nearly be the same.

The waste separation activity of SMEs are influenced by values and norms as well. Although the influence of these values could be slightly different for Small-Medium Enterprises (SMEs). The normative waste separation behavior of SMEs and households can be distinguished based on descriptive and injunctive norms.As per Scalco et al. (2017), SMEs may tend to identify themselves by descriptive norms making them "more influenced by information", while households may show injunctive behavior, making them "a source of normative influence". This implies that personal norms may have a stronger influence in setting up a normative behavior to separate more waste in households as compared to SMEs. Coversely, SMEs may be influenced by information (in form of policies) for setting up a waste separation behavior. This is an important insight because it tells us that a same set of values for household and SME would not result in a similar waste separation action.

The external factors or interventions (such as bin size) and their influence on the waste separation are discussed in the subsequent sections of this chapter. But before that, the local waste separation carried out by the agents is discussed in the next section.

4.4 Local waste separation

The organic waste generated by households and Small-Medium Enterprises (SMEs)is disposed off locally in bins. Usually each household & SME have their own local bins of fixed capacity. There may be two separate local bins, one for the organic waste and the other for the residual waste. Based on the decision making process of the agents, they can choose to correctly separate their organic waste in the local bin meant for organic waste. Otherwise, the waste usually ends up in the local bin meant for residual waste.

The local bin size (for organic waste) for households can be 25 Liters or more (Den Haag, n.d.), which is also one of the smallest bin sizes. For SMEs the local bin size would usually be higher due to more amount of organic waste generated by them. The local bin size for residual waste is not examined because it not within the scope of this research.

4.5 Centralized waste separation

Once the local bin is full, the agents look to clear their bins by disposing off the organic waste that has been collected. The waste from the local bin can be left to be picked up or the agent makes an effort to dispose and maybe separate the waste in bigger waste container, which can be 'centralized' for a set of agents perhaps in a neighbourhood.

Similar to local waste separation, the centralized waste separation undertaken by the agents goes through a decision making process. This again is influenced by certain internal and external factors. But unlike local separation of waste, the externals factors such as bin size, bin fullness, distance of bin and bin experience (or convenience) can play a major role in waste separation carried out (Bernstad, 2014; Ipsos, 2016; Meng et al., 2019).

Together the distance and bin size or bin fullness can determine the 'experience' of the agent when carrying out centralized waste separation. A bad experience, such as a nearly full bin or a far away bin, can have a negative influence on the centralized waste separation.

It is important to examine these external factors along with the data available about them in order to determine the total waste separated. In the following sub-sections the external factors pertaining to centralized waste separation are presented. The external factors mainly relate to the characteristics of the central bin and frequency at which waste is cleared from the bin.

4.5.1 Central bin

In the Netherlands, the municipality is responsible for setting up separate waste collection infrastructures for individual households or neighbourhoods (City of Amsterdam, n.d.-b). For a certain neighbourhood, a centralized collection bin is set up to collect the waste from households and SMEs.Also, sometimes the waste is collected from the local bins individually from each household.

In Amsterdam centralized waste container bins are usually set-up for the waste collection of 60 households, which the municipality plans to increase to 100 households by 2020 (Gemeente Amsterdam, 2016).

According to an expert the centralized waste bins in Amsterdam are located usually at a maximum distance of 160 m from the households (S. de Rijke, personal communication, November 15, 2019: See Appendix C.2.3). Another expert stated that centralized residual waste bin is place at a distance of 75 m from the agents (J. Reeze, personal communication, December 16, 2019: See Appendix C.2.1). Furthermore, based on a Geographical Information System (GIS) study the optimal distance of the bins should be between 60-75 m to optimize waste collection (Chalkias & Lasaridi, 2009; Nithya, Velumani, & Senthil Kumar, 2012). The distance of the bin can determine the waste separation carried out by agents (P. de Boer, personal communication, February 28, 2020: See Appendix C.2.2) . This is mainly due to the time taken by the agent to walk to the bin, which ideally the agent wants to minimize (Liu, Sun, Xia, Cui, & Coffey, 2018).

Furthermore, There can be separate container bins for plastic, paper, organic and residual waste(Den Haag, n.d.).Usually organic waste from households and SMEs is not separately collected by municipality of Amsterdam, except in a few districts(City of Amsterdam, n.d.-b). Otherwise it is disposed off in the residual waste bin(Gemeente Amsterdam, n.d.).The size of these container bins can range from 140 Liters to 240 Liters (Den Haag, n.d.). Based on discussions with experts in the Municipality of Amsterdam, the size of the organic bin is usually 240 Liters (J. Reeze, personal communication, December 16, 2019: See Appendix C.2.1).

In the case of this system, as seen from Figure 4.1, there are two types of central bins: one for the sorted organic waste and the other for the residual waste, which also collected the unsorted organic waste. But as mentioned earlier, the analysis of the residual waste stream or its bin is not within the scope of this research.

4.5.2 Waste transportation

The waste collected in the two central bins is cleared or collected with the help of trucks. These trucks may be responsible for collecting waste from the central bins of different neighbourhoods at fixed time intervals and transporting it to WtE technological infrastructures.

The frequency of waste collection from the centralized bin can be once a week, twice a week or once in two weeks(Heijnen, 2019; Rijkswaterstaat, n.d.). In Amsterdam it is carried out once in two weeks (Afval Monitor, n.d.).

According to (NVRD, 2016), the average cost of collection of residual waste once in two weeks in the Netherlands is 65 € per tonne. For OFMSW the average cost of collection (once in two weeks) is85 € per tonne. The cost of collection for the other two settings: 'once a week' & 'twice a week' is not available in the same report. But the collection costs for these two settings are necessary not doubled or tripled as compared to collection once in two weeks (Porter, 2010). Therefore, the cost of collection for once a week could be, for example, 1.5 times the collection cost for once in two weeks.

Furthermore, the bin type determines where the the waste ends up being processed to energy. The waste transported from the residual central bin would end up in the incinerator , while that from the organic central bin ends up in the anaerobic digester.

Lastly, the complete dynamics or characteristics of waste transportation are not examined as part of this research. The sole characteristic that is of interest is the frequency of waste collection.

The data discussed about the central in this section is summarized with the help of Table 4.5. The characteristics of the residual central bin could more or less be the same as the organic central bin, but as this is not the focus of this research it is not been addressed.

Table 4.5: Characteristics of organic central bin

	Number of agents allocated	**Size**	**Distance (Maximum)**	**Distance (Optimum)**	**Frequency of collection**
Organic central bin	100	140- 240 Liters	160 m	60-75 m	Twice a week Once a week Once in two weeks

Also, it is important to know that the values presented in Table 4.5 are for the baseline conditions. Changing these values would imply a structural intervention has to be implemented, something that is addressed further in this research.

4.6 Waste-to-energy technologies

In Phase 3 (See Figure 4.1) the waste is collected for transportation to WtE technological infrastructures. In Phase 4 (See Figure 4.1) the different WtE technologies convert this OFMSW into a source of energy.

As seen in Figure 4.1, there are two types of WtE technologies: anaerobic digester & incinerator. The anaerobic digester converts OFMSW into biogas- a source of energy used to generate electricity or heat. In the incinerator, the OFMSW is combusted to generate heat, which inturn can be converted into electricity.

As discussed in the end of the last section, the technological route taken to convert waste into energy depends on the bin type that in ends up being collected from in Phase 3. Thus, the energy output from OFMSW depends on the *waste to energy technological route* taken.

This section is divided as per the *waste to energy technological route or technological route*[4] taken to process OFMSW into energy. In the following subsections the characteristics & empirical data of different WtE are discussed and the expected energy output from the different technological routes.

The main take away is the energy output values or the energy conversion values i.e. the energy obtained from processing one tonne of OFMSW into energy. Also, the operating costs and the environmental benefits associated with it. All these are summarised for different technological routes in Appendix D.

4.6.1 Organic waste to biogas

The OFMSW obtained from centralized bins meant for organic waste is processed in an *anaerobic digester* to generate biogas. These terms are described in Chapter 3.

For this system, an existing anaerobic digester is chosen to operate on the organic waste collected from households and SMEs in Havenstad. That is the 'BIOCEL' reactor in Lelystad(the Netherlands). It has been operational for the last twenty years and processes OFMSW from Flevoland municipalities [5].

The choice of the 'BIOCEL' is made based on the characteristics of the organic waste, demographics of the waste sortation network, retention time,existing technological arrangements,commercial viability of the plant, availability of operational data and overall performance of the digester(Valijanian et al., 2018).

The selection of this anaerobic is attributed to the thesis research carried out by Goossensen (2017), wherein the author compared the suitability of the physical and operational characteristics of a anaerobic digester to the OFMSW found in Amsterdam. (Goossensen, 2017) advised to use an one-phase mesophilic batch reactor with dry influent, which the commercially available 'Biocel' reactor presents(Ten Brummeler, 2000).

A dry influent process requires less fresh water, less energy input and experiences lower system failures compared to wet influent process. Between one and two-phase digester, one-phase digester has lower invest and operational costs. Similarly, batch process has lower costs compared to continuous process. Lastly, the choice of a mesophilic process is based on its lower energy demands and high resistance to temperature fluctuations. For more details, refer the thesis conducted by Goossensen (2017).

In the following paragraphs the performance attributes and energy conversion values of the 'BIOCEL' digester are discussed:

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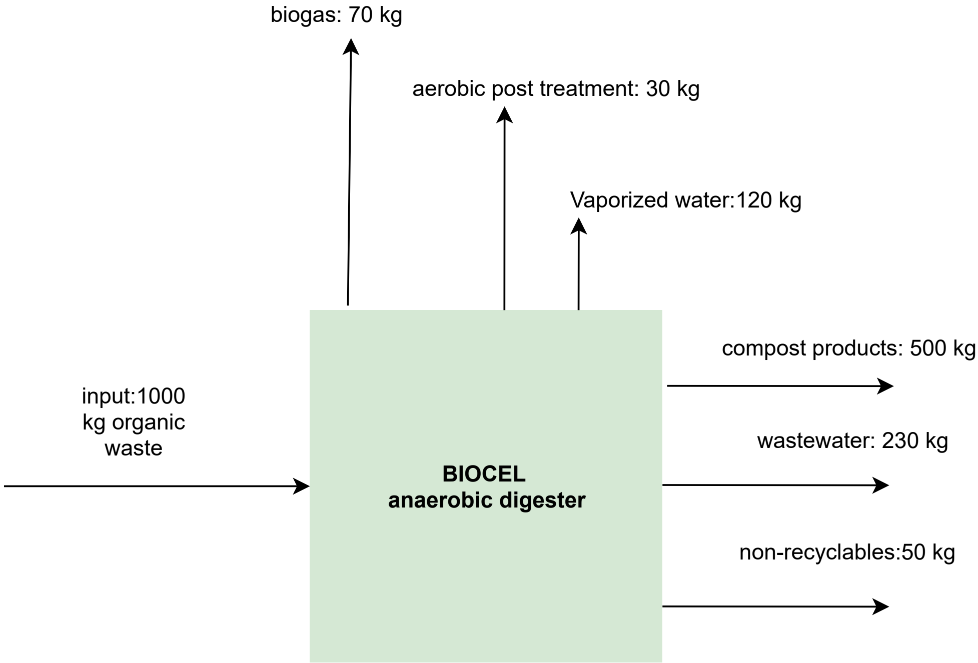
[4]In this chapter, the term *technological route* is used interchangeably with *waste to energy technological route*
[5]https://orgaworld.nl/meer-over-ons-bedrijf/onze-locaties/lelystad-biocel

Figure 4.2: Mass and energy balance of BIOCEL digester: Adapted from Ten Brummeler (2000)



In Figure 4.2, the mass balance of the anaerobic digestion process in the 'BIOCEL' reactor is depicted based on a report by Ten Brummeler (2000). The process involved converts one tonne of OFMSW into biogas and other by-products . Also, the digester has a net energy production by converting biogas to power and heat(Ten Brummeler, 2000)

As per literature the biogas yield per ton of OFMSW ranges from is about 59.1 to 160 m^3(Kigozi, Aboyade, & Muzenda, 2014; SEAI, 2016; Stan, Collaguazo, Streche, Apostol, & Cocarta, 2018; Stucki, Jungbluth, & Leuenberger, 2011). Also, most of the literature mentioned that the yield depends on the composition and the constituents of the organic waste. Given that the constituents of the OFMSW generated by the agents of Amsterdam is not examined and the wide range from literature, it is best consider the mass to energy value available for the 'BIOCEL' digester , i.e. 100 ^{3} of biogas per tonne of OFMSW (advies, 1994; Orgaword, n.d.).

The performance attributes of the digester extracted from Orgaword (n.d.), Ten Brummeler (2000) are presented in Table 4.6.Furthermore, it offers a Hydraulic Retention Time(HRT) of 21 days, which a reasonable time period to manage the digestion of OFMSW from households and SMEs. HRT or retention time is a measure of the average length of time that a soluble compound remains in a bioreactor(Lenntech, n.d.).

The breakdown of the operating cost mentioned in the last row of Table 4.6 is composed of the following costs: Raw material, Personnel, Maintenance, Material, Electrical, Insurance, Monitoring and Distribution (Haddad, 2014). The breakdown of the operating cost is discussed more extensively in Appendix B.1, along with the different operating costs obtained from literature (See Table B.1. The operating cost estimated by Olivard (2017) is chosen because it meant for a digester 50,000 tons of food waste a year, a characteristic observed in the 'BIOCEL' digester as well.

Table 4.6: Performance attributes of digester

Performance attribute	Value
Number of reactors/digesters	14
Number of compost tunnels	5
Effective digester volume	480 m^3
Capacity	30,000 to 50,000 tonnes per year or, 1,000 tonnes weekly
Operating temperature	35°C to 40 °C
Biogas generated	100 Nm^3 per ton of OFMSW (Methane content $\geq$ 55%)
Operating costs	61 € ton of OFMSW

4.6.2 Biogas to electricity & biomethane

Biogas obtained from the anaerobic digestion of OFMSW can be used to produce electricity and/or biomethane.

To generate electricity from biogas, internal combustion engines, gas turbines or Solid oxide fuel cells can be employed(Saadabadi et al., 2019).Otto cycle internal combustion engines and gas turbines are most commonly used technologies to convert biogas into power(Coelho, Velázquez, SILVA, et al., 2006).

The electricity generated per m^3 of biogas can be calculated with help of Equation 4.1. The Lower Heating Value(LHV_{BG}) of biogas with 60% methane content is given to be 6 kWh/m^3 (Cvetković, Kaludjerović Radoičić, Kragić, & Kijevčanin, 2016).Using the efficiency values of the technologies in the equation, the electricity generated per m^3 of biogas is presented in Table 4.7.

The values obtained are comparable to the ones found in literature.Whiting and Azapagic (2014) stated that a Combined-Heat and Power(CHP)of capacity 170 kW_el plant generates 1.46 kWh_el per m^3 of biogas. According to Achinas et al. (2017) for a CHP plant with an electrical efficiency of 35% the electricity generated per ton of organic fraction of municipal solid waste is given to be 207.2 kWh or 2.07 kWh/m^3 of biogas[6].

$$E_{BG} = \mu_e \cdot LHV_{BG} \tag{4.1}$$

Table 4.7: Electricity generated from biogas

Technology	Net efficiency (μ_e)	Electricity generated from biogas	Operations cost
Gas turbine	19-34%	1.14 - 2.04 kWh/m^3	1.67 €cents to 1.70 €cents/kWh
Fuel cell	36-50%	2.16 - 3.00 kWh/m^3	4.5 €cents to 7 €cents/kWh

In the last column of Table 4.7 the operating costs of the gas turbine and fuels cells are presented respectively.Papadias, Ahmed, and Kumar (2012) carried out a techno-economic investigation on an integrated SOFC-CHP plant combined Waste treatment plant and based on the results the price was roughly 4.5 €cents to 7 €cents per kWh.

There is limited about of data available about the operating cost for gas turbines that use biogas as fuel. Lantz (2012, p. 507) provides a summary of production costs of a gas turbine

[6]If the biogas generated from 1 tonne of OFMSW is said to be 100 m^3

producing 280 MWh annually at a net efficiency of 29%.Based on these costs, the maintenance cost is calculated to be 1.67 €cents per kWh generated.This operating cost is close to that stated by Leme et al. (2014). According to Leme et al. (2014, p. 11), the annual O&M costs for electricity generation from biogas obtained from landfill is 1.7 €cents per kWh generated. The average of these two costs is equal to 1.69 €cents per kWh.

Another technological route is the upgradation of biogas to produce biomethane. Biogas can be upgraded to biomethane by removing CO_2 and increasing the concentration of CH_4 in the gas to more than 96% (Wilken et al., 2019). Once upgraded, biomethane can be fed into the national grid replacing natural gas and can be used as fuel to run vehicles, generate heat or compressed in cylinders for domestic use(Wilken et al., 2019).

Using technological infrastructures for upgrading biogas, 1 cubic meter of biomethane can be obtained from 1.536 cubic of biogas (Goossensen, 2017).The list of commonly used technologies employed to upgrade biogas to biomethane are presented in Table 4.8 along with their technological and operating parameters(Vienna University of Technology, 2012). Water scrubbing is most used upgrading technology in Europe and the Netherlands (Beil & Beyrich, 2013; German Biogas Association, 2016). It has an average operating cost of 11.13 cents/m^3 of biomethane produced.

Table 4.8: Parameters for upgrading technologies (Source:Vienna University of Technology (2012))

Parameter	**Water scrubbing**	**Organic physical scrubbing**	**Amine scrubbing**	**PSA**[7]	**Membrane technology**
Methane recovery(%)	98	96	99.96	98	80-99.5
Methane slip(%)	2	4	0.04	2.0	20-0.5
Electric energy demand (kWhel/m^3 biomethane)	0.46	0.49-0.67	0.27	0.46	0.25-0.43
Investment costs (EUR/m^3/h biomethane)					
for 100m^3/h biomethane	10,100	9,500	9,500	10,400	7,300-7,600
for 250m^3/h biomethane	5,500	5,000	5,000	5,400	4,700-4,900
for 500m^3/h biomethane	3,500	3,500	3,500	3,700	3,500-3,700
Operational costs (cents/m^3 biomethane)					
for 100m^3/h biomethane	14	13.8	14.4	12.8	10.8-15.8
for 250m^3/h biomethane	10.3	10.2	12.0	10.1	7.7-11.6
for 500m^3/h biomethane	9.1	9.0	11.2	9.2	6.5-10.1

This biomethane generated can be used for space heating in households & SMEs. In the Netherlands, a gas-fired boiler is one of the commonly used technologies to generate heat from natural gas (Menkveld & Beurskens, 2009). It has a thermal efficiency (μ_{th}) of about 90% (Majcen, Itard, & Visscher, 2016; Saygin, van den Broek, Ramırez, Patel, & Worrell, 2013).

Assuming biomethane is used as a fuel source in the gas boiler, then in that case its thermal output can be calculated based on Equation 4.2, where LHV_{BM} is the Lower Heating Value or

[7]Pressure Swing Adsorption

the calorific value of natural gas (i.e. 36.2 MJ/m^3)

$$E_{BM} = \mu_{th} \cdot LHV_{BM} \tag{4.2}$$

Based on the above equation the thermal output is 32.58 MJ or 9.05 kWh$_{th}$ per m^3 of biomethane.

4.6.3 Biomethane to electricity

Biomethane obtained from OFMSW, can be used fuel in Combined Cycle Gas Turbine(CCGT) to generate electricity (GasTerra, 2009). Compared to biogas, biomethane has a higher calorific value and lower impurities.This would result in the extraction of more electricity from the OFMSW. The electricity obtained (in kWh) can estimated by using Equation 4.1. The calorific value of biomethane or natural gas is 36.2 MJ/m^3 (or 10.06[8] kWh/m^3)(Carvill, 1993) and the efficiency of a gas turbine can be range from 45% to 60%(GasTerra, 2009). Thus, resulting in a electricity generation of 6.03 kWh/m^3 of biomethane (at 60% efficiency). This is three times more than from biogas. The operations cost of the gas turbine range from approximately 0.25 €cents to 0.32 €cents per kWh (GasTerra, 2009; IEA, 2015). The average of these two costs is equal to 0.29 €cents per kWh.

4.6.4 Waste incineration

The unsorted OFMSW collected in the central residual waste bins is incinerated with other forms of waste comprising of plastics and metals to produce energy. But in this research the emphasis is only on the incineration of OFMSW.

The existing waste incinerator in Amsterdam is suitable for processing the unsorted OFMSW from Havenstad. In the city of Amsterdam, the *Afval Energie Bedrijf* - Waste and Energy Company runs Waste-to-Energy plants with an incineration capacity of approximately 1,400,000 tonnes per year, with a daily capacity of 4,400 tonnes.The plants offer a net electrical efficiency of 22% - 30% and its availability will be more than 90% of the time (Gemeente Amsterdam - Afval Energie Bedrijf, 2007).

The heat energy obtained from the incineration of organic waste along with other forms of waste can contribute towards the generation of electricity. To determine the potential amount of electricity generated from OFMSW , an equation (Equation 4.3) adapted from Gómez, Zubizarreta, Rodrigues, Dopazo, and Fueyo (2010) can be used to calculate the potential of electricity generated. In order to calculate the electricity generated the Lower Heating Value (LHV$_{OFMSW}$) of OFMSW is needed and the electricity efficiency (μ_{ei}) of the incinerator (for Amsterdam it is between 22 to 30%).

$$E_{IC} = \mu_{ei} \cdot LHV_{OFMSW} \tag{4.3}$$

According to Gómez et al. (2010) the LHV$_{OFMSW}$ of the OFMSW in Spain (2005) is 2720 MJ / tonne. While as per Faaij et al. (1997) the LHV$_{OFMSW}$ of the OFMSW in the Netherlands (1994) is 4000 MJ / tonne.

Applying an μ_{ei} of 30% and the two LHV$_{OFMSW}$ in Equation 4.3, the electricity generated by incinerating per tonne of OFMSW ranges between 228 kWh / tonne to 333.33 kWh/ tonne. The average of these two values is approximately 281 kWh / tonne. But given that OFMSW in the Netherlands showed higher LHV$_{OFMSW}$ than in Spain, the final value is rounded off to

[8]By considering 1 MJ = 0.28 kWh

300 kWh / tonne of OFMSW. Although the value 333.33 kWh/ tonne could have been taken as well but because the value is based on data taken observed in the year 1994, it may not accurately predict the LHV_{OFMSW} of the OFMSW generated in Havenstad.

The organic waste that is incinerated requires input of a fuel (such as natural gas) to start the combustion process.In order to incinerate one ton of OFMSW 14 MJ of natural gas is required (Hischier et al., 2010). This translates to 0.36 m^3 of natural gas per ton of OFSMW(assuming the calorific value of natural gas as 38 MJ/m^3). Alternatively, the biomethane generated from OFMSW can used as replacement for natural gas to aid the combustion process.

Furthermore, waste incineration of OFMSW releases CO_2 along with other gaseous components. The amount of CO_2 released from the the organic waste can depend on the fossil carbon content of the waste. According to data complied by Astrup et al. (2009) on the composition of European OFMSW, the biogenic based carbon content is 150 kg per tonne and fossil based carbon content is 2 kg per tonne. Assuming 1 kg of carbon on complete combustion results in 3.67 kg7 of CO2 , then per tonne incineration of OFMSW leads to 7.34 kg of CO2 emitted.

Lastly, the operating costs of the incinerator plants in Europe, is between 40 €/ton to 100 €/ton (Eunomia, 2001; WRAP, 2008) and according to one web article by Millicer (2018) the gate fees[9] of incinerating waste in the Netherlands is between 70 € to 75 €.

4.7 Environmental elements

Apart from the elements in Figure 4.1 that are described so far, there are environmental elements (or systems) in the System-of-Interest (SOI). Environmental elements can be described as an interface that acts as the interconnection between the SOI and the external environment (Faulconbridge & Ryan, 2014, p. 102). They may not be directly related to the project but can influence the outcome of the SOI

Within this SOI there are three environmental elements: *Electricity market, Gas Market & Awareness campaign*. These elements are described in the following sub-sections along with their relevance.

4.7.1 Electricity Market

Power generators involving nuclear plants, waste-to-energy(WtE) plants, coal power plants, wind farms and natural gas based power plants trade their electricity generated with the customers in the electricity market.Generally there are two types of market:Day-ahead market and Intra-day market. In the day ahead market the electricity is traded for the next day on an hourly basis(de Vries, Correljé, & Knops, 2017). Electricity traders can make anonymous auction bids for selling and buying electricity and the day-ahead market is cleared separately for each hour of the day based on a market clearing price.(Slingerland, Rothengatter, van der Veen, Bolscher, & Rademaekers, 2015). In the intraday market, traders can buy or sell electricity continuously upto an hour before delivery(Slingerland et al., 2015). Spot prices in the market can be highly volatile and unpredictable.Therefore, majority of the electricity is traded in the bilateral market(about 85% in the Netherlands), wherein electricity is sold directly by power generators to their customers for a certain duration of time(can be in weeks or months).

The market clearing prices for the electricity markets all in EU can be found in the ENTSO-E transperancy platform [10].The Amsterdam Power Exchange(APX) is the electricity market

[9]The gate fees is the fee paid to the waste-to-energy facility to process OFMSW
[10]https://transparency.entsoe.eu/dashboard/show

responsible for carrying out power exchange in the Netherlands. The average day-ahead electricity price in the Netherlands for the year 2018 was 50.7 €/MWh while the average intraday price was 53.1 €/MWh(Tennet, 2019).Figure 4.3 provides an glimpse of the the hourly prices and Figure 4.4 provides prices for a particular week for APX day-ahead market

Figure 4.3: Hourly day ahead prices for 21st November 2019; Source: ENSTO-E Transperancy Platform

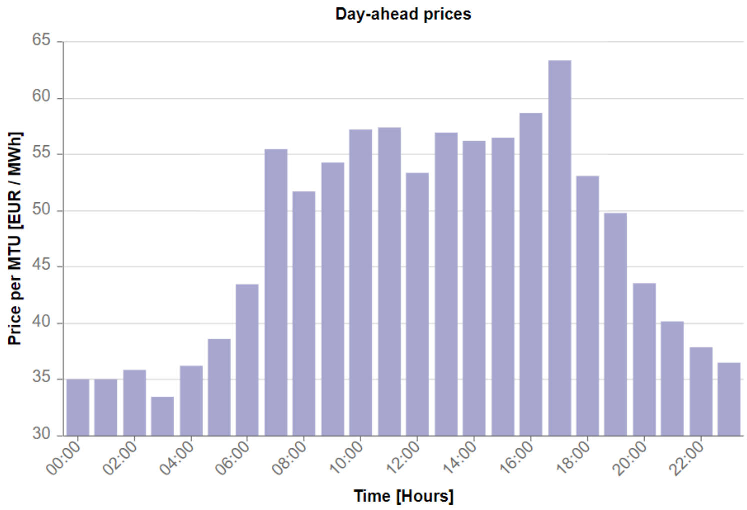
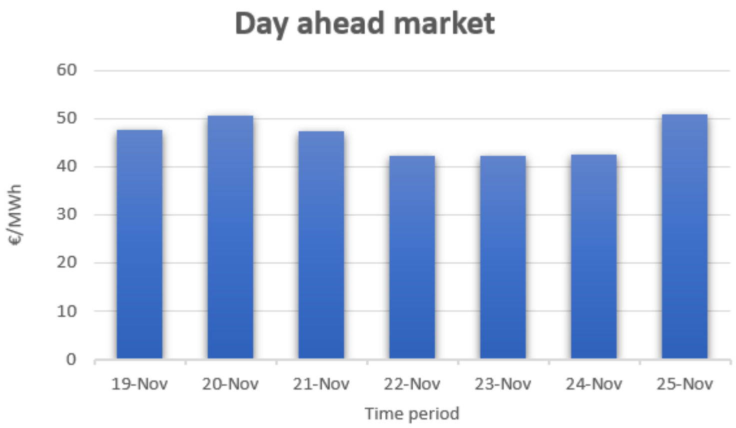


Figure 4.4: Day ahead prices; Source: EPEX SPOT



In this system (Figure 4.1), electricity is generated from OFMSW through three technological routes: Biogas to electricity, Biomethane to electricity and Electricity from Incineration. The electricity generated can be traded in the day-ahead market to generate revenue. The day-ahead market is chosen over the intra-day market because the intra-day market would require a power system with high flexibility, which is not addressed in this system-of-interest(SOI).

Apart from generating revenue, electricity generated from the OFMSW from Havenstad can abate CO_2 emissions caused by displacing the electricity generated by conventional power plants such as natural gas powered plants

In the Netherlands, Combined Cycle Gas Turbine(CCGT) plants have a high contribution towards the electricity production in the Netherlands.These plants tend to use natural gas to generate electricity, which results in CO_2 emissions. By displacinig the electricity provided by the CCGT plants with that from the OFMSW from Havenstad, the CO_2 emissions from the CCGT plants can be avoided.

The CO_2 emissions of CCGT plants depends on their efficiency. Plants with higher efficiencies emit less (Mearns, 2016) . In the Netherlands, some of the CCGT plants[11] have an efficiency values close to 60%.

According to Mearns (2016) for a CCGT plant with an efficiency close to 60%, approximately 325 kg of CO_2 are emitted per MWh of electricity generated. This is close to value (350 kgCO_2 / MWh) obtained by Mletzko, Ehlers, and Kather (2016) for a CCGT plant of net efficiency of 59.2%. Therefore, based on an approximate average of these values, the CO_2 emitted by a CCGT plant with an efficiency of 60% is assumed to be 335 kgCO-$_2$-eq/ MWh. This implies that for each MWh of electricity displaced with that from OFMSW, less than or equal to 335 kg of CO_2 can be avoided.

4.7.2 Gas market

Similar to the electricity market, there exists a bilateral market and spot market to trade natural gas in the Netherlands. Majority of the gas traded in the Netherlands is sold to GasTerra, which resell it to retail companies that inturn sell it to small end users.GasTerra is public-private organization responsible for trading of natural gas (or gas) in the Netherlands.The gas exchange takes place in the APX Gas spot market in combination with Title Transfer Facility(TTF), a virtual wholesale hub on the transmission system. On the APX gas spot market gas can be traded day ahead and similar to electricity spot prices the gas spot prices are highly volatile. In 2018 the average gas price in the Netherlands was 17.5 €/MWh and in 2019 it was 22.5 €/MWh[12](CREG, 2019).

The biomethane generated from the OFMSW of Havestad can be supplied to the gas grid and sold in the gas market to generate revenue. In the Dutch gas grid there are two types of natural gas: low-calorific(G-gas) and high calorific(H-gas). But most of the Dutch consumers(about 65%) use G-gas(Hisschemoller, Bode, F, & Stam, 2020). Furthermore, the Dutch gas grid requires gas with more than 88% methane content, which is possible to achieve by upgrading biogas to biomethane. In fact there are four (or more) plants in the Netherlands that upgrade biogas to feed into the Dutch gas grid(M. Persson, Jonsson, & Wellinger, 2006). The average calorific value of biomethane or natural gas is 36.2 MJ/m^3(Carvill, 1993), which is comparable to the gas found in the Dutch gas grid(Visser, 2014).

The supply of biomethane in the gas grid to displace natural gas can help avoid the CO_2 emissions caused by the combustion of natural gas. The direct displacement of natural gas in the gas grid with biomethane can result in abatement of 176.28 gCO_2-eq/kWh or 176.28 kgCO_2-eq/MWh (European Commission, 2016).Also, this value can be standardized to 1.766 kgCO_2-eq/m^3. This value obtained can be verified by calculating the amount of CO_2 emitted by the combustion of 1 m^3 of natural gas.

The combustion of natural gas (or methane) in the presence of oxygen gives the following

[11]https://www.power-technology.com/projects/enecogen-ccgt/
https://www.group.rwe/en/our-portfolio/our-sites/moerdijk-power-plant

[12]The taxes levied are not included in this price

1 m^3 of biomethane = 0.01 MWh

chemical reaction.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{4.4}$$

From the reaction it is seen than 1 mole of methane gives one mole carbon dioxide. Based on the molar mass of methane and carbon dioxide, 1 kg of methane produces 2.75 kg of carbon dioxide. Using the density value of methane (0.656 kg/m^3), if 1 kg of methane resulted in 2.75 kg of carbon dioxide or CO_2 , then combustion of 1 m^3 of methane results in 1.80 kg of CO_2 . This is close the value obtained from literature (1.766 kgCO_2 /m^3), but the value from literature is chosen here because the actual combustion of natural gas may produce less CO_2 due to the presence of impurities, something that is not accounted in the chemical reaction.

Therefore, given that combustion of biomethane results in zero net emissions, the per unit direct displacement of natural gas with biomethane can result in an abatement of 1.766 kg of CO_2 .

4.7.3 Awareness campaign

Awareness campaign is a form intervention that employs information provision to promote a change in the waste separation behavior. In the Netherlands, one such intervention strategy '100-100-100'[13] was designed and carried out by ROVA- a publicly owned Dutch Waste collection company (Van der Werff et al., 2019). It's aim was to get 100 households to live 100% waste free(i.e. no residual waste) for 100 days. It focused on increasing waste separation and waste prevention to get no residual waste.

This informational strategy was carried in the rural area of the Netherlands, which included cities with less than 150,000 inhabitants. About 409 inhabitants voluntarily signed up for the intervention and had to fill up a questionnaire four weeks before the start of the intervention, then seven weeks after the start of the intervention, one directly after the intervention ended and a fourth one six months after the intervention ended.Compared to the average household in the Netherlands, this sample is older and has a higher level of education(Van der Werff et al., 2019).

The intervention consists of a informational evening, an online platform where participants can receive tips on how to separate, recycle, and reduce their waste. Furthermore, they receibed 14 weekly assignments which gave them inight into their waste behavior.Also, in the online platform the participants could report their weekly residual waste.

The intervention begun on 1st of January 2015 uptil 10th April 2015 and lasted for a total of 100 days. During and after the intervention Van der Werff et al. (2019) monitored the participants for their waste separation and their residual waste. Furthermore,the study analysed the effect of the intervention in strengthening the variables of the VBN theory and its subsequent effect on increasing waste separation.

By doing so, they linked the change in waste separation behavior to the variables of VBN theory such AC, AR & PN. At the end of 100 days the personal norm values of the households increased by $\approx$ 9% and the waste separation increased by $\approx$ 18%

Thus, the authors concluded that informational strategies may be effective in minimizing household waste and increasing waste separation when the variables of the VBN theory are increased due to the informational strategy.

Molar mass of methane = 16g/mol
Molar mass of carbon dioxide = 44g/mol
[13]http://www.100-100-100.nl/

4.8 Summary

The data discussed in this chapter is summarised for different WtE systems in Table 4.9 . The table is constructed to compare the three important indicators (in blue columns) for the different technological routes. These indicators are calculated for per tonne of OFMSW processed through each technological route. The calculations of these indicators are explained in Appendix D.

Table 4.9: Characteristics of the different technological routes

	Technological Route	Carbon dioxide abated per unit	Electricity / Biomethane generated per tonne	Carbon dioxide abated per tonne	Total operating cost per tonne
1	Biogas to electricity	335 gCO_2 / kWh	204 kWh	68.34 $kgCO_2$	139.09 €
2	Biogas to biomethane	1.766 $kgCO_2$ / m^3	65.10 m^3	114.96 $kgCO_2$	140.14 €
3	Biomethane to electricity	335 gCO_2 / kWh	392.55 kWh	131.50 $kgCO_2$	134.45 €
4	Waste incineration	335 gCO_2 / kWh	300 kWh	92.01 $kgCO_2$	119.86 €

[a] Anaerobic digestion of 1 tonne of OFMSW results in 100 m^3 of biogas
[b] Operating cost of the anaerobic digester is 61 € per tonne OFMSW

In the first column, 'Carbon dioxide abated per unit' is the CO_2 abated by replacing per unit of energy from natural gas based energy systems with that from OFMSW . This value helps to calculate the 'Carbon dioxide abated per tonne' for different technological routes.

For example, taking the first technological route (Biogas to electricity), the CO_2 abated by processing one tonne of OFMSW into electricity using biogas gas as an energy source, is calculated in the following manner: Firstly, the amount of biogas generated from 1 tonne of OFMSW is calculated (i.e. 100 m^3). Secondly, the electricity generated from 100 m^3 is calculated (i.e. 204 kWh), which is also the electricity generated per tonne of OFMSW. Lastly, this value (204 kWh) obtained is multiplied with the value in the column 'Carbon dioxide abated per unit', for this technological route that is 335 gCO_2 / kWh. Therefore, this results in 68.34 kg of CO_2 abated from using the first technological route. Also, it is important to note here that combustion of biogas results in zero net emissions, resulting in a direct abatement of CO_2 .

By examining Table 4.9, it is observed that technological route 3 results in the highest electricity generated per tonne and the highest CO_2 abated per tonne. A correlation can be formed between the electricity generated and the CO_2 abated by examining the routes. It is observed that the electricity generated by a technological route to proportional to the CO_2 it abates.

The last column is the total operating cost of processing one tonne of OFMSW into energy. This includes the cost of producing biogas from 1 tonne of OFMSW through anaerobic digestion, cost waste collection, cost of generating electricity/biomethane and the revenue generated from selling electricity/biomethane. The calculations of the total operating costs are explained in Appendix D.3

From the values seen in the last column, the technological route 2 is the most expensive for processing one tonne of OFMSW and technlogical route 4 being the cheapest.

In the next chapter these values are captured in an Agent-Based Model(ABM) to help answer the rest of the research questions.

5. Model Description

The chapter provides a description of the model, its entities, its concepts and the model narrative. It also discusses the sensitivity analysis performed, model verification & validation.

In the previous chapters the first two steps needed to construct an ABM : Problem formulation & System decomposition are addressed. The following steps, as per Chapter 2, are: *Concept formalisation, Model formalisation, Software implementation, Model verification and Model validation.*

The next step after describing a system, its elements and interactions, is the formalisation of these concepts. Concept formalisation is necessary to generalize the system description to a model domain. This is because in the system description the concepts are not specific enough to be captured in a modeling software (Van Dam et al., 2013, p. 82-83).

As per Van Dam et al. (2013, p. 83), there are two ways to formalise concepts: Software data structure & Ontology. The latter is chosen in this chapter because it has more graphical representation of the conceptual model and can be more easily linked to the System description shown in Figure 4.1.

Ontology helps formally encode the elements of the system and their relationships in a model. It goes into specificities of the system elements necessary to construct a model out of the system. The ontology of the model is depicted by a set of figures in this chapter. The sections & figures are divided as per the four phases mentioned in Figure 4.1 (i.e. System description).

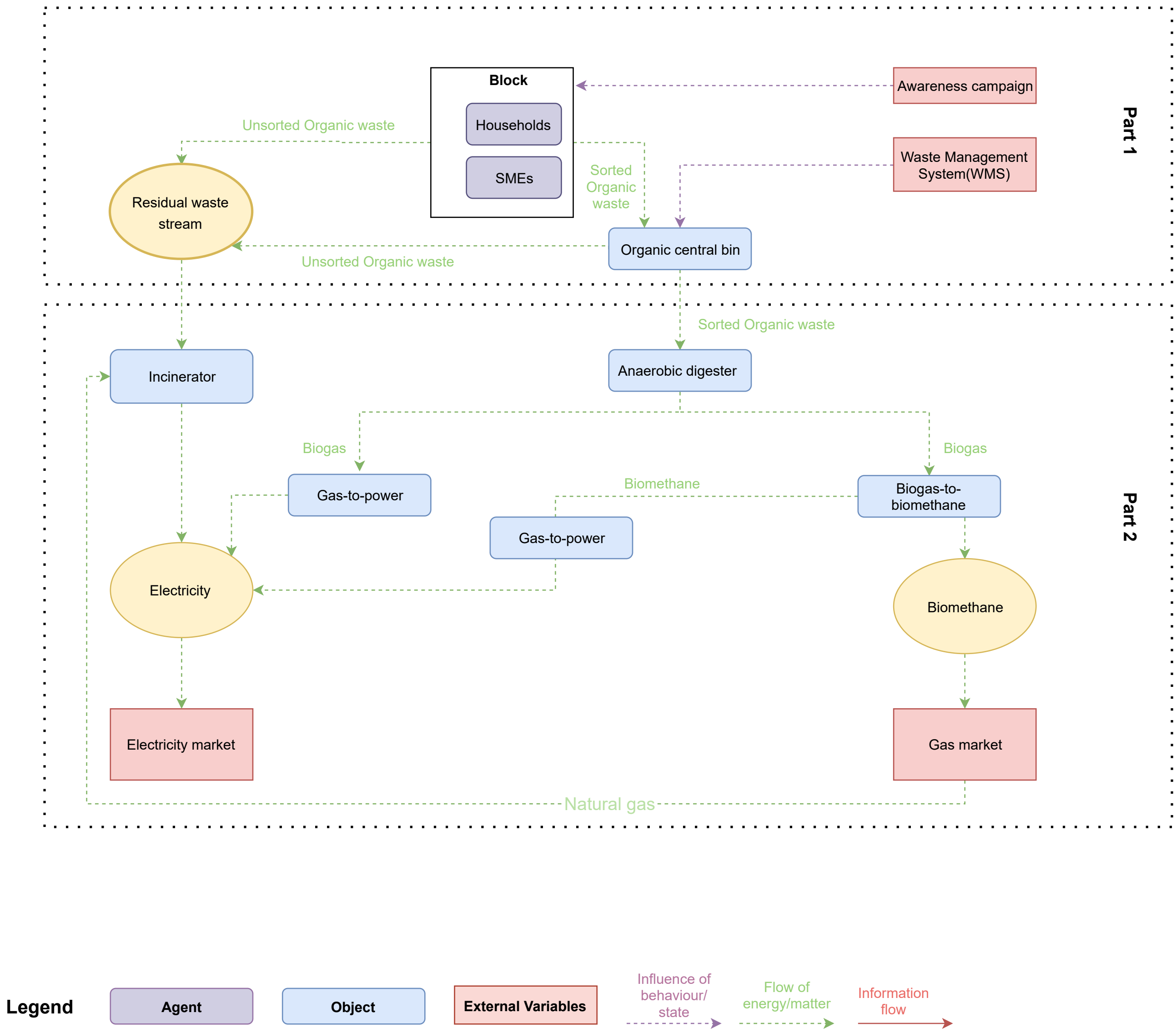
The next step after concept formalisation is *Model formalisation*. According Van Dam et al. (2013, p. 88), model formalisation is about establishing what an agent does and when does it do it. It about the describing the model narrative & the model logic.

In the next section an overview of the conceptual model is presented. After which the following sections address the steps: *Concept formalisation and Model formalisation* collectively. The last section addresses the *Software implementation, Model verification and Model validation.*

5.1 Overview of the conceptual model

The conceptual model is a high level description of the concepts and elements in a model. It is explained with the help of Figure 5.1. The diagram is divided into two parts. *Part 1* involves the interaction of the agents with the objects and external variables. The waste separation rate is the resultant output from these interactions. *Part 2* includes the WtE technologies used to process organic waste into usable energy. The resultant outputs in this part are: energy generated (kWh) from organic waste, net cost of processing organic waste to energy (€) and the CO_2 abated by generating & trading this energy in the energy markets.

Figure 5.1: Model conceptualisation



In *Part 1*, the households & SMEs form a block and are influenced by external variables such as the awareness campaign. These entities generate organic waste and based on certain factors they decide if they are going to separate their organic waste in their local bins (not shown in the diagram). Incase they don't then the waste is disposed off in the residual bin or the residual waste stream.This concept is elaborated in Section 5.4.1.

Once their local bins are full, the households & SMEs walk to dispose (& separate) their waste in the central bins. Based on factors intrinsic to the entities and they interactions with the central bin, they decide if they are going to separate their organic waste in the organic central bin. If they decide not to separate their waste, then they dispose the waste in the residual central bin (not shown in the diagram) or the residual waste stream. This concept is elaborated in Section 5.5

The two external variables awareness campaign & WMS influence the entities & organic central bin respectively. They are elaborated in Section 5.6 & Section 5.7

In *Part 2*, the different technological routes are depicted with help of WtE technologies.

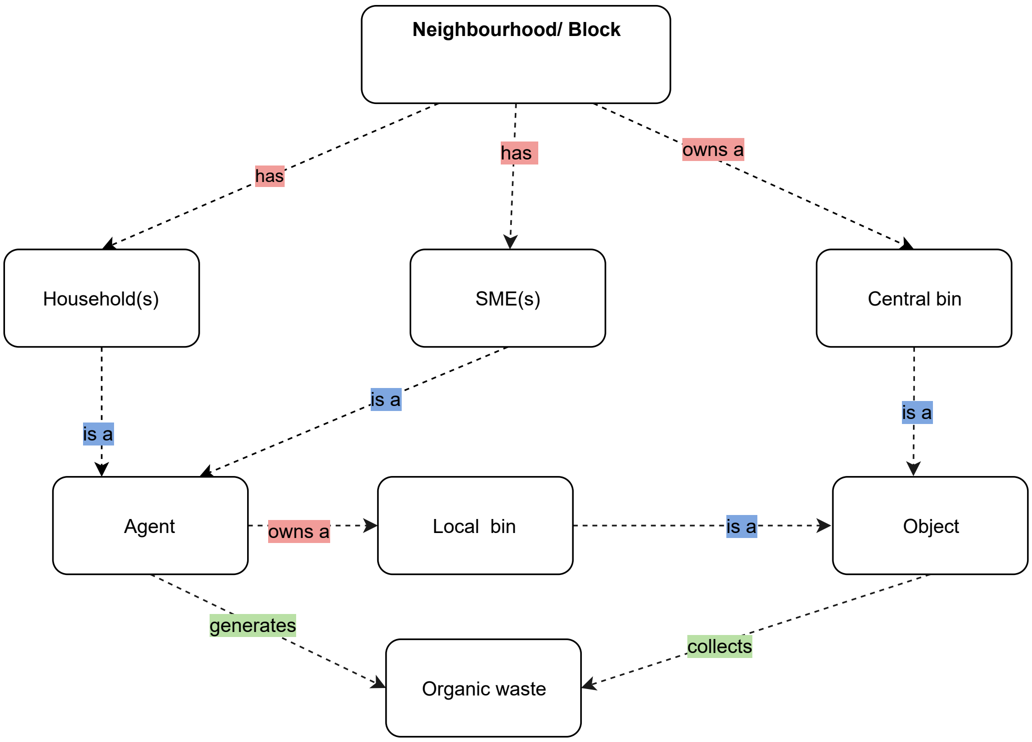
The technological route chosen is determined based on whether the organic waste is sorted correctly.

From the organic central bin, the sorted organic waste is transported to the anaerobic digester, while the unsorted organic waste ends up being transported to the waste incinerator. The incinerator, with a supply of natural gas, generates electricity from unsorted fraction of organic waste. The separated fraction of organic waste is processed by the anaerobic digester into biogas. The biogas obtained ends up be converted into biomethane or electricity. The electricity and biomethane generated is traded in the energy markets. This whole concept is explained in Section 5.8.

The ABM is primarily created to examine Part 1 because it helps capture the typical waste separation activity of households & SMEs and their interactions with other objects. Furthermore, it helps analyse the complex interactions of these entities with external variables and the organic central bin more closely.

5.2 Organic waste generation of a Block

Figure 5.2: Model ontology - 1



In the ABM, households & SMEs are classified as agents. Entities in ABM that are modelled to make independent decisions are known as agents (Van Dam et al., 2013, p. 79). A fixed set of agents form a neighbourhood or block.The number of agents in a block are assumed to depend on the central bin present in the block. In the previous chapter it is seen that in the case of Amsterdam (presumably also Haavenstad) the number is 100 agents (per block).

The central bin is classified as an object. An object is a software representation of a physical entity or a technical infrastructure, but unlike agents, they are are not capable of independent decision making. Agents tend to interact with objects to carry out certain actions. Each block owns one central bin for collecting the sorted organic waste and another one for collecting the residual waste.

Although it is important to note that the residual waste bin is not encoded in the model as an object. The interaction of the agent with the residual waste bin and the characteristics of the residual waste bin are not within the scope of this research. Also, the other types of waste collected in the residual waste bin are not included in the model as well.

Together the agents and central bin make up the block, as depicted in Figure 5.2. Furthermore, the figure depicts that an agent generates organic waste and owns a local bin.

The amount of organic waste each agent type generates per year is given in the previous chapter. In this model it is assumed that an agent generates waste 5 times a day , for 7 months. At each model tick an agent produces and looks to separate a fifth of its daily waste generation in its local bin, so at the end of 5 ticks the agent has produced its daily quota. The choice of 5 ticks make the agent interact with the local bin more often. This helps capturing the interaction more effectively. A higher number of ticks (or visits) is not expected usually by a person given the meal consumption in a day, while a lower number of ticks is not going to capture the interaction effectively.

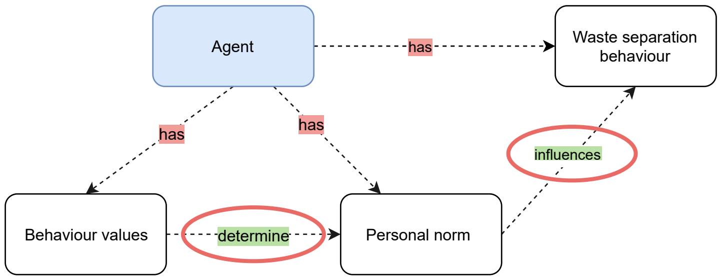
Subsequently, the waste generated daily by an agent is determined by diving the data about its yearly waste generation by 365 days.The total time period of each model run is 7 months or 1050 ticks (30 days x 7 months x 5 ticks) . The reason behind a short time duration is because there is a probability that the static parameters (behaviour values of agents) or subsystems (such as the Waste Management System) might undergo changes in the real world. Also, Wang and Deisboeck (2008) claimed an Agent-Based Model is too detailed to simulate over a longer duration due to the large number of parameters and rules. Although the interpretation of the term 'longer duration' may be different for each model, depending on the time scale. For example, the term 'longer duration' in a model studying evolution of a species may translate to some 10000 (or more) years. While in case of the model in this thesis, the term may imply a 2 to 10 years. Therefore, a sensitivity analysis is performed in Section 5.10.

Lastly, this organic waste generated by the agents is collected by the two objects of different characteristics and ownership. This is accomplished by the interaction of the agents with the objects. Before examining this interaction, it is important to describe the agents and their behaviour.

5.3 Agent behavior

In this section the narrative and logic behind determining the *Personal norm* & *Waste separation behaviour* of the agents is extensively described.An agent, as seen in Figure 5.3, has behaviour values, holds a personal norm and exhibits waste separation behaviour. The behaviour values of an agent determine its personal norm via the variables of the VBN theory. The personal norm of the agent plays a role in influencing its waste separation behaviour.

Figure 5.3: Model ontology - 2

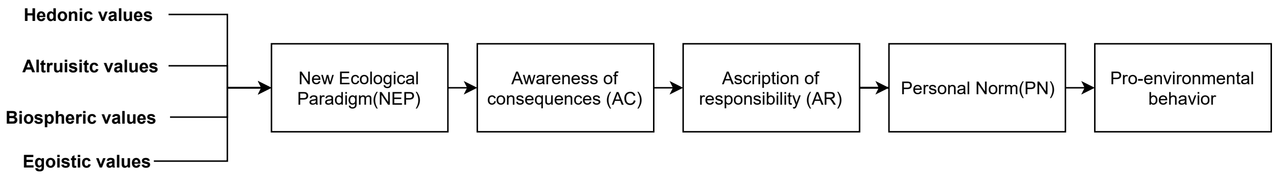


The agents in the model (Households & SMEs) go through certain decision making criteria to separate and dispose their organic waste.The decision making of these agents tends to be influenced by their waste separation behaviour , which inturn is dependent on the behaviour values of the agents. In order to examine this dependency VBN theory is employed.

The behavior of the agents in the model is based on the Value-Belief Norm(VBN) theory by P. C. Stern et al. (1999). As the three worded name suggests there are three types of variables in the theory- which are directly related to each other.Out of them, the behavior values of the agent serve as an input and proceed towards determining the other variables of the theory. The other variables being the:*New Ecological Paradigm (NEP), Awareness of Consequences (AC), Ascription of Responsibility (AR), Personal norm (PN) and Pro-environmental behavior*. Each of these variables are determined individually for each agent at the start of each model run and tend to remain constant (unless acted upon by environmental elements).

The relationship between the variables can be explain by Figure 5.4, where it is shown that each variable (except behaviour values) can be linked to the preceding variable. Furthermore, as mentioned in Section 3.1.1, the variables can be related to their preceding variable by a regression coefficient. The relationship between these variables and determination of their coefficient values is further discussed in Appendix E.

Figure 5.4: Value-belief Norm (VBN) model (P. C. Stern, Dietz, Abel, Guagnano, & Kalof, 1999)



There are four types of behavior values as per VBN the model: *Biospheric(b), Egoistic(eg), Hedonic(h) & Alustric(a)* and they usually determined by carrying out a specific survey known as Schwartz Value Survey(SVS) (Shalom H. Schwartz, 1992). There are multiple questions asked in this survey specific to respective behavior values, with the answer to each question having a six-point scale or nine-point scale (Shalom H. Schwartz, 1992; Shalom H Schwartz et al., 2012).

Based on the answers, the behavior values can be allocated a numerical value based on the scale. For example, a set of statements that portrays the values held by a person are shown to respondents. The respondents have to choose a rating based on how similar is the person in the statement to them. There can be six possible responses: 1 = not like me at all, 2 =

not like me , 3 = a little like me , 4 = somewhat like me, 5 = like me, 6 = very much like me (Shalom H Schwartz et al., 2012).

In the model the six-point scale is used to capture the ratings of the behaviour values. After the SVS is taken and analysed, the mean rating for each behaviour value of an agent is known, In the model, these mean values are scaled down by a factor of 6 and input in the model from a set of six numbers: *0, 0.2, 0.4, 0.6, 0.8, 1.0.* For example, a behavior value having a rating of 5 scaled down by a factor of 6 gives 0.833, for the sake of simplification and standardization this value is rounded off to 1 in order to use an input in the model.

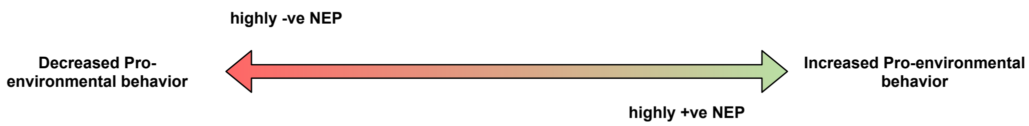
But to make sure that all the agents do not have the same input number for the all the behavioral values, there is a degree of randomization introduced in the model. This randomization is in the form of a normal-distribution, in which the input rating (ranging from 0 to 1) for the each of the four behavior values serves as the mean along with a standard deviation of 0.1. A standard deviation of 0.1 is chosen based on the value survey carried out by Namazkhan et al. (2019) for Dutch households.

Next, the behaviour values serve as an input to determine the New Ecological Paradigm (NEP), which is the next variable in the VBN theory.

$$NEP = 1.2 \cdot b + 1 \cdot a - 1 \cdot h - 1.2 \cdot eg \tag{5.1}$$

The New Ecological Paradigm (NEP) is a function of the four behavior values. The NEP value can be determined by Equation 5.1- whose formation is discussed in Appendix E. A positive NEP signifies that the alustric and biospheric values are higher. These values tend to be associated with high pro-environmental behavior. Conversely, a negative NEP signifies that the egoistic and hedonic values outweigh the former two values. Implying that the agents show decreased instances of pro-environmental behavior. Furthermore, the NEP indirectly determines the personal norm value of the agents while going through the different variables of the VBN theory.

Figure 5.5: Relationship between pro-environmental behavior and NEP



The remaining variables of the VBN theory are related to each other by a regression coefficient. Assuming the regression coefficient relating all the variables has a value of 0.5. This implies the next variable after NEP, accroding to VBN theory, AC has a value equal to *0.5 times the NEP*. Subsequently ,the next variable, AR is equal to *0.5 times the ac*. The value of the last variable, PN is equal to *0.5 times the ar*. The value can also be represented by the following equation:

$$PN = (\alpha \times AR).(\alpha \times AC).(\alpha \times NEP) \tag{5.2}$$

Although the value of the three regression coefficients linking the variables can be different. The value of the regression coefficients is determined by calibrating the model to behaviour values held by agents in Amsterdam and their waste separation %. This is discussed in Section 5.9.

5.3.1 Personal norm values and pro-environmental behavior

The PN value of an agent serves as a parameter to determine their pro-environmental behavior or more specifically in this thesis- the waste separation behavior. Furthermore, the personal norms values of the agents can be traced back to their behavior values or their NEP. An agent having a highly positive PN value would subsequently have a highly positive NEP value and a highly positive PN also implies that instances of agent showing pro-environmental behavior is higher.

Pro-environmental behaviour in the model is described by boolean values (TRUE/FALSE). When the value is 'TRUE' then the agent engages in pro-environmental behaviour (or waste separation behaviour).While when the value is 'FALSE' then the agent does not engage in pro-environmental behaviour (or waste separation behaviour).

In order to determine the conditions when the value is TRUE/FALSE, the distribution for a set of PN values have to be examined and a threshold value has to be identified. So when the PN value of an agent is equal to/greater than the threshold, then the waste separation behaviour is set to TRUE or in order words the agent would engage in waste separation.

Furthermore, it is assumed that agents with negative PN values tend to show a lower probability of waste separation behaviour. Similarly, a negative threshold PN value has to determined - lesser than which the probability of an agent engaging in pro-environmental behaviour is zero or FALSE

Therefore, it can be said that agents with positive pn values tend to show a higher probability of waste separation behaviour. At positive threshold PN value the probability of an agent engaging in pro-environmental behaviour is 1 or TRUE.

These two assumptions are based on literature, in which it has been shown that positive personal norm values may increase the probability of engaging in pro-environmental behaviour. Conversely, negative personal norms values may decrease the probability of engaging in pro-environmental behaviour (Davis, 2014; Ghazali et al., 2019).

The distribution of PN values can be generated by using different input values for the regression coefficients in Equation 5.2. The range of the input values for the three coefficients is given below

$$\alpha \Rightarrow [0.5, 0.6, 0.7, 0.8, 0.9, 1.0]$$
$$\beta \Rightarrow [0.5, 0.6, 0.7, 0.8, 0.9, 1.0]$$
$$\gamma \Rightarrow [0.5, 0.6, 0.7, 0.8, 0.9, 1.0]$$

Each of them can have 6 possible values ranging from 0.5 to 1.0.This range is similar to what is observed in literature (Ghazali et al., 2019; Lind et al., 2015). This results in 216 (6 x 6 x 6) possible combination of coefficient values.

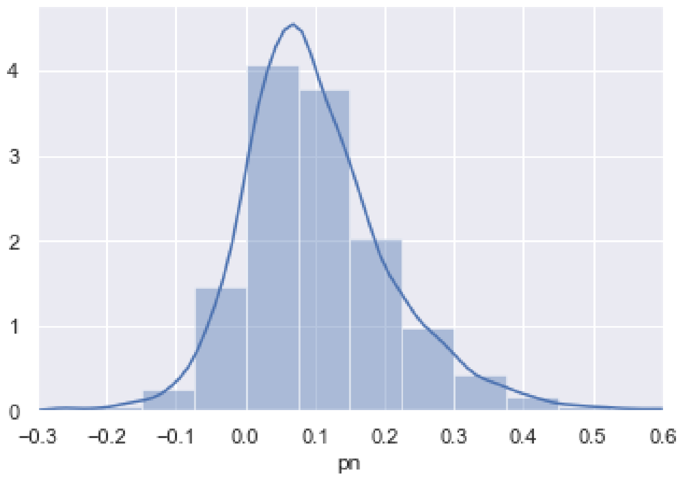
To get the distribution of the PN values of the agents, model runs for all 216 combinations are carried out. The result is presented in Figure 5.6 in the form of a normal distribution that shows the PN values of 60 agents.

The total number of agents in a block are 60, which is based on the current setting for Amsterdam. The choice of these variables is related to the model calibration, which is explained in Section 5.9.

Additionally, the behavioural values used as an input to determine the values in Figure 5.6, are based on the value survey conducted by Namazkhan et al. (2019) on Dutch households.

The resultant NEP of these behaviour values is 0.24.

Figure 5.6: Personal norm values of 60 agents



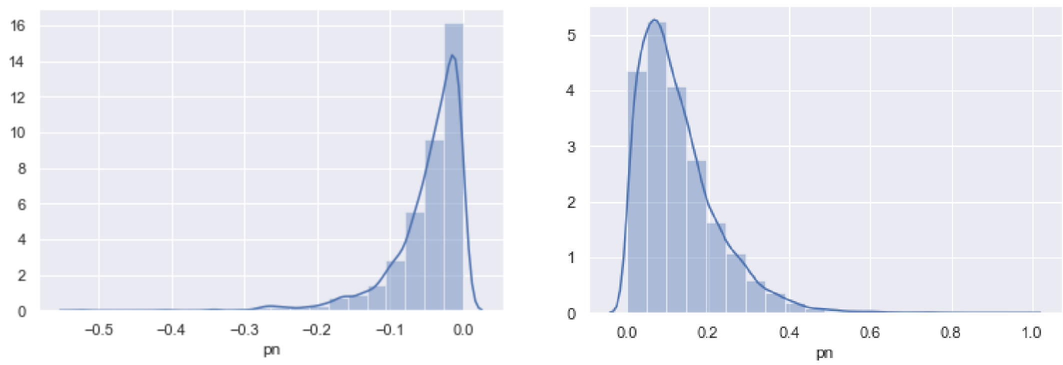
To determine the threshold values the distribution of PN values of the agents (Figure 5.6) is analysed by assuming that an agent has a 100% probability of showing pro-environmental behavior when its PN value is greater than the mean of the normal distribution shown in Figure 5.6.

Majority of PN values in the normal distribution (Figure 5.6) are greater than 0 and the mean of the whole dataset lies at 0.1. This value can be considered as a positive threshold PN value. Also, the reason behind more positive PN values is because the NEP value used as an input is positive.

This dataset is divided into two parts: Figure 5.7b contains the the positive PN values and Figure 5.7a contains the negative pn values. The mean of the positive pn values lies at 0.12, which also can serve as a positive threshold PN value.

The two positive threshold values can be allocated between households and SMEs. Given that waste separation behaviour of households tends to be more easily influenced by personal norms compared to SMEs (Scalco et al., 2017), the positive threshold PN value for households is set to *0.1*. While in case of SMEs it set to be higher at 0.12. This implies for a same PN value (lesser than the positive threshold) a household has a higher probability to engage in waste separation behaviour than a SME.

Figure 5.7: Distribution of the personal norm values



(a) Negative pn values

(b) Positive pn values

The Figure 5.7a contains the PN values of agents that are less inclined to show waste separation behaviour. The mean of negative PN value is -.0.04. Assuming -0.04 is the negative threshold value, then the all the agents having a pn value less than -0.04 would have zero probability of engaging in waste separation behavior.But this would mean that the model would be highly sensitive to the change in the egoistic and hedonic behavior values compared to biospheric & altruistic values.

To prevent this bias the negative threshold PN value for the agents is set at (-)0.01, equal to the positive threshold PN value. This makes sure the value for the waste separation behaviour is equally dependent on the four behaviour values.

To conclude, in this section the agent behaviour is examined with the help of VBN theory and its variables. Furthermore, the quantification of the VBN theory for this thesis research is discussed and the influence of PN values in determining pro-environmental or waste separation behaviour is analysed.

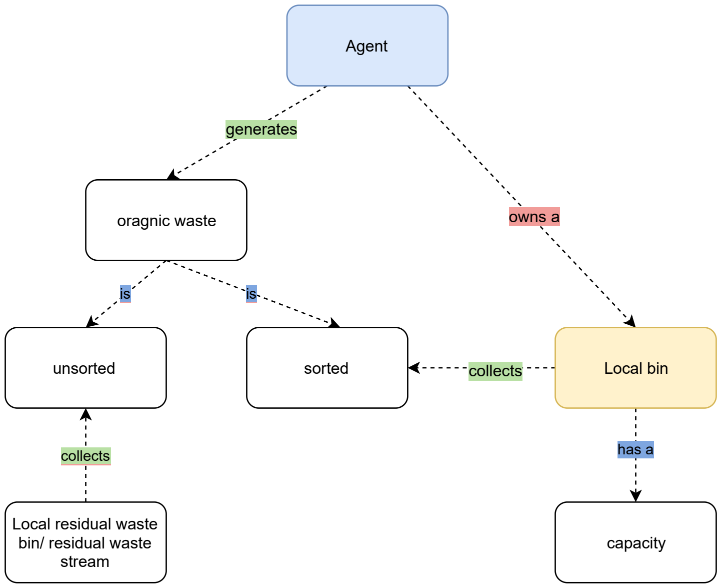
5.4 Waste separation

As mentioned earlier, the agents separate their organic waste first in their individual local bins and once their local bin is full, then they proceed to dispose or separate in the central bin that is meant for the whole block.

In the following sections the ontology of the model is further described and the narrative behind the waste separation carried out by the agents is explained.

5.4.1 Local waste separation

Figure 5.8: Model ontology - 3



In Figure 5.8, the ontology of the local waste separation in the model is depicted. From the figure it is seen that an agent generates organic waste, which is either sorted or unsorted. The local bin, owned by each agent, is an object which collects the sorted organic waste, until it reaches its capacity.

While the unsorted waste ends by being collected in the local residual waste bin/ residual waste stream. It is not modelled therefore it does not have any characteristics.

The waste separation carried out by the agent depends on its pro-environmental behavior, which in turn tends to depend on the personal norm value it holds (Mtutu & Thondhlana, 2016). If an agent 'shows' pro-environmental behavior at a particular instance or tick, then it will correctly separate its waste in a local organic waste bin of fixed capacity. Otherwise, it will dispose of the organic waste in the local residual waste bin.

The Pro-environmental Behaviour (PEB) is determined to be TRUE or FALSE depending on the PN value of the agent. If the PEB is TRUE then then the agent will separate its organic waste correctly in the local bin.If the PEB is FALSE then the agent will dispose its organic bin in the residual waste bin. The TRUE/FALSE condition is determined by checking the PN values of the agents with the threshold values that is discussed in the previous section.

But incase the PN of the agents lie between the positive and negative threshold values then in that case the probability of the agent is determined based on a function to determine the probability *P(x)* of a house engaging in PEB.

$$P(x) = (5 \times pn) + 0.5 \tag{5.3}$$

This function is determined by solving the following system of equations. In the first equation the probability of showing PEB is 1 (when pn = 0.1) and in the other it is 0 (when pn = -0.1).

$$1 = pn.x + c \quad (1)$$
$$0 = pn.x + c \quad (2)$$

Similarly, the function to determine the probability *P(y)* of a SME engaging in PEB is computed:

$$P(x) = (4.54 \times pn) + 0.45 \tag{5.4}$$

By examining Equation 5.3 & Equation 5.4, it is observed that for a same PN value, the SME shows a lower probability of engaging in PEB. This is based on hypothesis made earlier that SME are not affected by equally by personal norms.

Based on the functions and threshold values the probability distribution for determining the PEB of the agents is presented in Table 5.1. When the probability is 1 then the PEB is TRUE and conversely when it is 0 then it is FALSE. If the value lies in between it either be TRUE or FALSE.

Table 5.1: Probability distribution of PEB

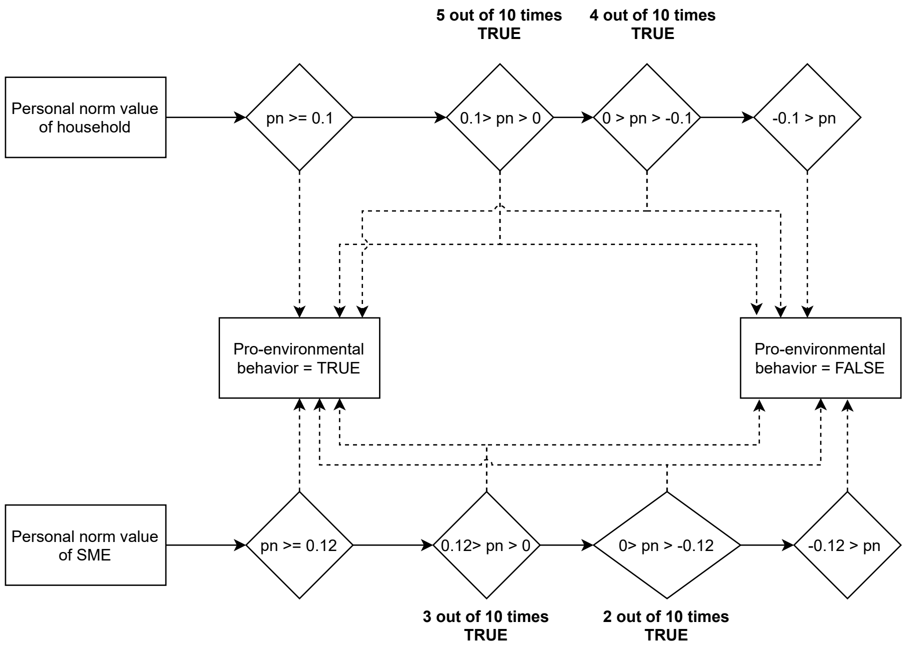
House	**pn≥ 0.1**	**0.1 >pn >-0.1**	**pn≤ -0.1**
P(x)	1	(5 * pn) + 0.5	0
SME	**pn≥ 0.12**	**0.12 >pn >-0.1**	**pn≤ -0.1**
P(y)	1	(4.54 * pn) + 0.45	0

An agent whose pn value lies between the positive and negative threshold values has its PEB determined based on a probability function that is dependent on personal norm values of the agent.

For example, a household with a PN value of 0.08 will have a P(x) value of 0.9 according to Equation 5.3. This implies that the household has a 90% probability of engaging in PEB.

The operation of separating the organic waste is visualised in Figure 5.9. As seen in the figure, if the PEB is TRUE then the organic waste is sorted in local bin and when it is FALSE the waste ends up the residual bin. Each agent has a local bin as an object, which is of certain capacity. For households a local bin of 25L is considered while for SMEs it is thrice as big owing to fact that they produce more organic waste. The capacity of the residual waste bin is not captured in the model and it has no influence on the behavior of the agents.

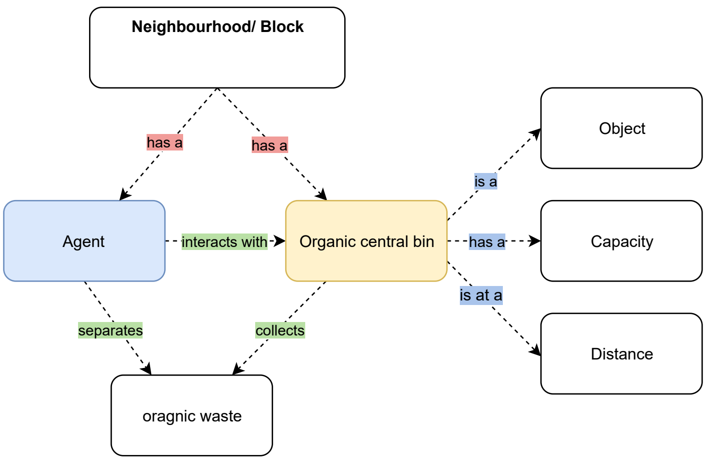
Figure 5.9: Algorithm for local separation of organic waste



If the PN value of agent lies between the threshold values then the probabilities for the PEB being TRUE for them is shown in Figure 5.9.

5.5 Disposal and separation of waste centrally

Figure 5.10: Model ontology - 4



The agents can separate their organic waste in the local bins until these local bins reach their predefined capacity. When that happens the agent recognises that and proceeds to decide whether it would like to walk to the central bin allocated for the neighborhood block it resides in and dispose the organic waste accumulated in its local bin correctly(or not).

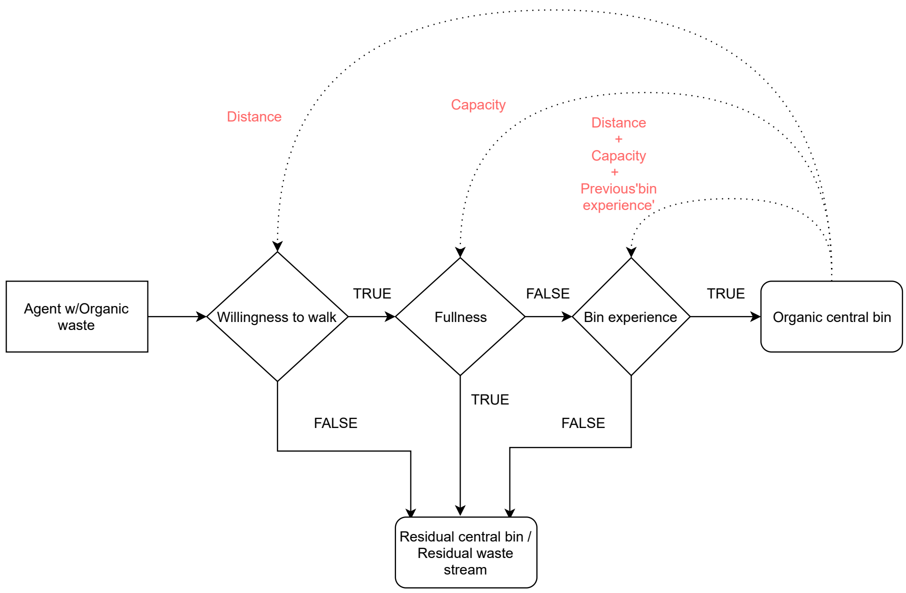
The central bin is an object in this model and is classified into two types: Organic central bin and Residual central bin. The characteristics of the 'Residual central bin' are not captured in the model. It makes up for the residual waste stream which also consists of the the local residual bin.

The ‘Organic central bin’ is characterised by its capacity and distance from the agent. This type of bin is meant for collecting the organic waste that is correctly separated by the agents.

Based on the interaction of the agent with the ‘Organic central bin’, it is determined whether the agent chooses to correctly to separate its waste. The decision making steps for the agent are given in Figure 5.11.Also, as seen in the figure the characteristics (in red) of the ‘Organic central bin’ influence the decision making steps.These would be discussed further in the next section.

The three decision making steps that each agent has to go through to to separate its organic waste centrally are: *Willingness to walk, Bin experience and Fullness*. Each step has two outputs (TRUE or FALSE), based on which an agent will choose whether to separate its organic waste correctly or not.

Figure 5.11: Decision making for separating organic waste centrally



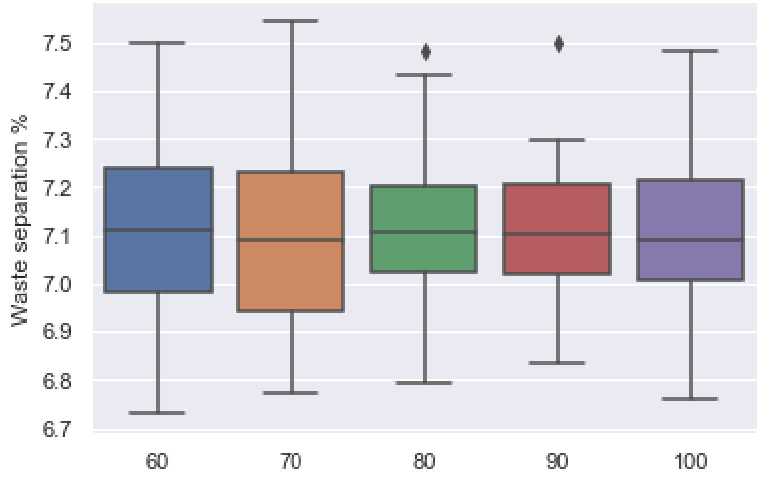
Firstly, the agent proceeds to decide if it willing to walk to the central bin or not. This depends on the distance of the central bin from the agent, which is set to a random value between 0 to 160 m, for each individual agent at the start of the model run. If the distance of the agent from the central bin is less than(equal to) 75 m then the willingness to walk is TRUE. Conversely, if it is more than 75 m then the willingness to walk is FALSE. In that case the agent would dispose the organic waste collected in its local bin in the residual waste stream.

This value of 75 m or the maximum distance an agent is willing to walk is chosen based on literature discussed in the previous chapter. To validate this choice, a sensitivity analysis is performed for a range of maximum distance values in Section 5.10 . According to it, the waste separation rate is not sensitive to maximum distance values greater than 60.

In a situation if the distance of the bin from the agent is greater than 75 m, but its personal norm value is greater than the agent’s positive threshold value then there is a 90% probability that the willingness to walk is TRUE. Or in other words, 9 times out of 10 the agent is willing to walk to the bin irrespective of the distance.

This is based on an assumption. Therefore, a sensitivity analysis is performed for different probability values and is shown below. Based on Figure 5.12, it is seen that waste separation rate is not very sensitive to the probability value chosen. Thus, it can be said that the choice of the assumed value does not influence the model output significantly.

Figure 5.12: Waste separation vs Probability of walking to the bin



Secondly, the agent proceeds to check if the central bin is full. If it is full (or the variable 'full' is TRUE) then the agent disposes the organic waste from the local bin to the residual waste stream.

Lastly, the bin experience an agent has depends on the distance of the bin from the agent and the available capacity of the bin. Under two conditions the bin experience is TRUE: If the distance of the bin from the agent is between 50 to 100 m (or less); Second, if the available capacity of the central bin is more than or equal to 20% of its capacity. Furthermore, if the agent has positive bin experience (or its variable 'bexp' is TRUE) then its next experience to the central bin is assumed to be positive as well.

In conclusion, this section discussed about the narrative and algorithms about the decision making surrounding the waste separation activity carried out by agents. Beyond this, the agents do no not interaction with the WtE technologies, but the amount of waste separated by them may impact the energy output of from the WtE technologies. In the next section the variation of the central bin characteristics is discussed, which can influence the agent interaction.

5.6 Structural intervention: Waste Management System

In the model the waste management system is mainly defined by 'Organic central bin', its capacity and frequency of waste collection from the central bin. This 'Organic central bin' along with the 'Residual central bin' is assigned to collect waste from the agents of a neighbourhood block and to transfer this collected organic waste to waste-to-energy(WtE) facilities.

The capacity of the 'Organic central bin' has two input values: 240 Litres and 480 Litres, which can be set before the start of a model run and remains constant. capacity and its collection frequency or bin clearing frequency. This is for the central bins of all the blocks in the city and can be specified before running the model.

The frequency of waste collection or the fixed time at the 'Organic central bin' is cleared can be set before the start of a model run. Again, two choices are presented: waste collection once a week and waste collection once in two weeks. Also, this input value applies to 'Residual central bin' and it cleared at same time as the 'Organic central bin'.

Lastly, in the model it is assumed that the waste collected from the central bins is transported to WtE facilities but the whole transportation operation is not captured in the model. Only the cost of transporting of waste is captured in the model, which differs based on the input value for the frequency of waste collection.Transportation costs for waste collected once in two weeks is deemed to be cheaper per tonne of waste than waste collected every week.

5.7 Informational intervention: Awareness campaigns

The informational strategy of '100-100-100' discussed in Section 4.7.3 is captured in the model as an informational intervention. The reason behind considering this intervention is because it has already been tried and tested in the Netherlands. It is well within the time period of the model and suited for block size in the model. Also, the study on this intervention by Van der Werff et al. (2019) links the intervention to the waste separation behavior via the variables of the VBN theory. Furthermore, they measure the influence of this intervention on the variables of the VBN theory, which makes it possible to capture and test in this model.

Given that the personal norm values of the agent tend to dictate their waste separation behavior therefore the informational strategy is assumed to affect all the personal norm of the agent but rather unequally. The personal norm values of SMEs are assumed to be doubly affected by the intervention as compared to households. This is because they are more sensitive to descriptive norms (Scalco et al., 2017).

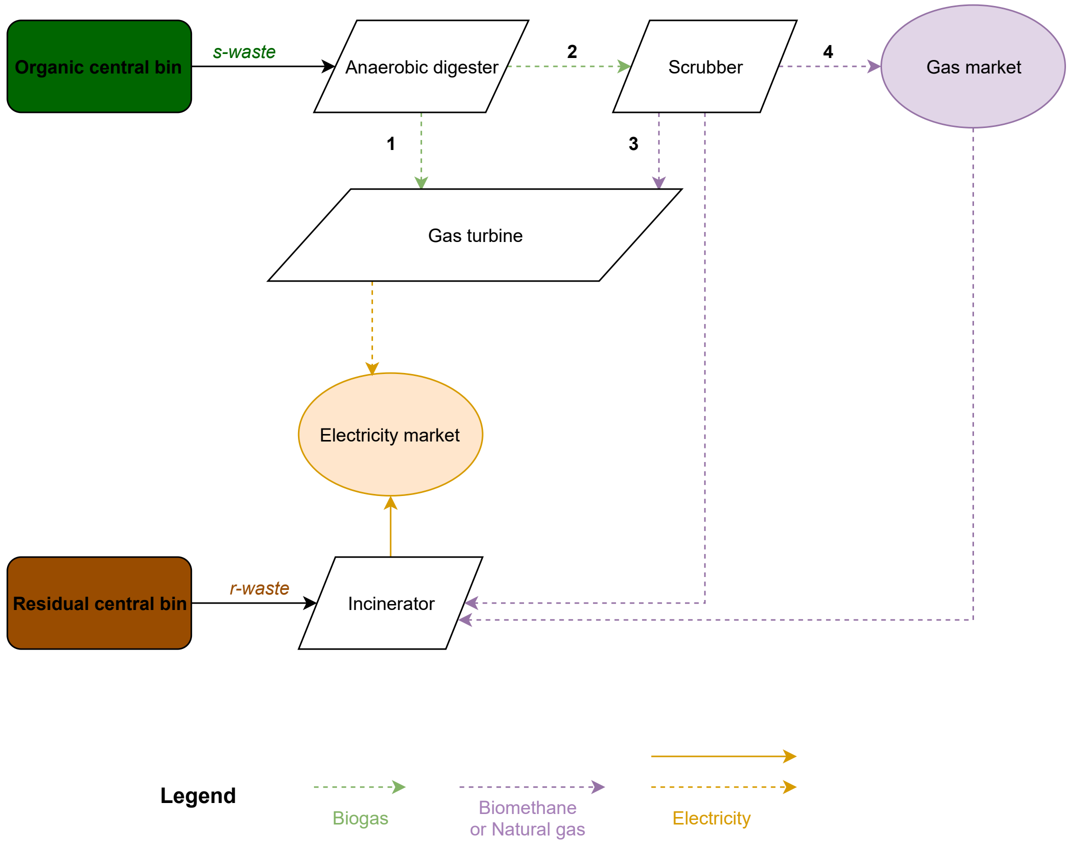
But these personal norms values are indirectly influenced by the policy via the Awareness of consequences($Awoc$) variable. The influence of the intervention on the Ascription of responsibility($Ascor$) is not considered because according to Van der Werff et al. (2019) it is not that significant compared to the other variables.

The informational strategy is implemented in the model for the whole model run. At the end of each model run nearly doubles the PN value of the block or the average PN value for a set of agents.

5.8 Conversion of organic waste to energy

The organic waste generated by agents is processed into energy by waste to energy technologies. The path to convert the organic waste into energy hugely depends if the waste is correctly separated or not. Or which bin type does the organic waste end up in.

Figure 5.13: Reprentation of Havenstad in the model



Waste that is not separated correctly (or *r-waste*) has a fixed path towards incineration. The process through which electricity is generated and sold in the Dutch electricity market.

Waste separated correctly (or *s-waste*) is taken to the anaerobic digester to produce biogas.Based on the model inputs, the anaerobic digester can either dispatch the biogas produced to the gas turbine(path 1: See Figure 5.13) turbine or to the scrubber(path 2). Another input from the model is for the scrubber to decide whether it would dispatch the biomethane generated to the gas turbine to get electricity or sell it in the gas market.

The path-dependent waste to energy conversion is determined by choosing one of the three options, each of which represent a path as depicted in Figure 5.13.

The first option is 'Biogas to electricity' (path 1), second is 'Biogas to biomethane' (path 2 and path 4) and the third being 'Biomethane to electricity' (path 2 and path 3).

Also, another important thing to note is that certain % of the biomethane is supplied to incinerator to combust the organic waste that ends up in there. If this option is not selected in the model input then it is assumed that the incinerator buys the gas from the market.

5.9 Model calibration and verification

The model is calibrated to the socio-demographics and waste separation activity observed in Amsterdam. The purpose of calibrating the model is to determine the three regression coefficients.

Based on Equation 5.2 and relationship between PN value and waste separation behaviour, it can be deduced that the waste separation is proportional to the three coefficient values.

$$Waste\ separation \approx f(\alpha, \beta, \gamma)$$

Increasing the coefficient values, increases the instances of engaging in waste separation behaviour. This may lead to an increase in the waste separation rate, based on the characteristics of the WMS.

The coefficient values are found out by conducting a parameter sweep, whose procedure is described in Appendix E. Parameter sweep involves varying the value of a parameter within a certain range and examining its output on the system. In this case, the value of the three coefficients (α, β, γ) is varied individually from 0.5 to 1.0 (with an increment of 0.1) and the resultant waste separation rate is measured.

In the procedure described in Appendix E, the waste separation measured during the parameter sweep is compared to that of Amsterdam. Based on which it is found that for $(\alpha, \beta, \gamma) = 0.5$, the waste separation rate is equivalent to that observed in Amsterdam.

This value of the three coefficients is used in the experiments carried for the case of Havenstad to help determine the waste separation rate.

5.9.1 Model verification

Model verification is to check that all concepts, entities and their relationships discussed so far are correctly translated to the model code (Van Dam et al., 2013, p. 98).

As per (Van Dam et al., 2013) there are four main parts to verify Agent-based Models(ABMs): *Recording and tracking agent behaviour, Single-agent testing, Interaction testing in a Minimal Model & Multi-agent testing.* Due to time constraints only the first part (*Recording and tracking agent behaviour*) is covered in this thesis.

Here, the model verification specifically checks the internal processes involved with the agent behaviour and their waste separation activity. It is presented in Appendix F. Based on the verification analysis the internal processes and commands operate as intended.

Also, the link to the model code is given in Appendix F.

5.10 Sensitivity analysis

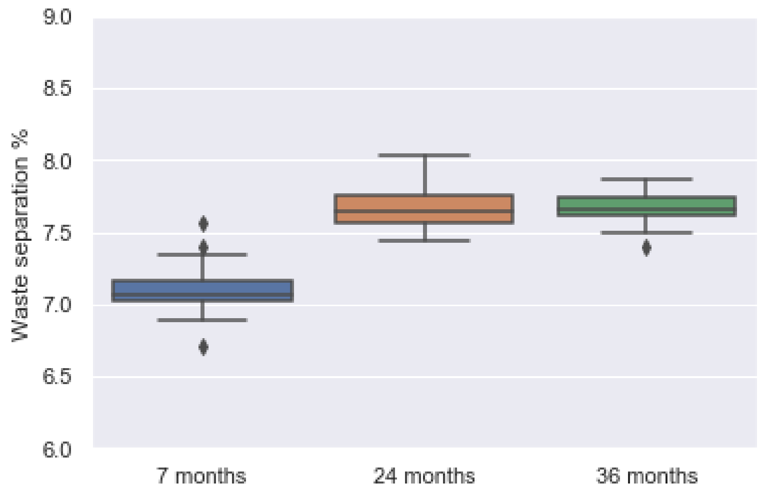
A sensitivity analysis is carried out to ascertain the extent to which the model output is dependent on some of its input parameters. The objective of conducting a sensitivity analysis here is that it helps examine the influence of parameters that are not varied in the experiments, on the model output. Also, it examines the influence of assumptions made on the model output.

In the sensitivity analysis presented in this section, only one model output is measured, i.e. waste separation %. This is because the input variables only directly effect this model output. Moreover, rest of the model outputs are determined based on the waste separation %.

The sensitivity analysis conducted looks at two aspects: *Influence of model duration on waste separation* & *Influence of distance on waste separation.*

The default model duration is 7 months or 1050 ticks. Or in other words one model run is equal to 1050 ticks Based on this model duration the experiments are carried out. In Figure 5.14, the waste separation % is measured by varying the duration of each model run.Furthermore, each model run is repeated 30 times to account for the randomness.

Figure 5.14: Waste separation vs Model duration



The waste separation rate increases with the increase in the model duration upto to 24 months. Further increase to 36 months, does not increase or change the waste separation %. Instead the spread of the datavalues decreases. This implies the waste separation % does not vary once the model duration exceeds 24 months.

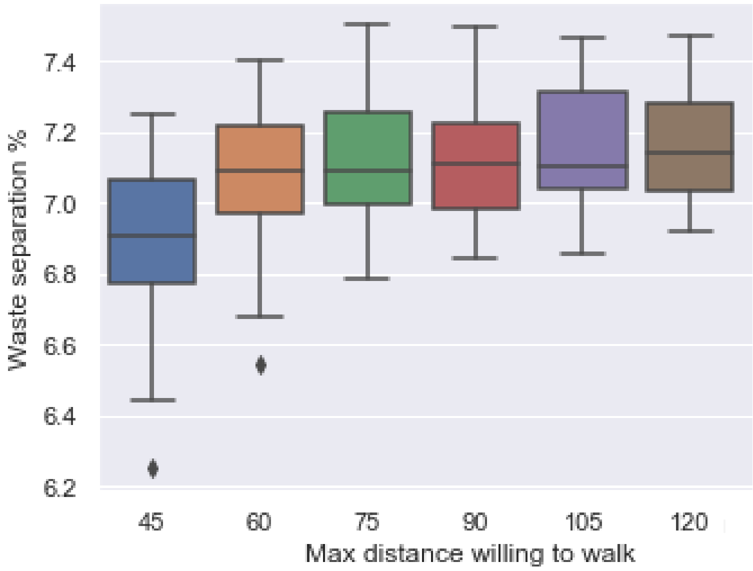
Furthermore, the reason for this increase in waste separation rate is due to the defination of the model output or indicator, Waste separation %. *Waste separation %* is the ratio of the organic waste in the central organic bin to the total organic waste generated by the agents in a single model run. But this indicator does not account for the organic waste separated in the local bins of these agents. As the duration of the model increases, the agents get an opportunity to separate the organic waste collected in their local bin correctly in the organic central bin. Therefore, the waste separation rate increases with increase in the model duration.

In Appendix G, the influence of model duration on the three model KPIs[1] is examined. Based on which, it is observed that increase in model duration increases the energy obtained from one tonne of OFMSW and the cost of generating per kWh of energy from OFMSW respectively. But this increase is not significant to influence the research conclusion from a qualitative perspective.

Next, the influence of distance on the waste separation is presented in Figure 5.15. The parameter measured here is the maximum distance that an agent is willing to walk to the central bin[2]. This concept is discussed in Section 5.5, where it forms a part of the decision making criteria an agent uses to separate its waste in the organic central bin. The default value for the parameter in the x-axis is 75 m, this is based on literature discussed in Chapter 4.

[1]The three model KPIs are introduced in the start of the next chapter
[2]The central bin can be placed at a maximum distance of 160 m. This number is randomized for each agent.

Figure 5.15: Waste separation vs Maximum distance willing to walk



By examining Figure 5.15, it is seen that waste separation rate increases with the increase in the maximum distance that an agent is willing to walk. Although the increase is not linear. The waste separation increases from when the maximum distance is increased from 45 to 60 m. Any further increase in the distance does not increase the waste separation rate significantly. Thus, it can be said that the choice of the default value does not influence the model output significantly.

5.11 Model validation

Model validation is to check if the "right" model is made to answer the research questions. Also, to evaluate if the outcomes of this model are convincing (Van Dam et al., 2013, p. 127).

Unlike the traditional view on validation, the validation of an Agent-Based Model does not aim to compare the experimental results with that of the real world (Van Dam et al., 2013, p. 127). This is because traditional methods of validation do not always apply to Agent-Based Models, specially those models that focus on evaluating 'what-if scenarios (Louie & Carley, 2008; Van Dam et al., 2013).

Instead the aim of model validation in this research is to check if the model outcome is convincing for the different sets of experiments that are carried out. Furthermore, it is not the KPI values or the quantitative results that are necessary to be validated, but instead it is the *insights* gained from the results.

According to Van Dam et al. (2013, p. 127), there are four methods of validating an ABM: *Historic replay, Validation through expert consultation, Literature validation and Model replication*. In this study, expert consultation and literature are used a source of validation. Using these two methods, the model results are validated in Chapter 8.

6. Experimental setup

In this chapter the experiments carried out in the model and the Key-Performance Indicators (KPIs) that evaluate these experiments are defined & discussed. The first section (6.1) looks at the KPIs. Section 6.2 lists the experiments and their relevance to the sub-questions. From Section 6.3 to 6.8 the experiments are described in detail. The chapter ends at section 6.9, where the repetition of the model runs is discussed.

6.1 Model KPIs

Key-performance indicators or *KPIs* represent the key outputs of a model that are needed to answer the research questions. The model updates the KPIs at fixed intervals during the model run. These fixed intervals occur whenever the central bin is cleared in a model run. The three KPIs are listed below:

KPI 1 Energy generated per tonne of waste (KWh/ tonne)

KPI 2 (Net) Cost of generating 1 kWh of energy (€/ kWh)

KPI 3 (Net) Cost of abating 1 kg of CO_2 (€/ kgCO_2)

KPI 1 is measured by dividing the total energy (or electricity) generated from: a)incinerating the residual OFMSW and b)the biogas(or biomethane) obtained from the source separated OFMSW, by the total OFMSW generated by households and SMEs in a model run. This KPI provides a measure of the energy that can be obtained from per tonne of OFMSW.

KPI 2 is measured by dividing the cost of processing per tonne of OFMSW into usable energy, by KPI 1. The cost of processing is the operations costs of the WtE technologies minus the revenue generated by them in the energy markets. KPI 2 measures the cost of generating 1 kWh of energy from per tonne of OFMSW. With the help of which it provides insights on the economics of power generation.

KPI 3 is measured by dividing the the cost of processing per tonne of OFMSW into usable energy, by the CO_2 abated from using this energy. The energy generated from OFMSW displaces the energy obtained from gas-fired power plants or the combustion of natural gas. The avoided CO_2 emissions from displacing per kWh of energy is the CO_2 abated.KPI 3 measures the cost of abating 1 kg of CO_2 from the energy generated per tonne of OFMSW. By doing so, this KPI provides insights on the economic efficiency of abating CO_2 by generating electricity from OFMSW.

Apart from these three KPIs, in certain instances the waste separation(%) is studied as well. In the model the waste separation % is measured by diving the total OFMSW separated at the central organic bin, by the total OFMSW generated by households and SMEs in a model run.

6.2 Experimental design

To answer the research questions given in Chapter 1 a set of experiments are carried out in the ABM. The experiments are listed below:

Experiment 0: Base scenario

Experiment 1: Urban planning

Experiment 2: Awareness campaign (Informational intervention)

Experiment 3: Waste Management System (Structural intervention)

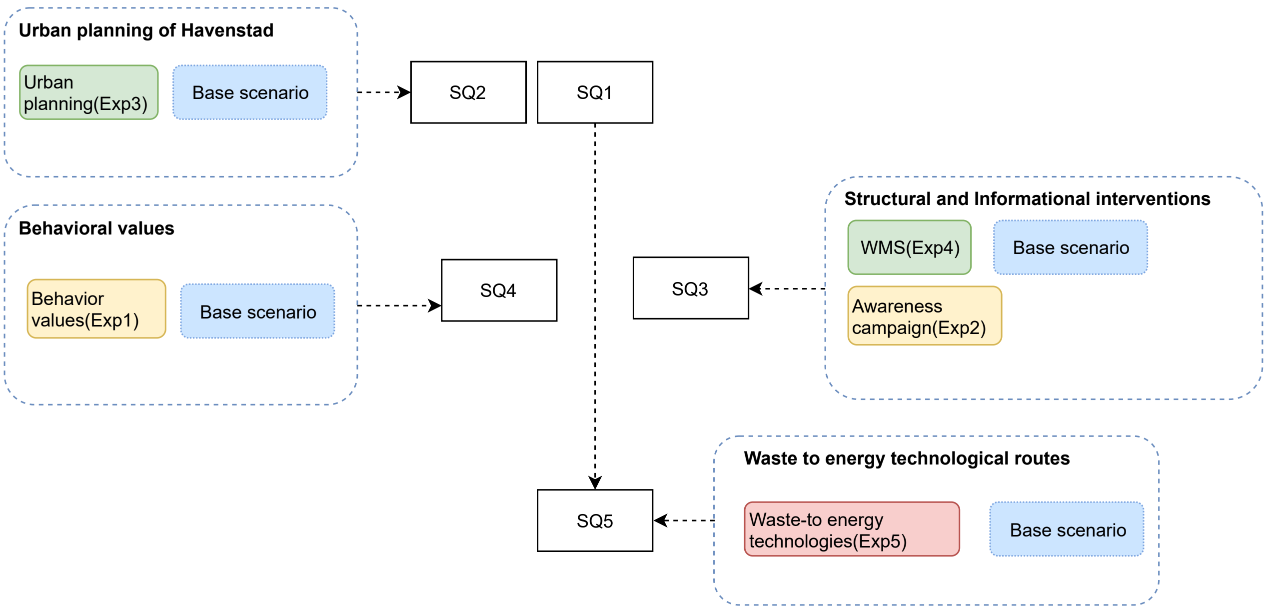
Experiment 4: Behaviour values

Experiment 5: Waste-to-energy technologies

The experiments are designed and represented by the model parameters that are varied before the start of a model run. Most of the parametric values for the experiments are chosen based on the empirical data and literature discussed in Chapter 4 and the data & opinions gathered from experts (see Appendix C).

In Figure 6.1, each experiments carried out is allocated to a theme. Together, under a theme, they help answer a particular sub-question. In following sections of this chapter, the experiments, their model parameters and purpose are discussed.

Figure 6.1: Allocation of experiments to research questions



6.3 Base scenario

The base scenario or baseline scenario is a benchmark to "depict a future state of society and/or environment" in which no interventions or changes are implemented (EEA Glossary, n.d.).The experimental results obtained for the base scenario would be used a reference to compare with the results of the other experiments

In this case the base scenario depicts approximate planned setup of Havenstad, which is described with help of the model parameters and its values in Table 6.1.

Table 6.1: Parametric values for baseline scenario

Parameter	Value	Parameter	Value
Biospheric value	0.4	Number of houses (per block)	50
Altruistic value	0.4	Number of SMEs (per block)	50
Hedonic value	0.4	Size of central bin	240 (L)
Egoistic value	0.2	Collection frequency	once in two weeks
Technological route	Biogas to electricity	% of single bed room houses	5
Awareness campaign	No	% of two bed room houses	35
% of three bed room houses	38	% of four bed room houses	22

In the base scenario the fully completed city of Havenstad (or uptil Phase 4) is captured. The waste management system of Amsterdam is implemented here and the source separated organic waste is converted into biogas which inturn is used as power source. The four behavioral values for the households and SMEs of Havenstad are set based on the Schwartz value survey conducted by Namazkhan et al. (2019) on about 1400 Dutch households. But they are subject to change in future when an actual value survey is carried out for the future households and SMEs of Havenstad.

6.4 Urban planning

The experiment examines the effect of urban planning of Havenstad on the waste to energy system that is modelled. The results of this experiment are of interest to a stakeholder of Havenstad (See Appendix C).Furthermore, the results help answer sub-question 2.

The urban planning of Havenstad in this experiment is defined by *two* sub-experiments: distribution of household types in a neighbourhood block(Exp 3a) and ratio of households & SMEs in a block(Exp 3b)

In Table 6.2 the parametric values for the three sub-experiments and their respective runs are given.The parameters whose values are varied for each sub-experiment are highlighted with red boxes.

Table 6.2: Parametric values for experiment 1

	single_bed (%)	two_bed (%)	three_bed (%)	four_bed (%)	number_houses	number_smes
Exp 3a						
1	55	18	18	9	50	50
2	5	55	28	12	50	50
3	5	28	55	12	50	50
4	5	20	20	55	50	50
Exp 3b						
1	5	35	38	22	70	30
2	5	35	38	22	30	70

In each of the four runs carried out in Experiment 3a, a household type is assumed to form a majority or 55% of the total distribution of households. The distribution values for the other household types for that particular run are approximately scaled down according to the household distribution in the baseline scenario (i.e.values in white cells in the first four columns of Table 6.2).

Experiment 3b involves two types of runs. In the first run the number of households form a majority, which is assumed to be 70% of the total agents in a block(or 70 households). The remaining are the SMEs. For the second run these values are interchanged.

The selection of these values are based on the data collected from a interview (See Appendix C).

From this experiment the possible insight is that with the % increase in household types with more inhabitants, the waste separation rate of the block will decrease.

Also, it is expected that having a higher number of SMEs in a block would result in higher electricity generation per tonne of OFMSW. This is due the fact that SMEs generate more organic waste and tend to separate their waste less often as compared to households. Thus, a high amount of waste ends up being incinerated.

6.5 Awareness campaigns

The second experiment is about evaluating the influence of awareness campaign, which is an informational intervention, on the base scenario. The results of this experiment help partially answer sub-question 3.

The awareness campaign described in Section 4.7.3 is captured in the model and it aims to double the personal norm values of the agents during the course of a model run (i.e. households & SMEs).

It is expected that the setup of awareness campaigns would increase the waste separation % . But results of the KPI values are highly dependent on the waste to energy technology employed for processing source separated OFMSW.

6.6 Waste Management System

This experiment aims to provide insights on the role that a waste management system can play on the energy recovered from the OFMSW. Furthermore, the results of this experiment help to partially answer sub-question 3.

The waste management system, as described in Section 5.6, deals with collection and transportation of organic waste to waste-to-energy facilities. It is implemented in the model as a structural intervention.

The waste management system for Havenstad is described by *size of the central bin* and the *frequency of waste collection from the central bin*. In this experiment (i.e. Experiment 3), these two parameters of the WMS are varied.

There are two standard central bin sizes of 240 Liters and 480 Liters for the organic central bin that can be chosen in the model. Furthermore, it can be chosen to clear the central bins (organic & residual central bins) 'once a week' or 'once in two weeks'. These values are assumed based on the empirical data available about the waste management system in Amsterdam.

Each of these parameters have two values and all possible combinations for these parametric values are tested in the model, resulting in a total of 4 combinations or runs.

Additionally a central bin size of 3000 L is considered for the subsequent experiments. The reason for considering a larger bin capacity is that it helps prevent the limitations posed by the organic central bin on the waste separation activity of the agent. One of the limitations could be that the central bin may fill up faster due to an quick 'overflow' of organic waste. Also, the waste management expert in the municipality mentioned the possibility of this phenomenon (Personal communication with expert, February 28, 2020: See Appendix C.2.2).

The organic central bin size of 3000 L is decided based on the average instance of an agent encountering a full organic central bin. For example, if the average instance has a value of 2, then it implies that the an agent, in average, can encounter a full organic central bin twice during a model run.

A set of model runs are carried to examine the influence of the bin size on previously mentioned indicator[1]. The values of this indicator is plotted in Figure 6.2. By examining the line plot, the organic central bin size of 3000 L is chosen because the average instance of an agent encountering a full bin is close to zero.

[1]The model runs are carried out for the baseline conditions described in Experiment 0

Figure 6.2: Evaluation of organic central bin size

6.7 Behavioral values

By carrying out Experiment 4 and its runs, the impact of the four behavioral values on waste separation and subsequently the energy obtained from Organic Fraction of Municipal Solid Waste (OFMSW) of Havenstad can be studied and analysed. Furthermore, the results of this experiment would help answer Sub-question 4 and would highlight the importance and role of the behavioral values is obtaining energy from waste.

In this experiment the numerical values for the four behavioral values are varied from that of the base scenario. There are a total of six runs that are carried out in this experiment(Table 6.3)

Table 6.3: Experimental runs for different behavioural values

Run	**Biospheric**	**Altruistic**	**Hedonic**	**Egoistic**	
1	1.0	0.2	0.2	0.2	Highly Biospheric value
2	0.2	1.0	0.2	0.2	Highly Altruistic value
3	0.2	0.2	1.0	0.2	Highly Hedonic value
4	0.2	0.2	0.2	1.0	Highly Egoistic value
5	0.8	0.8	0.2	0.2	Pro-environmental
6	0.2	0.2	0.8	0.8	Not-so-environmental
7	0.4	0.4	0.4	0.2	Baseline

The first four runs look at scenarios when a behavioral value is dominant. It is assumed that the dominant behavior value has an input of '1.0', while the others are set to '0.2'.

The last two runs look at scenarios when the agents are Pro-environmental and Not-so-environmental.

Pro-environmental agents are described by the high input of their 'Biospheric' & 'Alustric' behavioral values as compared to the remaining two behavioral values. In case of Not-so-environmental agents, the input of these behavioral values are interchanged with 'Hedonic' & 'Egoistic', which tend to describe less environmentally friendly behavior.

Terms such as 'Pro-environmental' & 'Environmentally friendly' imply higher waste separation behavior.

It is expected that agents in runs 1,2,5 show higher waste separation behavior than the agents in the remaining runs.

6.8 Waste-to-energy technologies

The focus of this experimental setup is to examine the role of different waste-to-energy technologies on the energy obtained from source separated OFMSW.The results of this experiment (i.e. Experiment 5) help to answer sub-question 5.

In the baseline experiment, a gas turbine converts biogas obtained from the source separated OFMSW into electricity. But in the model source separated OFMSW can follow three technological routes such as: *Biogas to electricity, Biogas to biomethane and Biomethane to electricity.*

There are three possible technological routes to examine for the base scenario. Therefore, this implies three possible experimental runs

The energy output of the waste-to-energy technologies is indirectly dependent on the pro-environmental behavior of the agents and the setup of the waste management system. Therefore, this experiment is also carried out in combination with experiment 3 and experiment 4 respectively.

It is expected that the application of different waste to energy technologies could affect the outputs of experiment 3 & 4. An expected insight is higher electricity obtained per tonne of OFMSW when biomethane generated from the source separated OFMSW is used to generate electricity.

In the next chapter the results obtained from running all the five experiments are presented and discussed.

6.9 Repetition of model runs

Each experimental run or model run is repeated 30 times to capture the randomization within the model. This is because the coefficient of variance for the model output (in this case the waste separation rate) is low. Coefficient of variance is a measure of the relative variability. It is the ratio of the standard deviation to the mean of a dataset.

The mean and standard deviation of the waste separation rate for the base scenario are 7.05 and 0.16 respectively. Therefore, the coefficient of variance is 2.3%.

According to Belsare and Gompper (2015) , if the coefficient of variance of model output is less than 10%, then in that case 30 consecutive simulations are adequate for running experiments in an ABM.

7. Results and analysis

This chapter presents the results of the experiments discussed in Chapter 6. The results include the three KPI values for each experiment. The analysis of these results is presented as well, which helps provide answers to the main research question and its sub-questions. The results of the experiments are divided into four sections. Section 7.1 is about the influence of urban planning of Havenstad on the model KPIs. Section 7.2 is about the influence of the interventions. Section 7.3 discusses the influence of behaviour values and Section 7.4 is about the influence of different Waste-to-Energy (WtE) technologies on the model output.

By running experiments described in Chapter 6 in the model, datasets are obtained for the four model outputs: *Waste separation rate, Electricity/ Biomethane generated per tonne OFMSW, Cost of generating per kWh of electricity and Cost of abating per kg of* CO_2 .

Each experiment is repeated 30 times, resulting in 30 values for each model output. The reason of repeating an experiment and its runs is to effectively capture the randomization within the model and to examine the variability in data values for each model output.

These data values are then plotted in the form of a barplot or boxplot. Also, some of these plots contain outliers, which can be due to model randomization. They are not considered as part of the analysis of the data set.

7.1 Urban planning of Havenstad

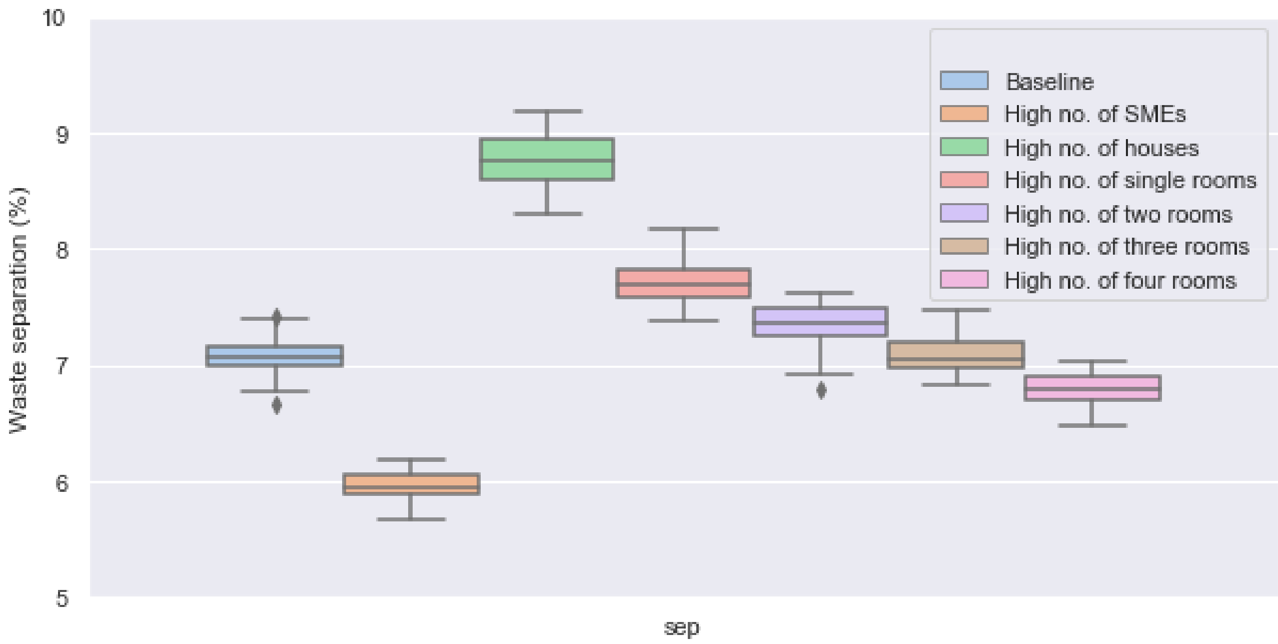
In this section the results of Experiment 1 are presented. Experiment 1, as described in the previous chapter, is about examining the effect of Urban planning of Havenstad on the energy obtained from per tonne of OFMSW generated.

The results of this experiment are obtained by varying the baseline conditions or parameters and plotting the observed model output values in the form of boxplots. The parameters that are varied in the experimental runs are listed below; for more information refer Section 6.4.

- *Ratio of households to SMEs in a block* : In the baseline scenario, the two agent types (households & SMEs) are equally distributed within a block. But in the experiment runs carried out the distribution of is increased to 70% for each agent type.
- *Distribution of the four household types in a block* : In each experimental run in this case, a single household type is set to have a higher share in the block, as opposed to the baseline scenario. Similarly, four experiments runs are carried out for the four different household types.

Before examining the boxplots of the KPI values. The waste separation rate obtained for the different conditions or experimental runs are presented in Figure 7.1. This is the waste separation % for the whole block. Each box in the graph represents the spread of the waste separation % of a particular condition, which are represented by different colors as seen in the legend of the figure.

Figure 7.1: Waste separation % (Experiment 1)

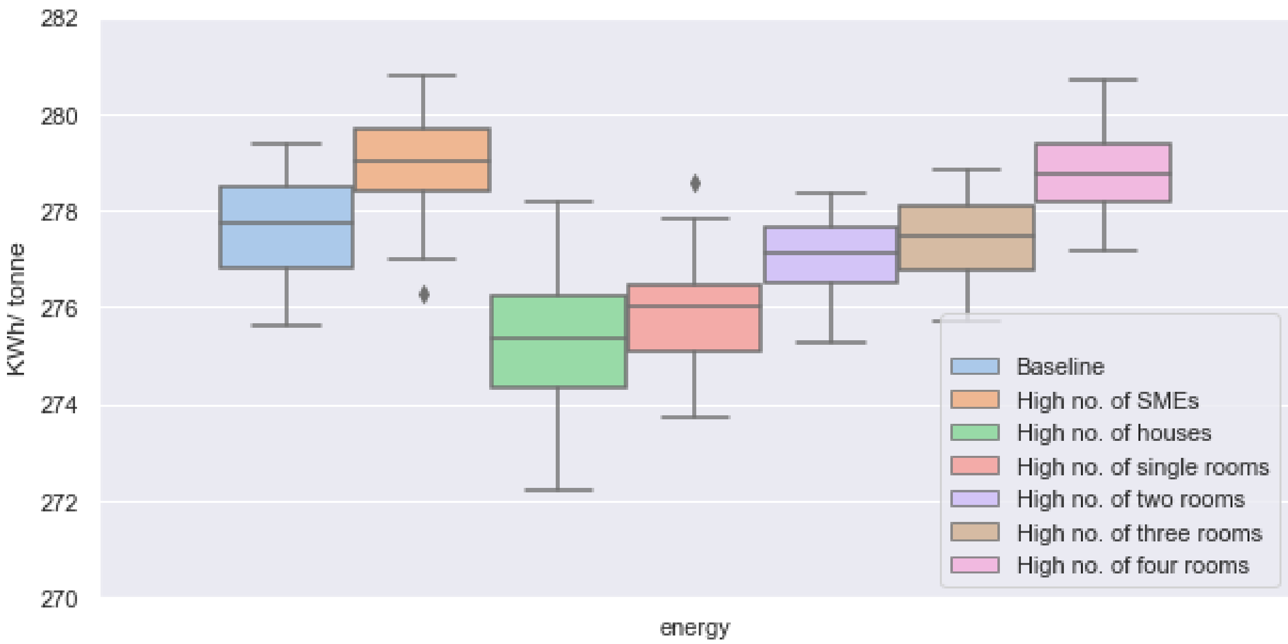


By examining the Figure 7.1, two conclusions can be made. *Firstly*, households may participate in higher waste separation activity than SMEs. Thus, an increase in the waste separation % of a block is observed when the number of households are higher. Although the distribution of households and SMEs in the baseline scenario is equal, the waste separation % of the block is closer to the experimental run where a block has a higher number of SMEs. This implies that the increase in waste separation % of a block may not be liner to the increase in households.

Secondly, the waste separation % of a block is observed to decrease when there an increase in the share of households with a higher number of rooms. Another way of interpreting this result is that, the increase in number of inhabitants in a block may decrease the waste separation. This is observed in the model because the increase in the number of inhabitants increases the overall organic waste generation of a block, which fills up the central bin faster. Subsequently, agents encounter a filled up central bin more often and have no choice but to dispose in the residual waste stream or bin.

In the next boxplot, instead of waste separation %, the energy (or electricity) obtained from tonne of OFMSW generated (or KPI 1) is plotted for the different experimental runs. In this experiment, similar to the baseline scenario, the biogas obtained from source separated OFMSW is used to generate electricity. While, the OFMSW that is not separated is incinerated.

Figure 7.2: Electricity generated per tonne - KPI 1 (Experiment 1)



By examining Figure 7.2, the effect of urban planning on the electricity generated from OFMSW (or organic waste) can be studied. This leads to the following analysis: *First*, the electricity generated per tonne of organic waste is higher when there are high number of SMEs in a block. Nearly, 25% of the data values in case of *high number SMEs* is greater than that of the baseline experiment and it goes upto 75% when compared to *high number of households*. This observation stems down to the waste separation % of the block, which steers to the *second* analysis made.

Comparing Figure 7.1 & Figure 7.2, it is observed that with the increase in waste separation %, the electricity obtained per tonne of organic waste decreases. This is due to the fact that higher waste separation leads to lower input for the waste incinerator. Compared to a gas turbine running on biogas, an incinerator is shown to give higher output (See Table 4.9). Therefore, based on this analysis, it may be deduced that for the baseline conditions, higher waste separation of organic waste may not be environmentally & economically the best solution. The economic & environmental benefits of waste separation on the energy obtained from organic waste depend on the technological route chosen to extract electricity from the source separated organic waste. This is addressed in the further sections of the chapter.

Third, the increase in the number of inhabitants or the increase in household types with more number of rooms in a block, increased the energy obtained from organic waste. This is due to fact that waste generated increases and waste separated (Figure 7.1) decreases as the number of inhabitants increase. Subsequently more organic waste ends up in the incinerator, resulting in a higher energy output.

Next, the barplots for remaining two KPIs are presented. Figure 7.3 depicts the cost of generating 1 kWh of electricity from organic waste for a varying distribution of agent types. Figure 7.4 depicts the cost of abating 1 kg of CO_2 by generating electricity from organic waste for a varying distribution of agent types. By collectively examining the bar plots the following analysis are made:

As seen from Figure 7.3, the data values of KPI 2 for different household types does not seem to vary alot. In fact, the data values obtained for a three-room household type is nearly similar to that of of a single room. While, the data values of KPI 3 (Figure 7.4), are shown vary more and it is observed that as the inhabitants increase, the cost of abating CO_2 is decreasing. Therefore, this implies that increasing the number of inhabitants in a block may decrease the cost of abating CO_2 but conversely, the cost of generating electricity may not always decrease.

The reason behind this observation and analysis can be partially explained by Figure 7.2. The increase in inhabitants has shown to increase the electricity generated per tonne of organic waste.

This implies, as the inhabitants increase, one tonne of organic waste leads to more displacement of electricity generated from fossil-based plants, subsequently more CO_2 can be abated.

Figure 7.3: Cost of generating per kWh electricity - KPI 2 (Experiment 1)

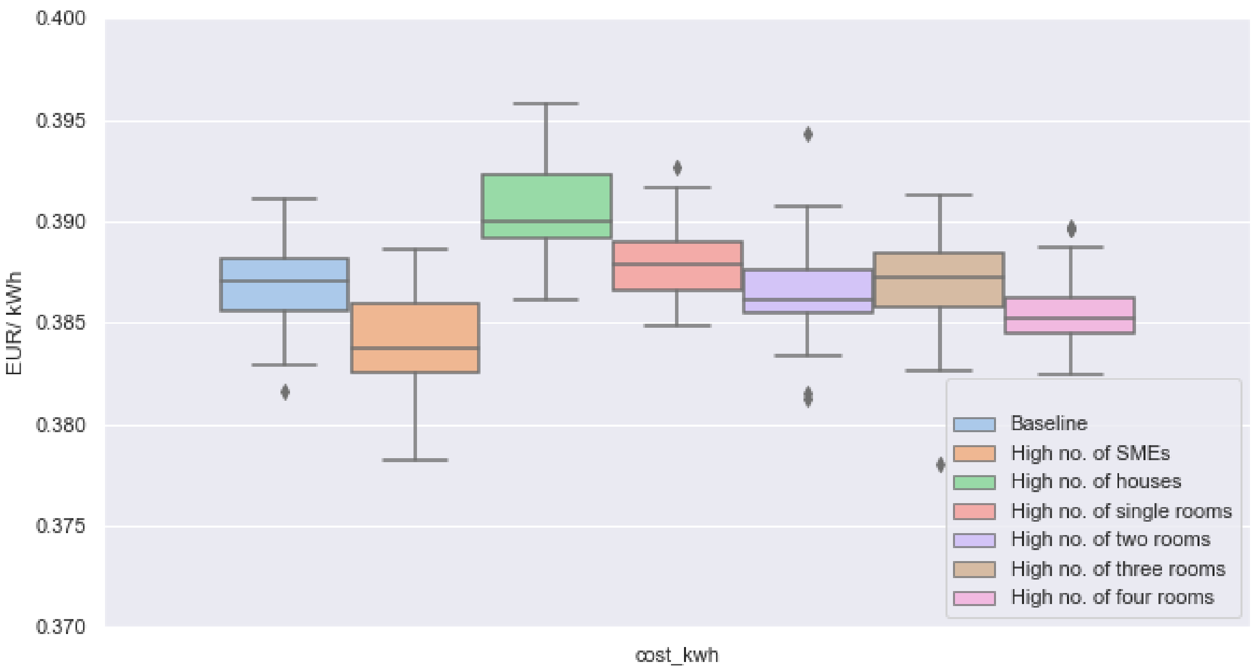
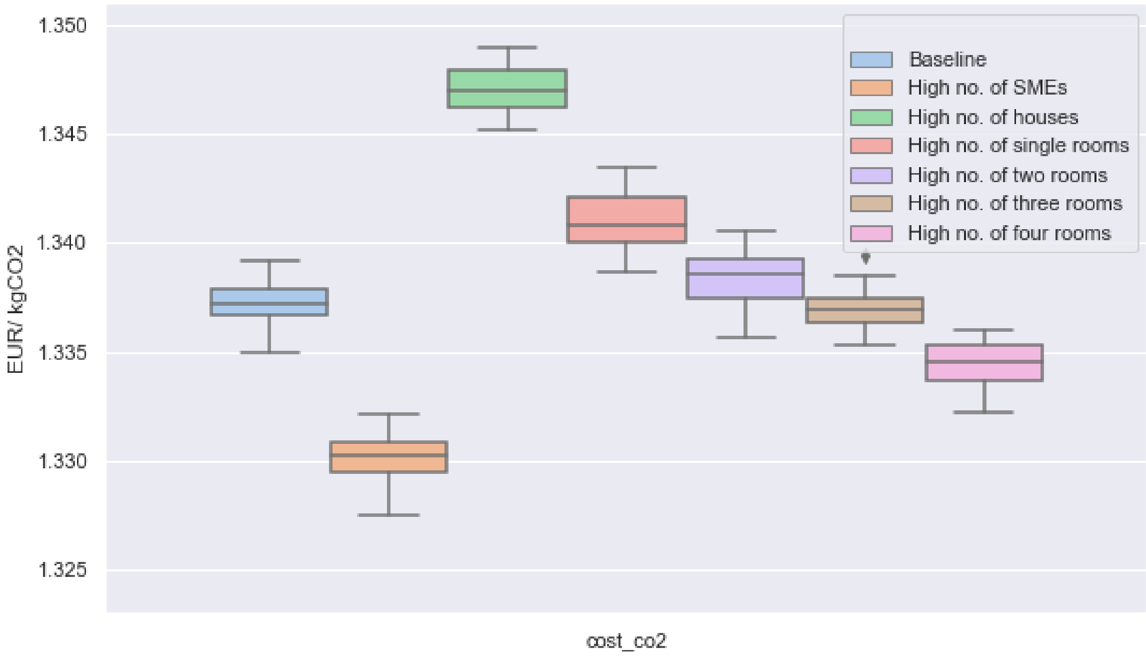


Figure 7.4: Cost of abating per kg of CO_2 - KPI 3 (Experiment 1)



7.2 Influence of structural and informational interventions

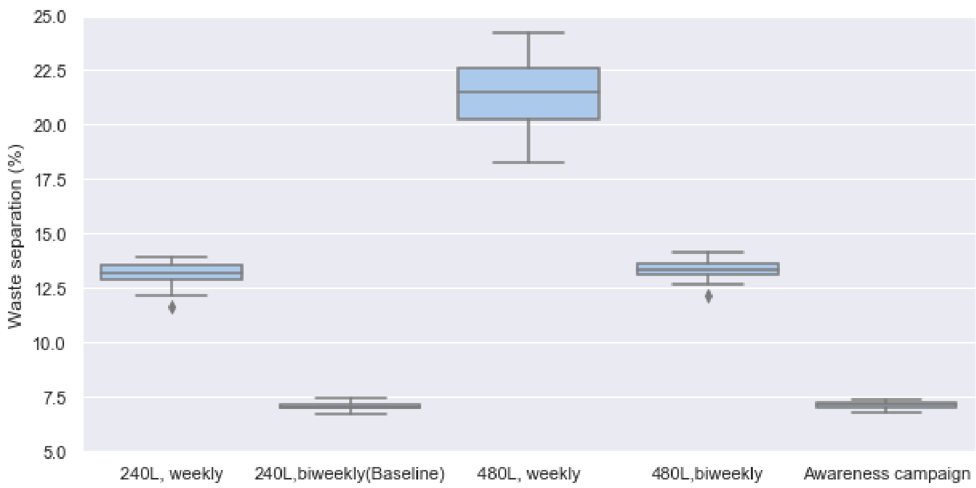
In this section the results of experiments 2 & 3 are presented and analysed. Experiment 2 is about studying the influence of the awareness campaigns- an informational intervention. In this experiment all the parametric values of the model remain same as the baseline scenario, only at each model tick the personal norm values of the agents to separate waste increase by a fixed value.

Experiment 3 is about studying the influence of the Waste Management System (WMS)- a structural interventions. The WMS is defined by the bin capacity and the frequency of waste collection from the central bin. In this experiment two bins sizes (240 L & 480 L) and weekly & biweekly collection of waste are collectively examined.

The objective of carrying out these experiments is to compare the two types of interventions and to analyse the influence of the WMS on the system output. The datavalues of the three KPIs and waste separation rate are obtained from the two experiments (and their runs) are plotted in the form of boxplot.

In Figure 7.5, the waste separation rate for the two interventions are shown on the y-axis. Additionally, waste separation rate for the four runs of experiment 3 are shown as well.

Figure 7.5: Waste separation rate (Experiment 2 & 3)



By examining Figure 7.5, the influence of the structural intervention (i.e. WMS) on the waste separation rate is shown to be higher than the informational intervention (i.e. awareness campaign). Based on this observation, it can be said that the agents in the model are more sensitive to structural interventions rather than informational interventions.

Furthermore, the informational intervention does not seem to influence waste separation rate because the overall pro-environmental behaviour (or personal norm values) observed in the block increases. Based on model analysis presented in the next chapter (section 8.2), it is shown that increase in the pro-environmental behaviour (or personal norm values) of a block may lead to a decrease in waste separation rate in certain cases.

In the case of the structural intervention, the increase in bin size and/or increase in frequency of collection resulted in more waste separation. This is due to the fact that probability of an agent encountering a central bin that is not full is lower. Thus, the agent may have an opportunity to separate its waste.

But with increased waste separation, the electricity generated per tonne of organic waste (Figure 7.6) may decrease. This is again due to the fact that less waste ends up in the incinerator- which has a higher energy output compared to producing electricity from biogas.

Although, doubling the bin capacity (as compared to the baseline) or the frequency of collection resulted in nearly similar waste separation rates. But the costs incurred to abate CO_2 (See Figure 7.7) and generate electricity (See Figure 7.8) are higher when the frequency of collection is increased. Therefore, it may imply that increasing the bin capacity instead of frequency of collection is more environmentally & economically cost-effective.

Furthermore, doubling the bin capacity (240L to 480 L) and doubling the frequency of collection (biweekly to weekly) may result in a variable waste separation rate. This can be observed by examining the spread of the datavalues for the third box (480L,weekly) in Figure 7.1.

The reason for this variation maybe because the bin is not always completely filled up when it organic waste is collected from it.

To conclude, increasing the central bin size to collect more waste or increasing the availability of the bin (by increased frequency of collection) may not lead to added economic and environmental benefits when compared to the baseline scenario. Especially when biogas obtained from source separated OFMSW is used to generate electricity.

Figure 7.6: Electricity generated per tonne - KPI 1 (Experiment 2 & 3)

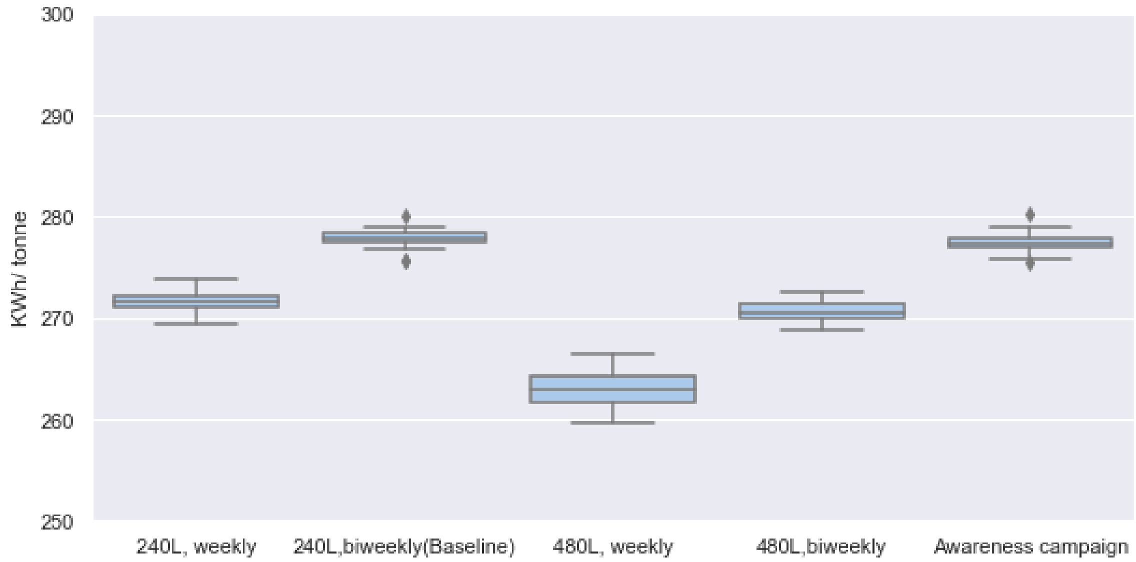


Figure 7.7: Cost of generating per kWh electricity - KPI 2 (Experiment 2 & 3)

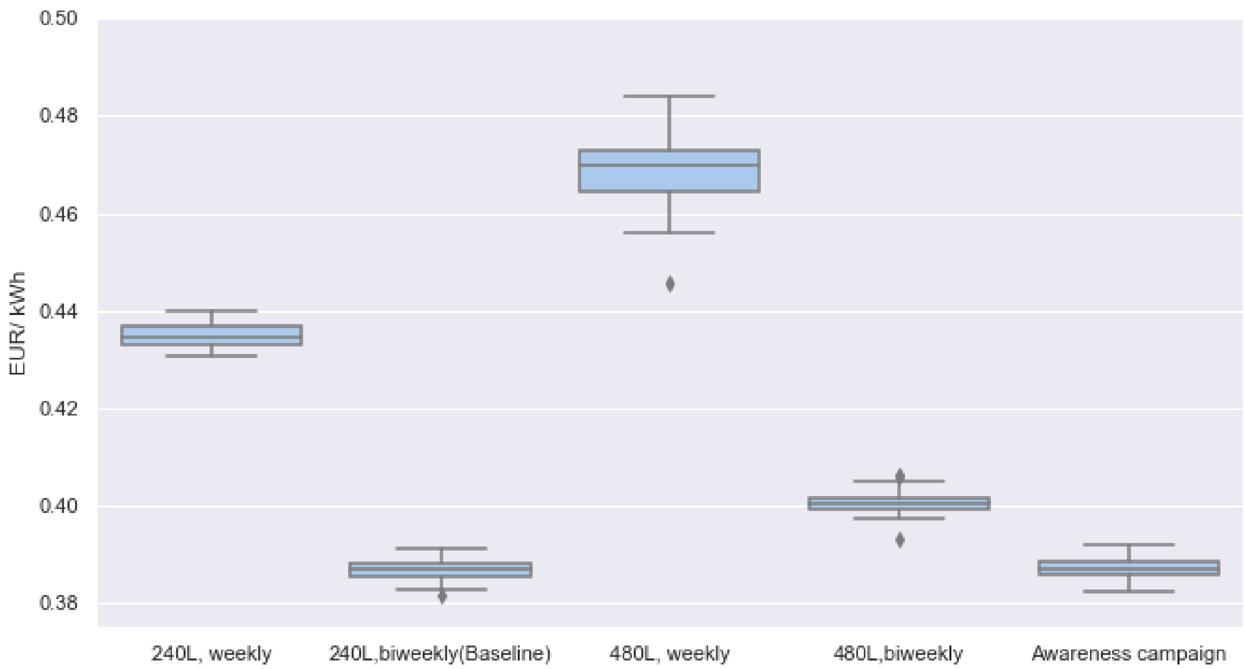
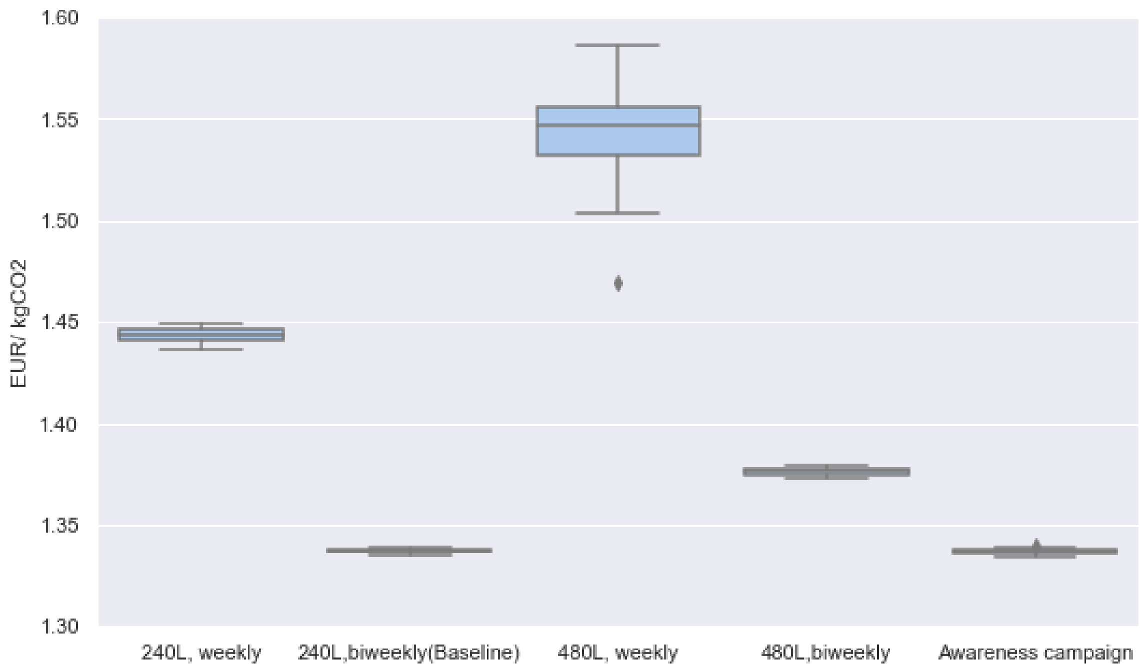


Figure 7.8: Cost of abating per kg of CO_2 - KPI 2 (Experiment 2 & 3)



7.3 Behaviour values

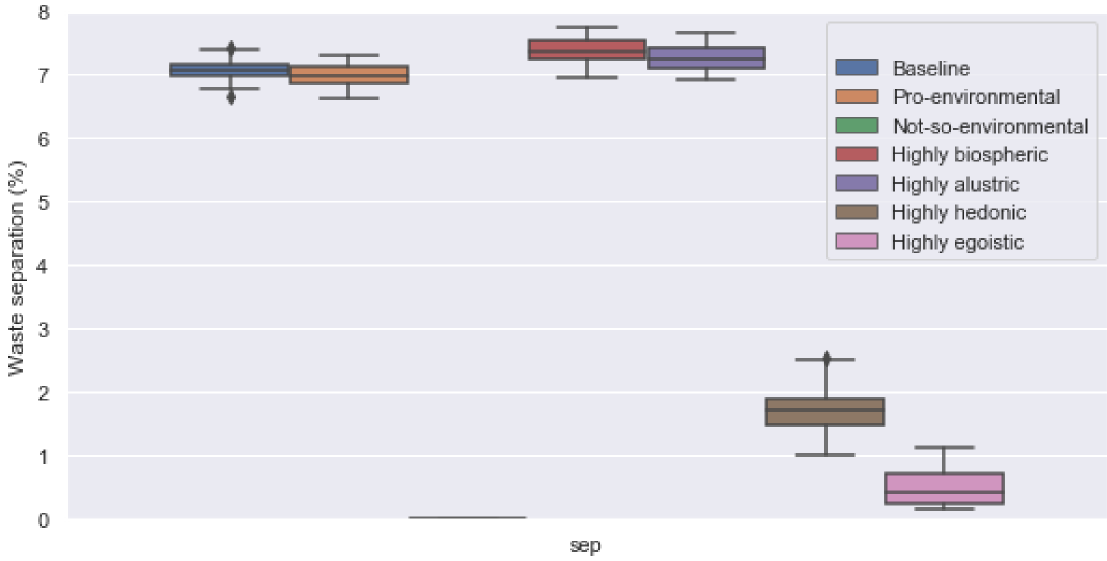
In this section the results of experiment 4 are presented and analysed. Experiment 4 is about studying the influence of different behaviour values. The experiment consists of six experimental runs. The first run examines when the agents in a block are *Pro-envrionmental* or have high[1] biospheric & altruistic values. The second run examines when the agents in a block are *Not-so-environmental* or have high hedonic & egoistic values. The subsequent runs examine each of the four behaviour values. For example, in the experimental run *Highly biospheric*, the agents of the block score more on the biospheric scale compared to other values (which are set to be equal to each other). For more information regarding the experimental design refer Table 6.3.

The objective of analysing the results of this experiment is to highlight the impact of behaviour values on the energy output from OFMSW and to compare the impact of these values between themselves & the baseline conditions.

In Figure 7.9, the waste separation rate for the experimental runs is presented. Figure 7.10, Figure 7.11 & Figure 7.12 present the three KPI values for the experiment 4 and its runs.

[1]It implies that the agents have high rating in the scale measuring the behaviour values

Figure 7.9: Waste separation rate (Experiment 4)



In the baseline scenario, the behaviour values measure equal on scale (except egoistic value; it measures lesser). When compared to agents that are *Pro-environmental*, *Highly biospheric* & *Highly altruistic*, the agents in the baseline scenario separate slightly less waste at most instances.While those agents that are *Not-so-environmental*, *Highly hedonic* & *Highly egoistic* separate far less organic waste than the agents in the baseline scenario. This shows that waste separation rate is highly sensitive to egoistic & hedonic values.

Additionally, the waste separation rate of agents that are *Pro-environmental* is shown to be slightly less compared to the baseline scenario, highly biospheric & highly altruistic experimental runs respectively. This is due to fact that the central bin fills up faster when the agents in a block are pro-environmental. Thus, reducing the availability of the bin to separate waste. This result is further analysed in Section 8.2.

In Figure 7.11, agents that are *Pro-environmental* tend to reduce the cost of producing 1 kWh of electricity as compared to agents that are *Highly biospheric & Highly altruistic*. Therefore, it may be stated that having a mix of biospheric & altruistic values is economically more desirable to generate electricity, when compared to set of agents having a majority of either of these values.

Additionally, having a near equal mix of all the four values (as in seen for the baseline scenario in Figure 7.11) may result in higher costs of producing electricity and a higher variability compared to the other experiment runs.

Lastly, in terms of electricity generation (Figure 7.10), agents that are *Highly hedonic* & *Highly egoistic* are shown to produce a higher output. This again stems down to the lower waste separation rate (See Figure 7.9) and the fact that more organic waste ends up being incinerated. Furthermore, for these two values, the cost of producing a unit of electricity (Figure 7.11) and abating a kg of CO_2 (Figure 7.12) is shown to be lower compared to other experimental runs. Based on this analysis, it can be said that for that presence of agents with high hedonic & egoistic values for the baseline conditions is shown to environmentally and economically better. Or in other words, lower waste separation for the baseline conditions may be economically & environmentally more desirable.

Figure 7.10: Electricity generated per tonne - KPI 1 (Experiment 4)

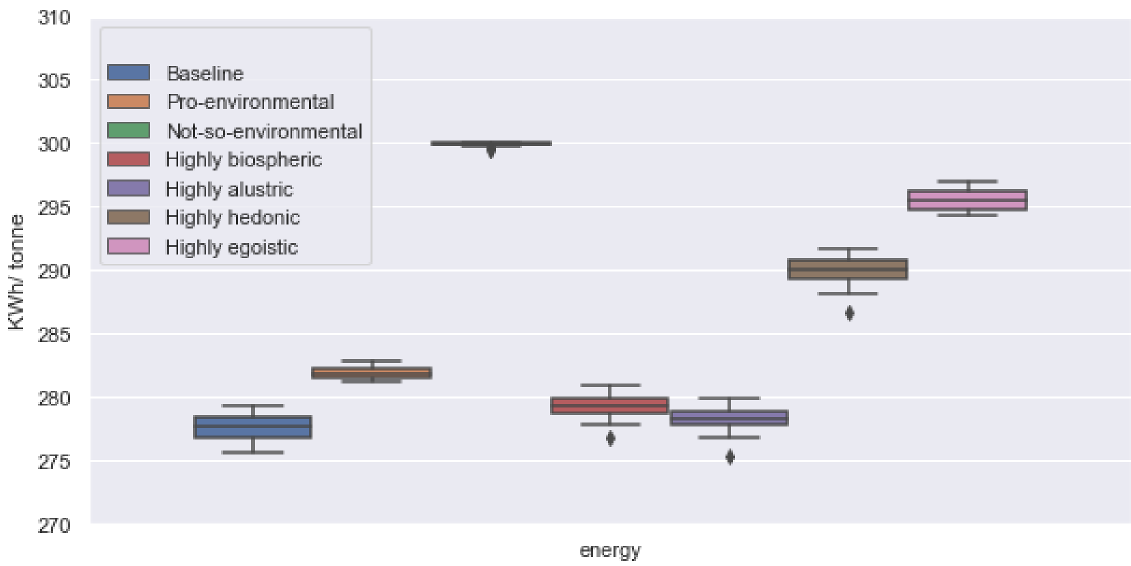


Figure 7.11: Cost of generating per kWh electricity - KPI 2 (Experiment 4)

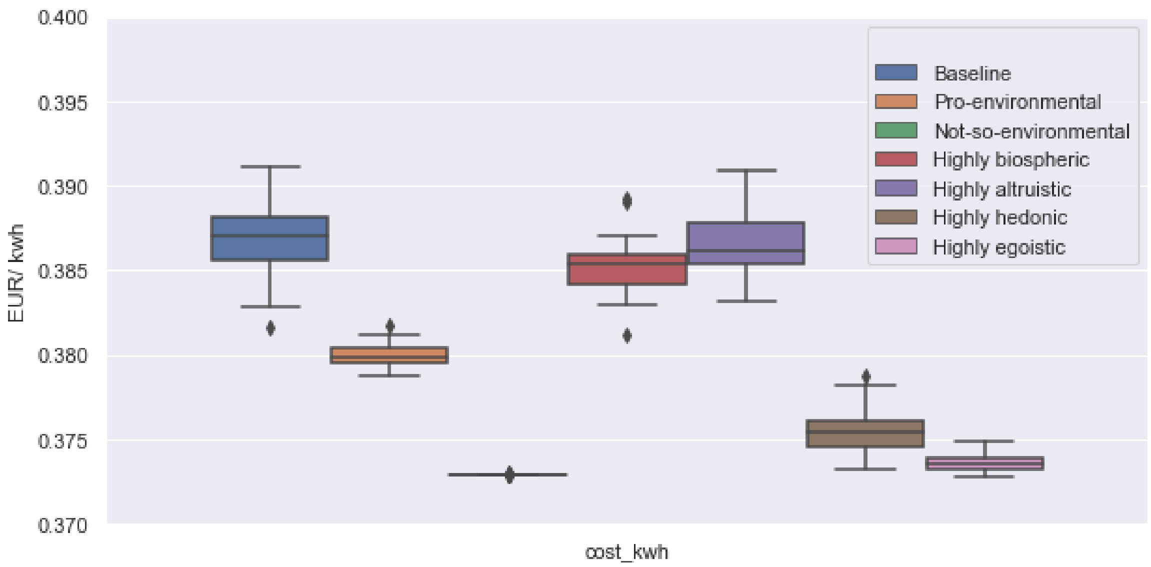
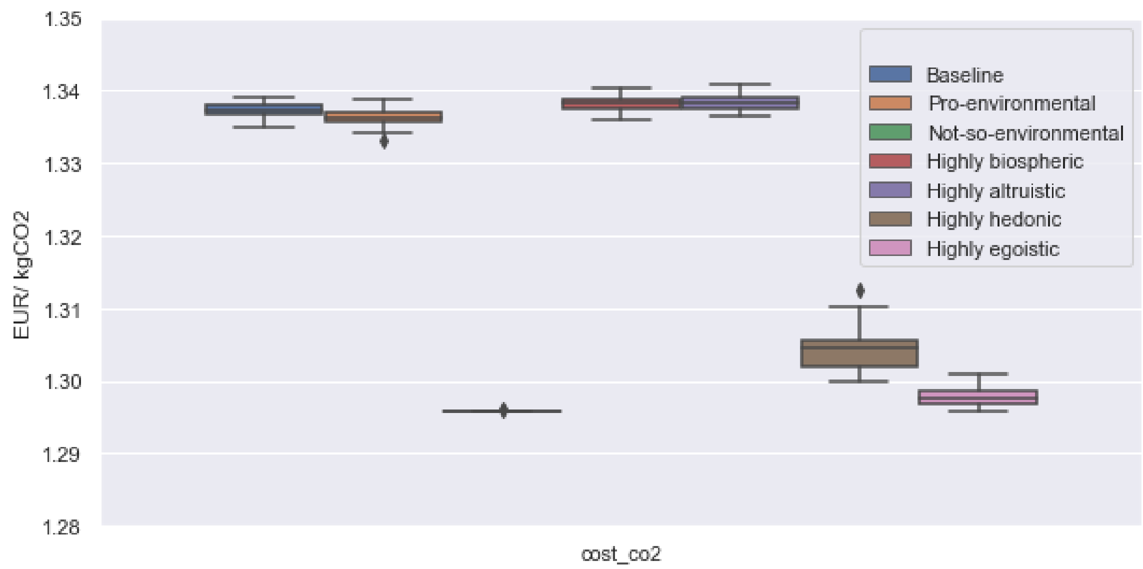


Figure 7.12: Cost of abating per kg of CO_2 - KPI 3 (Experiment 4)



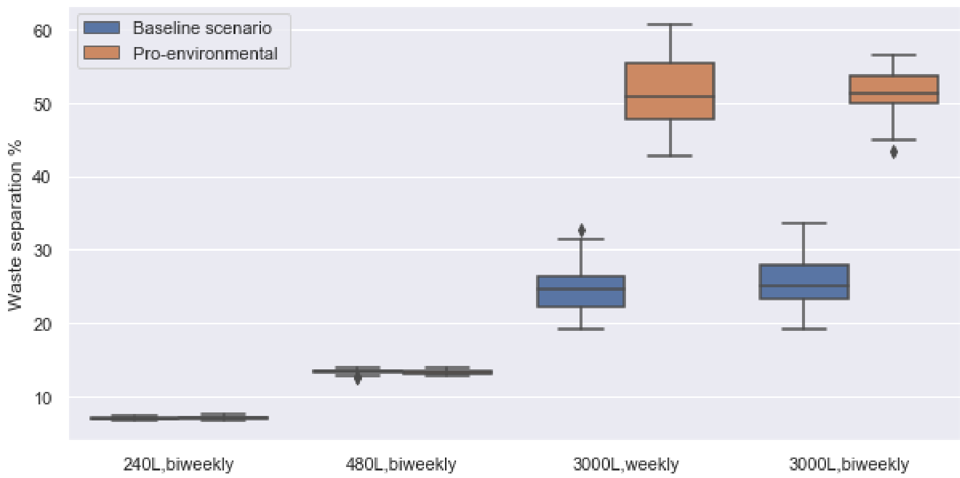
7.3.1 Pro-environmental behaviour & central bin size

In this subsection the combined influence of a large organic central bin size & Pro-environmental agents is examined on the waste separation rate of a block.

Previously, it is observed that when the agents are *Pro-environmental*, then the waste separation rate is slightly lower than the baseline scenario. One of the main reason for this observation is that the agents encountered a full bin more often, therefore reducing the waste separation rate.

Therefore, in this subsection the influence of an increasing bin size on the waste separation rate of Pro-environmental agents is analysed.

Figure 7.13: Waste separation rate (Pro-environmental behaviour & Cental bin size)



In Figure 7.13, the waste separation rate is given in the y-axis for the different bin sizes in the x-axis. In case of the highest bin size (3000L), the varying frequency of waste collection is also considered. By examining this graph, the following conclusions can be made:

Firstly, doubling the bin size from 240L to 480L increased the waste separation rate, but the presence of Pro-environmental agents did not increase the separation rate further. This may be due to the fact that agents still encounter a filled up organic central bin.

On the contrary, an increased bin size of 3000L gave different waste separation rates for the Baseline scenario & Pro-environmental runs.

Compared to the baseline scenario, agents that are *Pro-environmental* nearly doubled the waste separation rate. Furthermore, at certain instances the waste separation rate is nearly 60%, which is close to the target set by Municipality of Amsterdam for the year 2020 (Gemeente Amsterdam, 2016).

Secondly, the variation of frequency of waste collection incase of a 3000L central bin did not majorly influence the waste separation rate. Although in case of weekly waste collection, the waste separation rate is shown to reach the maximum value of 60%.

Although the frequency of waste collection does not majorly impact the waste separation rate, it does has its advantages and disadvantages for central bin of size 3000L.

In case of weekly waste collection, the cost of collecting waste is higher than collecting it once in two weeks. But on the other hand, it reduces instances of the bin becoming smelly and unhygienic due to longer storage of the organic waste. If the bin is smelly and unhygienic then an agent may not separate its organic waste correctly (Personal communication with expert, February 28, 2020: See Appendix C.2.2). Thus, weekly collection of organic waste may avoid this.

To conclude, the increase in waste separation rate of *Pro-environmental* agents is dependent on the increase in the organic central bin size. This can be validated with help of literature and expert opinion.

According to a study conducted in the UK, increasing the bin size is shown maximize the waste collection (WRAP, 2008). Something similar is stated by an waste management expert in the municipality of Amsterdam (Personal communication with expert, February 28, 2020: See Appendix C.2.2). As per the expert, the size could matter incase of an quick overflow- (when there is low capacity and high frequency of disposal).

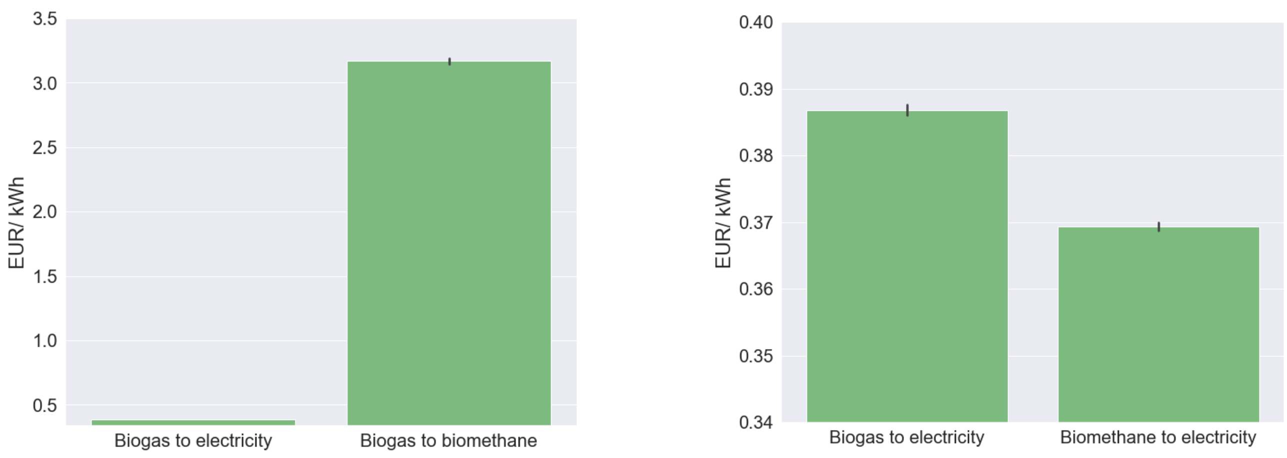
7.4 Waste-to-Energy(WtE) technologies

In this section the results of Experiment 5 are presented and analysed. Experiment 5 is about studying the influence of WtE technologies on the system output or KPI values. The main parameter that is varied in this experiment is the technological route taken to process source separated organic waste, which can be either one of the three: *Biogas to electricity, Biogas to biomethane & Biomethane to electricity* . For the baseline conditions, the first route is taken (i.e. *Biogas to electricity*). In the second route instead of generating electricity from the biogas obtained from organic waste, the biogas is used to generate biomethane, which is sold to the gas grid. In the third route, this biomethane is used to generate electricity instead of being sold to the gas grid.

The objective of analysing the results of this experiment is that it helps highlight the importance of choosing a technology to process source separated organic waste. Additionally, this experiment is carried out in combination with experiments 3 & 4, to examine the influence of different WtE technologies on the output of these experiments.

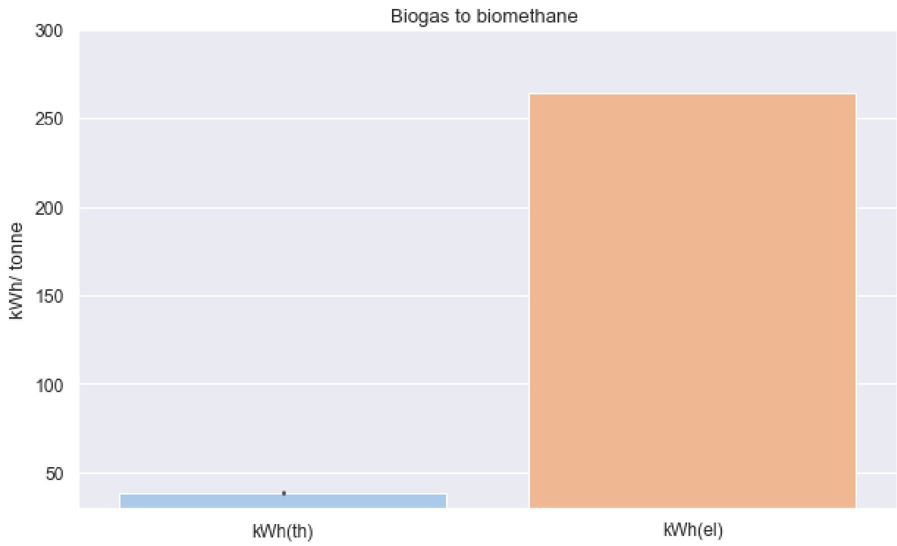
In Figure 7.14 the cost of generating per kWh of electricity for the other two technological routes are compared with that of baseline scenario.

Figure 7.14: Cost of generating per kWh electricity - KPI 2 (Experiment 5)



The energy obtained in the first and third route is purely in the form of electrical energy (kWh_{el}). While in the second route it is mix of thermal and electrical energy ($kWh_{el} + kWh_{th}$). This is because in the second route the biomethane from the source separated organic waste is used for generation of thermal energy in the form of heat via a gas fired boiler.

Figure 7.15: Breakdown of the energy generated per tonne for second route



In Figure 7.15, the breakdown of electrical and thermal energy obtained per tonne of organic waste for the second route is presented. The thermal energy from source separated organic waste accounts for 12% of the total energy obtained from organic waste. While the rest is in the form of electrical energy, which is obtained from incineration of organic waste that is not separated.

On the basis of the comparison presented in Figure 7.14, it is observed that that the third route (*Biomethane to electricity*) is economically more viable as compared to the first (*Biogas to electricity*) and second route (*Biogas to biomethane*).

The reason for this observation is due to two reasons: *Firstly*, the third route produces nearly double the amount of electricity from 1 tonne of organic waste, when compared to the baseline scenario[2], that too at a slightly lower cost (See:Table 4.9).

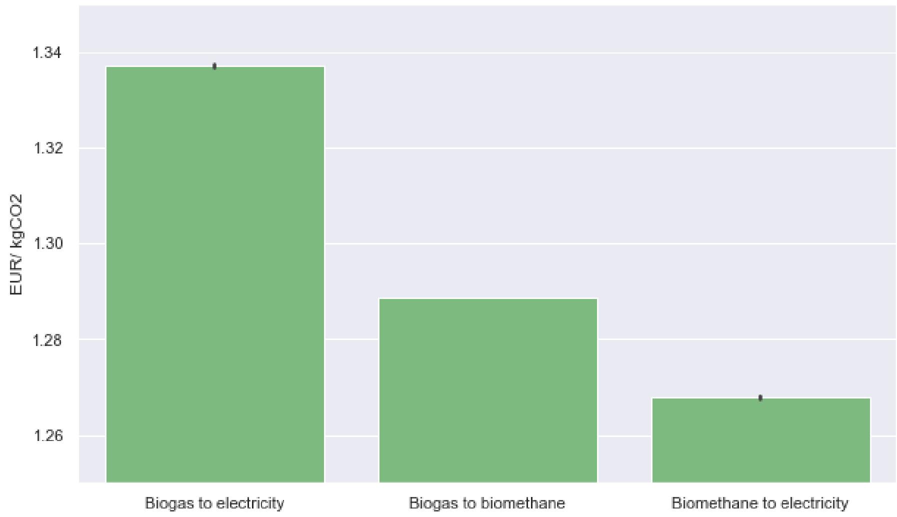
Secondly, in the second route, the biomethane sold to the gas market is not able to generate higher revenues as compared to when it is converted to electricity and traded in the electricity market.

Lastly, when comparing the cost of abating per kg of CO_2 (Figure 7.16), the third route is environmentally more economical than the first route. While the second route is not economical in terms of energy generation, it is environmentally more economical than the first route.

To conclude, the technological route, *Biomethane to electricity* is more environmentally & economically desirable than the first route (i.e. *Biogas to electricity*), to process source separated organic waste into energy in the baseline scenario.

[2]Choosing the route 'Biogas to electricity' results in 204 kWh generated per tonne of OFMSW; 'Biomethane to electricity' results in 392.55 kWh generated per tonne of OFMSW

Figure 7.16: Cost of abating per kg of CO_2 - KPI 3 (Experiment 5)



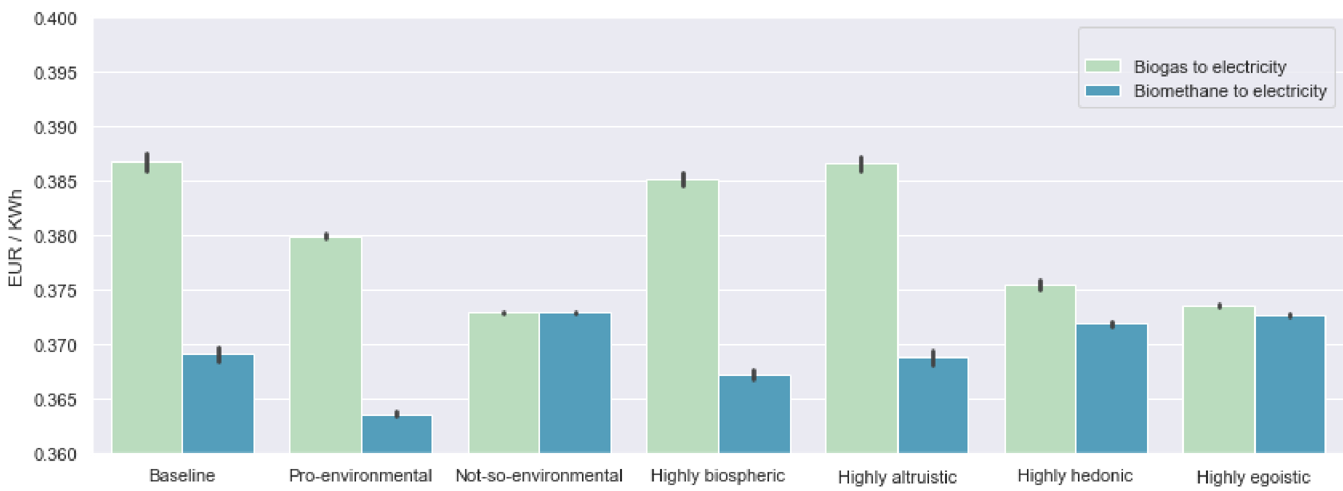
7.4.1 WtE and behaviour values

In this section the results of a combined experiment involving experiment 4 & experiment 5 are presented. In this combined experiment the resultant values for KPI 2 & KPI 3 are presented for the parameters of experiment 4, but for two different technological routes: *Biogas to electricity & Biomethane to electricity.*

The objective of presenting and analysing the results of this combined experiment is to highlight the influence of different technological routes on the output from the behaviour values.

In Figure 7.17 the cost of generating 1 kWh of electricity for different runs or behaviour profiles is plotted in the form of a barplot. The light green bars signify the route: *Biogas to electricity.* The blue bars signify the route, *Biomethane to electricity.* Similarly, in Figure 7.18 the cost of abating 1 kg of CO_2 for different runs is plotted in the form of a barplot

Figure 7.17: Cost of generating per kWh of electricity (KPI 2)



By examining Figure 7.17 & Figure 7.18, the following analysis is made: *Firstly*, the second route (*Biomethane to electricity*) is environmentally and economically more desirable as compared to the first route, irrespective of the behaviour profiles.

The reason behind this observation is that the second technological route nearly produces double the amount of electricity & consequently abates nearly double the amount of CO_2 as compared to the first route, that too at a slightly lower cost (See : Table 4.9).

Except, for the *Not-so-environmental*behaviour profile. This is because the waste separation is nearly zero and most of the waste is incinerated rather being converted into biogas.

Secondly, unlike in the first route, presence of high biospheric & high altruistic values, in case of the second route (Figure 7.17), reduces the cost of generating per kWh of electricity. Or in other words, increased waste separation (Figure 7.9) due to the presence of high biospheric & high alustric values may reduce the cost of generating electricity in case of the second route.

For example, in Figure 7.17 cost per kWh generated in the run 'Pro-environmental' (high biospheric & high alustric values) is lesser than in the runs 'Hedonic' & 'Egoistic'. In fact, cost per kWh generated is the least for the run 'Pro-environmental'. Thus, it can be said that for the second technological route having a combination of biospheric & altruistic values may be economically beneficial for power generation.

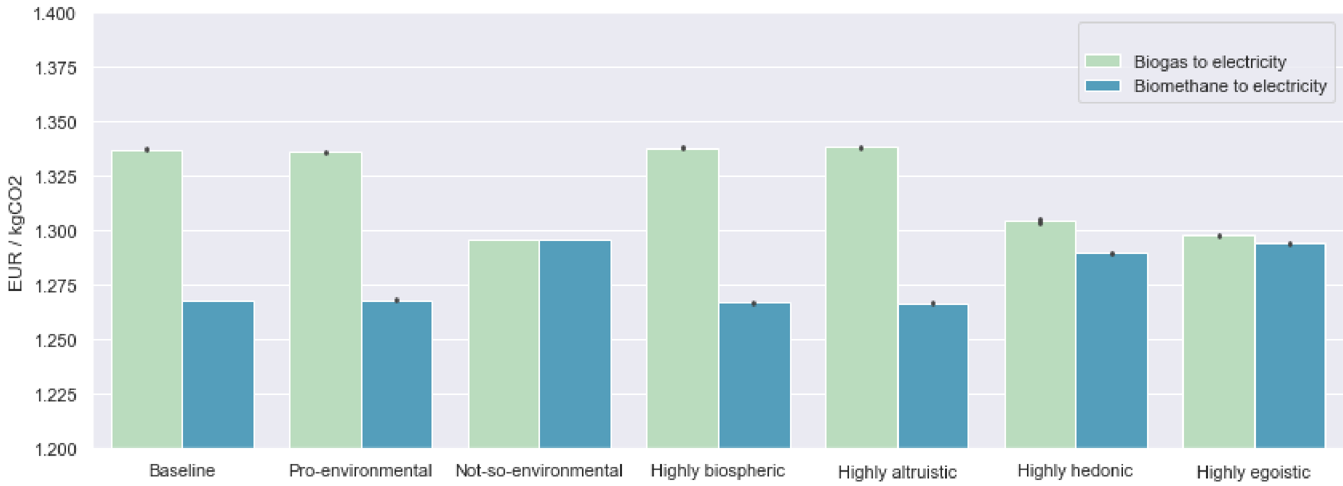
Conversely, presence of high hedonic & high egoistic values or decreased waste separation, increases the cost of generating per kWh of electricity in case of the second route.Thus, in case of the second route it is economically not desirable for the agents to be highly hedonic or highly egoistic.

Thirdly, in Figure 7.18, the presence of high biospheric & high altruistic values did not influence the cost of abating per kg of CO_2 as compared to the baseline scenario, irrespective of the technological route.

Even in the case of the second technological route, the presence of high biospheric & high altruistic values did not influence the value of KPI 3. The reason for this observation is that the waste separation rate (Figure 7.9), as compared to the baseline scenario, does not significantly increase in case of high biospheric & altruistic values. Also, the cost abating per kg of CO_2 (Table 4.9) in case of the second route is just slightly lower than the first route and waste incineration. This implies that an slight increase in the source separated organic waste for the second technological route (due to a slight increase in waste separation) does not necessarily decrease the cost abating per kg of CO_2 .

On the contrary, for the second technological route the presence of high hedonic & high egoistic values increased the cost of abating per kg of CO_2 . Thus, in this case it is not environmentally desirable for the agents to be highly hedonic or highly egoistic.

Figure 7.18: Cost of abating per kg of CO_2 (KPI 3)



To conclude, the presence of altruistic & biospheric values is environmentally and economically favourable when an efficient technological route is employed to treat source separated organic waste.

Furthermore, the cost of generating per kWh of electricity (KPI 2) is slightly more sensitive to the presence of altruistic & biospheric as compared to the cost of abating per kg of CO_2 (KPI 3).

7.4.2 WtE and structural intervention

In this section the results of a combined experiment involving experiment 3 & experiment 5 are presented. In this combined experiment the resultant values for KPI 2 & KPI 3 are presented for the parameters of experiment 3, but for two different technological routes: *Biogas to electricity & Biomethane to electricity.* Additionally, a bin size of 3000L is examined as well.

The objective of presenting and analysing the results of this combined experiment is that it highlights the influence of different technological routes on selection of the structural intervention or in this case the Waste Management System (WMS).

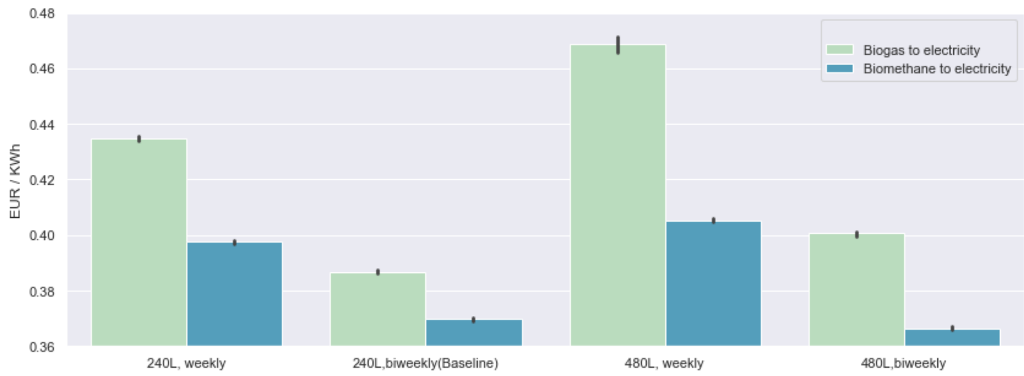
In Figure 8.1a & Figure 8.1b the values of KPIs 1& 2 are plotted for the combined experiment.

By analysing both the plots, the following conclusions can be made: *Firstly*, in case of the first route (*Biogas to electricity*), the WMS in the baseline scenario performs better economically & environmentally than other iterations of the WMS. The reason being that lower waste separation is preferable in case of the first route and the WMS setup for the baseline scenario gives the lowest waste separation rate.

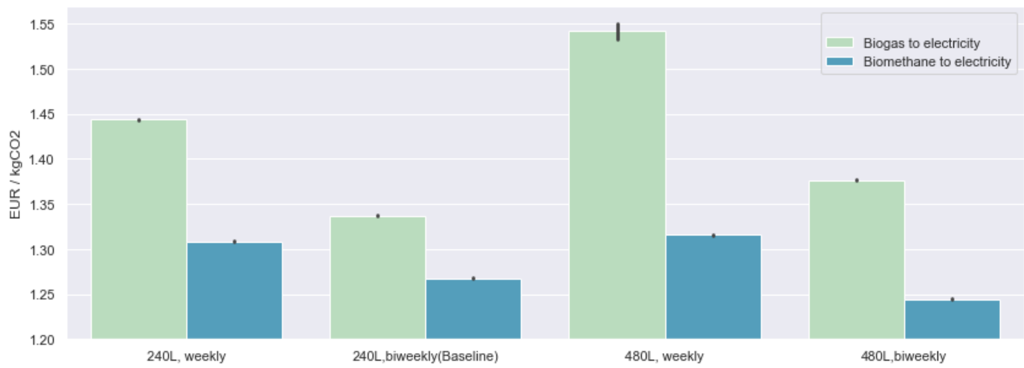
While in the case of the second route (*Biomethane to electricity*), increase in the bin size from 240 Liters to 3000 Liters is slightly more economical & environmental in terms of power generation. This might be due to the increase in the waste separation rate, which is preferaable in the second route.

Secondly, increasing the bin size is more economically and environmentally beneficial as compared to increasing the frequency of collection, irrespective of the technological route. This is because with the increase in frequency of collection, the cost collection increases as well.

Figure 7.19: Resultant KPI values for combination of experiments 3& 5



(a) Cost of generating per kWh of electricity (KPI 2)



(b) Cost of abating per kg of CO_2 (KPI 3)

To conclude, in case of the second route, the increase in bin size is economically & environmentally more desirable to generate power from organic waste.

8. Discussion

In this chapter, the model results are discussed and validated with help of literature and expert opinion. Based on which a system design is proposed. In Section 8.1 the choice of the technological route for this system is discussed. Section 8.2 discusses the influence of pro-environmental behaviour. Section 8.3 discusses the role of interventions in increasing the waste separation rate of the system. Lastly, the system design is proposed in Section 8.4 and compared with the system in the baseline scenario.

The Waste-to-Energy (WtE) system is mainly described by the choice of technological route, the waste separation behaviour by the agents and the presence of structural & informational interventions.

This chapter discusses these three elements based on the model results presented in Chapter 7, literature & expert opinion and proposes a new system design based on these elements.

8.1 Choice of Waste-to-Energy(WtE) technological route

In this report three different WtE technological routes to treat source separated OFMSW are analysed based on literature (Chapter 4) and through Agent-Based Modelling (Chapter 7).

The three technological routes are : *Biogas to electricity, Biogas to biomethane & Biomethane to electricity.*

These technological routes are evaluated for the energy produced from source separated organic waste, their total operating costs (including the revenue) and the total CO_2 abated. By comparing the evaluation of these routes, it is concluded that the route:*Biomethane to electricity* is economically and environmentally more desirable for power generation from source separated OFMSW.

In this route, biogas is produced from anaerobic digestion of source separated OFMSW. Instead of producing electricity directly from biogas, it is upgraded to biomethane. Due to a higher calorific value of biomethane, it nearly doubles the electricity generation as compared to biogas. Due to an increase in electricity generation, it able to displace more electricity from fossil-based energy systems. Thereby increasing the amount of CO_2 abated.

Furthermore, low cost of producing electricity from biomethane, an increased electricity generation and the subsequent revenue from the electricity market is able to cover the cost of the additional process of upgrading biogas to biomethane. Resulting in a lower total operating costs as compared to the other two routes.

The selection of this route based on the results is compared with that of literature. According to most of the literature that is studied, biomethane is primarily injected into the gas grid or used as fuel for vehicles (Beil & Beyrich, 2013; Scarlat, Dallemand, & Fahl, 2018), but it can have a significant value for power generation (Parkes, 2017). In terms of power generation biomethane is used as a renewable energy source to help balance the electricity grid provide flexibility to the grid (Adnan, Ong, Nomanbhay, Chew, & Show, 2019; T. Persson et al., 2014; Thrän et al., 2015). For example, intermittent renewable energy sources (such as solar or wind) are not reliable to meet high power demands, then in that case biomethane can be used to produce electricity. One of the reasons being that biomethane can be used in place of natural gas in highly efficient CCGT plants for flexible power generation (T. Persson et al., 2014).

Although bio-electricity is a cleaner source of energy, its high costs pose a barrier towards its implementation (Adnan et al., 2019).According to literature the operating costs for the production of biomethane (or biogas) are indeed high (Parkes, 2017; Wilken et al., 2019).

In this thesis the following operating costs associated with production of bio-electricity (from biomethane) are considered,: cost of waste transportation, cost of biogas generation, cost of upgrading biogas to biomethane & cost of generating electricity from biomethane.

It is important to note that these costs are based on the literature available and are roughly approximated for different set of systems. In this thesis these costs are mainly used to compare the different technological routes. But in the real world these costs may vary based on the size of the operation, location of the Waste-to-Energy system, choice of technological infrastructure & other socio-economic factors such as labour costs.

Apart from operating costs, there are capital costs associated with the generation of bio-electricity, which are not considered in this thesis. According to literature the capital costs associated with the production of biogas from anaerobic digestion & the infrastructure used to upgrade biogas to biomethane are high and may serve as a barrier towards its implementation (Adnan et al., 2019; European Compost Network, 2016; Parkes, 2017).

Thus, the costs considered in this thesis may not exactly represent reality. In fact if capital costs are considered, then the presence of an additional infrastructure for converting biogas to biomethane may actually increase the cost of producing per kWh of electricity from biomethane, than shown here. Subsequently it may affect the choice of the technological route.

To address the high costs associated with the generation of bio-energy, various countries or institutions have made use of financial instruments to help set up the required infrastructure. The financial instruments include the provision of subsidies in Denmark, tax exemptions in Sweden , certificates for energy renewability in the UK or feed-in-tariffs in Germany (Achinas et al., 2017; Parkes, 2017).

Germany has one of the highest number of biogas based plants in Europe. The success can be attributed to the provision of feed-in-tariffs (European Compost Network, 2016; Parkes, 2017). Feed-in-tariffs provide the bio-energy producers a guaranteed price, over a fixed period of time, for the energy supplied by them to the grid (Wilken et al., 2019).

Thus, with help of financial or policy instruments the technological route *Biomethane to electricity* can become economically feasible.

8.1.1 Waste incineration vs Electricity generation from biogas

The results of the baseline scenario in Chapter 7 show that incineration is economically & environmentally a better technological route than *Biogas to electricity*. This is mainly due to the higher energy output from incinerating waste as compared to biogas.

Such a phenomenon is seen in some of the literature as well. According to Ulf Sonesson, Dalemo, Mingarini, and Jönsson (1997), waste incineration has a higher energy ratio as compared to anaerobic digestion. Energy ratio is defined as the ratio of the output energy to the input energy. Di Maria and Micale (2015) stated that incineration generates larger amount of net renewable energy as compared to Anaerobic digestion, followed by composting.

Di Maria and Micale (2015) performed a Life Cycle Assessment (LCA) of incineration and compared it with that of anaerobic digestion for an Italian district. Based on the results, one of conclusions is that incineration of OFMSW leads to maximum environmental benefits compared to anaerobic digestion. As per the authors this is mainly due to high amount of energy recovered from incineration.

Furthermore, based on the analysis of more than 200 LCA studies of waste management, Laurent, Bakas, et al. (2014) & Laurent, Clavreul, et al. (2014) noticed that there is no conclusive agreement on which technology, incineration or anaerobic digestion, is better for OFMSW.

But this model result for the baseline scenario does not necessarily imply that incineration of OFMSW is a better option over production of biogas. This is due to the following reasons: *Firstly*, the OFMSW considered in this research is assumed to be dry and have Lower Heating Value (LHV) of 4000 MJ/tonne. But as discussed in Chapter 4, the LHV of OFMSW can be lower. Also, high moisture content of OFMSW can reduce the efficiency of the process and subsequently the energy output.

Furthermore, the exact composition needed to determine LHV & moisture content of the OFMSW is not examined due lack of literature pertaining to it. But if the relevant data is available, it may lead to a lower energy output from the waste incineration of OFMSW. At certain instances this output can be less than from biogas.

Secondly, there are other environmental indicators other than the Global Warming Potential (GWP) or the amount of CO_2 abated, which are not evaluated in this thesis. Moreover, the amount of CO_2 abated by each WtE technology in this research is mainly a consequence of the energy generated by them. Higher the energy generated by a WtE technology, higher is the fossil-fuel based energy displaced. Subsequently, more CO_2 is abated.

But studies have shown that as compared to anaerobic digestion, incineration of OFMSW may release a higher amount of other Green House Gases (GHG) (or increase the values of the environmental indicators) such as Sulphur Dioxide (or Acidification potential), Phosphates (or Eutrophication potential) and Alkenes (or Photochemical ozone creation potential) (Khoo, Lim, & Tan, 2010; Sonesson, Björklund, Carlsson, & Dalemo, 2000).

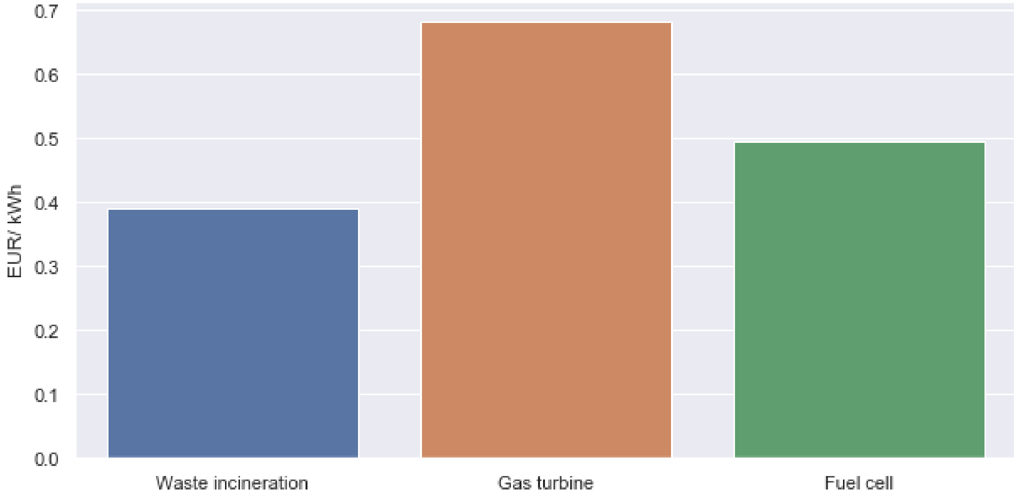
Therefore, if the other environmental indicators are compared for the two WtE technologies, then in that case the technological route *Biogas to electricity* may be more environmental than waste incineration.

Secondly, use of a more efficient technology to convert biogas to electricity gives the same output as the waste incinerator and a slightly higher CO_2 abated per tonne of OFMSW.

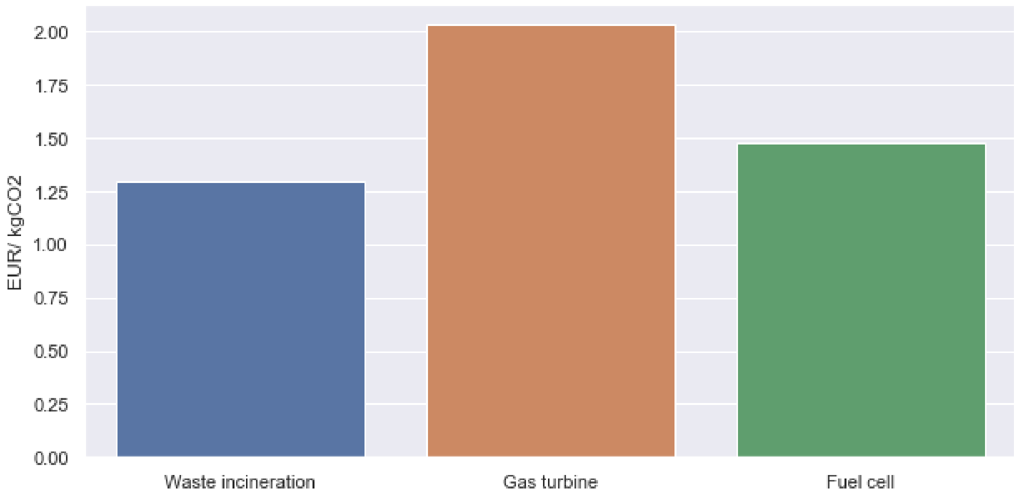
In Chapter 4, Table 4.7 there are two technologies listed to generate electricity from biogas: Gas turbine & Fuel cell. The former has a lower efficiniency (34%), lower operations cost and is more widely used. While the latter has a higher efficiency (50%), higher operations cost and still yet to be commercially viable.

By replacing the data values for a gas turbine with that of a fuel cell, the Table 4.9 can be recalculated. Based on which the two model KPIs are compared for the different technologies in Figure 8.1 .

Figure 8.1: Comparison between Gas Turbine, Fuel cell & Waste incineration



(a) Cost of generating per kWh of electricity (KPI 2)



(b) Cost of abating per kg of CO_2 (KPI 3)

Although using a fuel cell produces equal amount of electricity from one tonne of OFMSW as the waste incinerator in this case (300 kWh), but its higher cost imply that waste incinerator is economically & environmentally more viable if the two KPIs are compared.

The operations costs of a technological route involving fuel cells is high due to the following reasons: the collection cost of organic waste is higher than residual waste and the cost of generating per kWh of electricity in case of a fuel is high.

Although biogas based fuel cell technology or Solid Oxide Fuel Cell (SOFC) technology is said to reach its mature technology status, but there several barriers towards its commercialization (Saadabadi et al., 2019, p. 210). Due to this reason gas turbine is selected over SOFC in this thesis

Presuming the technology commercialization over time, the cost of generating electricity may reduce and subsequently it may be economically & environmentally more viable than waste incineration.

8.2 Influence of Pro-environmental behaviour

As stated in the earlier chapters that pro-environmental behaviour, as per VBN theory, is primarily formed based on the biospheric & altruistic values of individuals. Individuals with presence of high biospheric or high altruistic values may show high instances of pro-environmental behaviour or high waste separation behaviour (Davis, 2014; Lind et al., 2015; Steg et al., 2005).

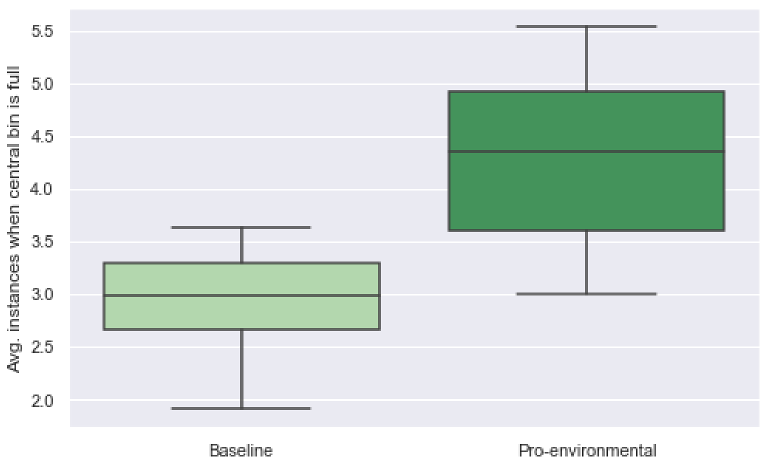
Furthermore, values are intrinsic to individuals (or agents) and they are the internal factors that facilitate the waste separation activity. But the based on the results presented in Chapter 7, it is observed that internal factors (such as values) can determine the waste separation action upto a certain *limit*. They cannot solely be a factor to increase waste separation, it is also the external factors pertaining to the WMS that play a role in determining their influence.

In the baseline scenario conditions (Bin size: 240 L & Frequency of collection: Once in two weeks), the set of that agents are *Pro-environmental* (or the experimental run 'Pro-environmental') have a waste separation rate is lower than the agents in the baseline scenario[1].

The possible reason for this result is that when agents have high biospheric & altruistic values (as in the case of the experimental run 'Pro-environmental'), they tend to have higher personal norm (PN) values. Higher than the baseline scenario agents and even the 'Highly biospheric' agents . The high PN value prompts agents to separate more. Because of which the central organic bin fills up faster. So, when an agent goes to separate its organic waste, it encounters a filled up organic bin more often.

This can be validated by the analysis of the model runs and expert opinion. In the y-axis of Figure 8.2, the average of the instances when an agent encounters a central bin is plotted for the baseline scenario and the 'Pro-environmental' run. As seen from the plot, agents that are 'Pro-environmental' tend to encounter a full organic central bin more frequently than the agents in the baseline scenario. Therefore, the agent has no choice but to dispose it's organic waste in residual waste bin, thus decreasing the waste separation rate.

Figure 8.2: Average instances of an agent encountering a full central bin



Furthermore, according to a waste management expert in the municipality of Amsterdam, this could happen during a quick overflow i.e. when there is a low bin capacity and

[1]The agents in the baseline scenario have an equal mix of biospheric, altruistic & hedonic values. They represent the values held by Dutch households and presumably by the households & SMEs in Havenstad

high frequency of disposal (Personal communication with expert, February 28, 2020: See Appendix C.2.2)

This result highlights how a smaller bin size can reverse the intended effect of Pro-environmental behaviour. Therefore, in Section 7.3.1 the influence of different bin sizes & frequency of waste collection on waste separation rate of *Pro-environmental* agents is examined. Based on the results presented, it is observed that waste separation rate of *Pro-environmental* agents increased than their baseline scenario counterparts when the bin size increased from 480 L to 3000 L.

In conclusion, to achieve high waste separation not only do you need the presence of high biospheric and high altruistic values but also a suitable infrastructure that is able to collect higher amounts of sorted waste.

8.3 Structural & informational interventions

Apart from internal factors, external factors are important for facilitation of waste separation activity. In this thesis these external factors are modelled as structural and informational interventions. Structural interventions involve varying the parameters of the WMS, such as *bin size & frequency of collection*. Informational intervention is modelled in the form of a *awareness campaign*, which aims to increase the personal norm values of the agents, thereby making them more *Pro-environmental*.

8.3.1 Structural intervention vs Informational intervention

In Section 3.2, the influence of the two types interventions on the model KPIs is analysed with the help of plots. According to the analysis presented, in case of the baseline conditions, structural intervention is shown to be more influential towards the waste separation rate (and subsequently the model KPIs) as compared to the informational intervention.

This maybe due to two reasons: *Firstly*, the informational intervention that has been modelled is based on awareness campaign which has been already implemented in the real world and its influence has been studied. Thus, the results of the study can be compared with the model results in this thesis. According to Van der Werff et al. (2019), the awareness campaign did not manage to increase the waste separation significantly. In fact the % increase in waste separation rate by implementing the awareness campaign, as measured by the authors, is 18%. As compared to the model results, there is no change observed by implementing the intervention in the baseline scenario. This could be due to difference in socio-demographics & behaviour values of agents in the baseline scenario of the model experiment and the agents that are studied by Van der Werff et al. (2019).

Secondly, the informational campaign tends to effect the waste separation behaviour of agents, by increasing their PN values. But as discussed previously , high personal norm (pn) values (or high Pro-environmental behaviour) may not necessary increase the waste separation rate.

In conclusion, according to the model results, implementing a structural intervention is shown to be more influential on the waste separation rate and subsequently model KPIs than the informational intervention.

Furthermore, a similar observation is made by Meng et al. (2019). According to the authors, the effect of external factors (such as interventions) on household's waste separation is twice that of internal factors such as values or personal norms.

But ofcourse, this result can be different in case another informational intervention is considered or if the values of the agents are different from the ones in the baseline scenario of this study.

8.3.2 Role of structural & informational interventions

In order for agents in the baseline scenario to become 'Pro-environmental', there is need for informational intervention such as a awareness campaign.

Furthermore, in the previous section it is highlighted that there is need for a structural intervention such as increase in bin size, in order to increase the waste separation rate of Pro-environmental agents.

Thus, there is need for both the interventions to be in place and act together to achieve high waste separation rate and subsequently desirable KPI values. To examine such a scenario, in this sub-section the combined influence of the structural & informational interventions on the model KPIs is discussed.

Assuming a scenario wherein the technological route is *Biomethane to electricity* and the agents are *Pro-environmental* due to an informational intervention , two organic central bin sizes (480 L & 3000 L) are examined for the model KPIs in the following plots. Also, the KPIs values for the these runs are compared with that of the baseline scenario. In the baseline scenario, the agents are not *Pro-environmental*, the bin size is fixed at 240 L and the technological route is *Biogas to electricity*.

Figure 8.3: Electricity generated per tonne - KPI 1

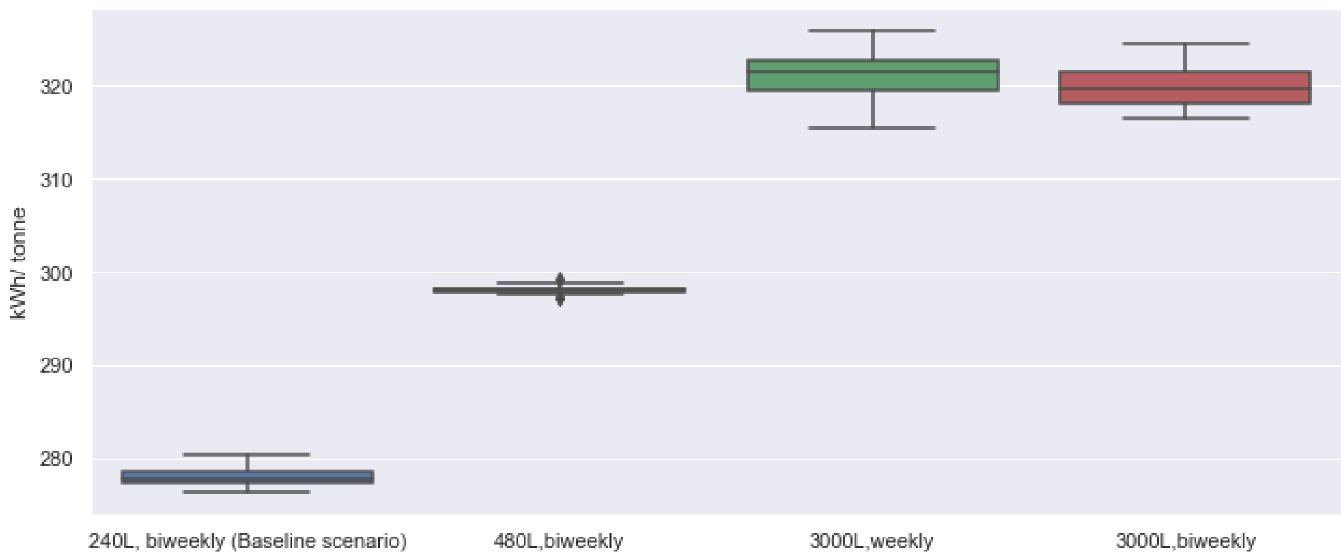


Figure 8.4: Cost of generating per kWh electricity - KPI 2

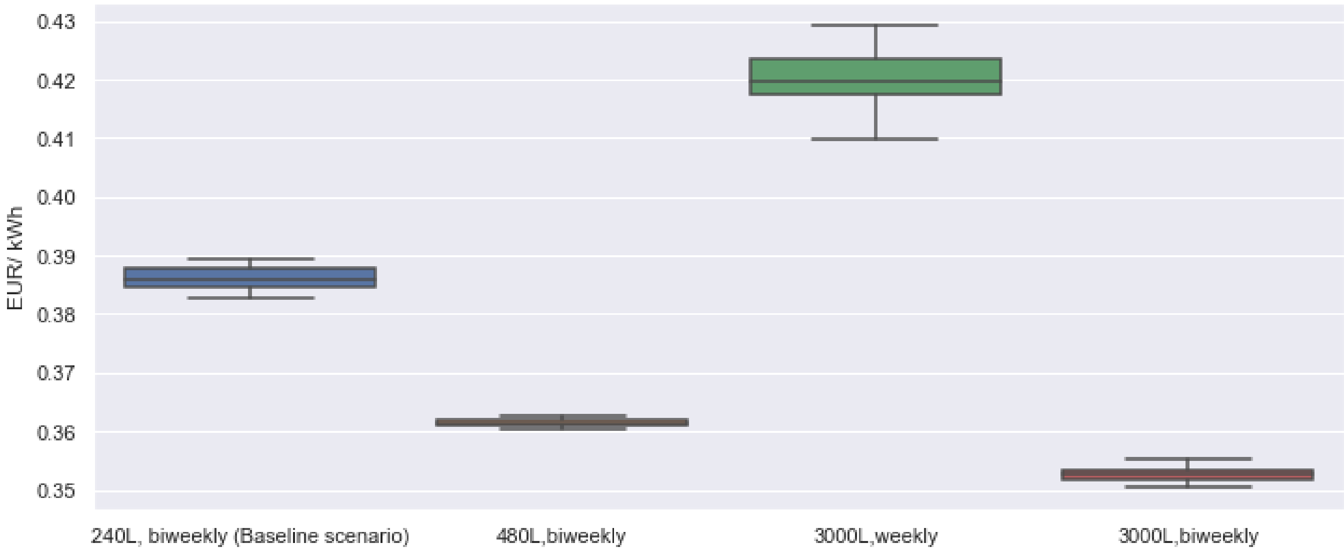
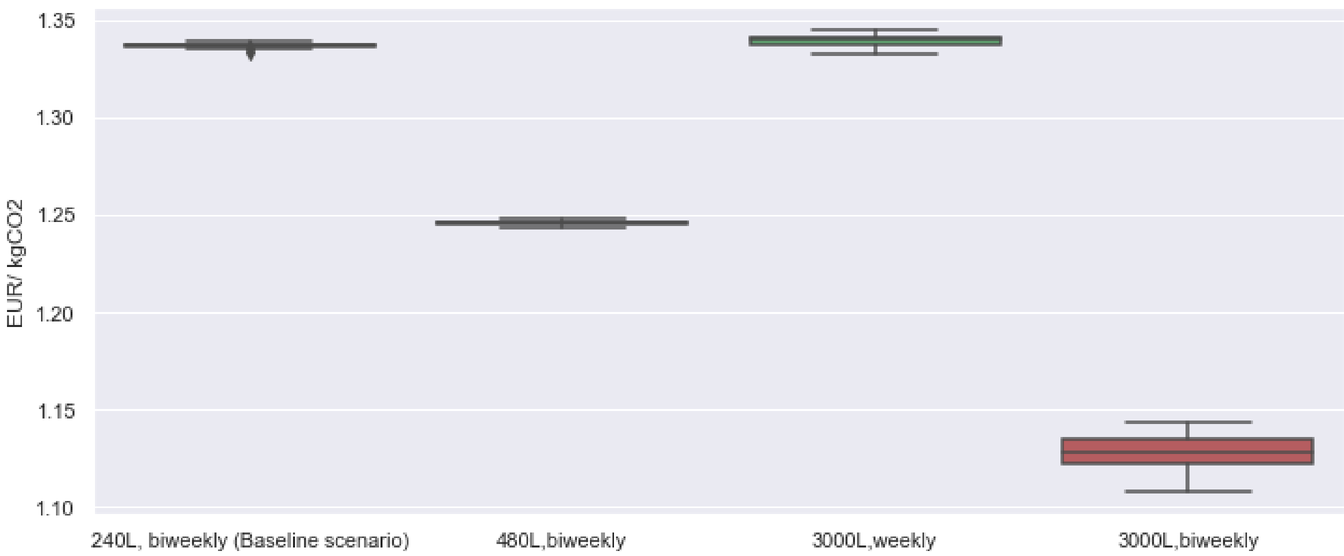


Figure 8.5: Cost of abating per kg of CO_2 - KPI 3



By analysing the plots for the different bin sizes & comparing them with that of the baseline scenario, the following conclusions can be made: *Firstly*, employing the technological route *Biomethane to electricity* and structural & informational interventions, the amount of energy obtained from one tonne of OFMSW (Figure 8.3) is higher as compared to the baseline scenario.

Secondly, increasing the bin size from 480 L to 3000 L resulted in more energy (in kWh) obtained per tonne of OFMSW, at a lower generation cost (Figure 8.4) and a higher amount of CO_2 abated (Figure 8.5).

Although increasing the bin size from 480 L to 3000 L is the preferred choice, but it has certain drawbacks. Increasing the bin size and storing the waste longer may make the bin more unhygenic and smelly. Thus, decreasing the instances of an agent separating its waste. Also, it may reduce the calorific value of OFMSW (Personal communication with expert, February 28, 2020: See Appendix C.2.2).

To prevent this the waste can be collected more frequently or the design & construction of the bin can be changed. The latter option is more economically, owing to higher costs of increasing the frequency of waste collection.

8.4 System design

Based on model results and discussions a system design for managing & processing OFMSW is proposed. The system design mainly involves changing the parametric values of the elements in the baseline scenario with the help of interventions.

Firstly, the technological route is changed from 'Biogas to electricity' to 'Biomethane to electricity'. This is because the latter is a more economical & environmental route to generate energy from OFMSW.

Secondly, the pro-environmental behaviour of the agents is increased with help of informational interventions. This is accomplished when the agents have high biospheric & altruistic values and low egoistic & hedonic values respectively.

Thirdly, the bin size is increased from 240 L to 3000 L because it gives a high waste separation of the whole block. High waste separation is economically & environmentally more desirable.

Fourthly, the proportion of households to SMEs is increased in the block. This is based on the result shown in Section 7.1, which shows that the presence of higher number of households, as compared to SMEs, result in a higher waste separation rate. Therefore, in the block of the system proposed, the proportion of households to SMEs is 70% to 30%.

To conclude, the mean values of three model KPIs & waste separation rate for the baseline scenario and the system proposed are compared in Table 8.1. The values for the system proposed are obtained by running the model based on the parameters described above.

Table 8.1: Comparison between baseline scenario and the system proposed

Output	Baseline	System proposed	% change
Waste separation rate	6.9%	53.43%	+ 674.34%
Energy generated per tonne OFMSW	277 kWh	322 kWh	+ 16.24%
Cost of generating per kWh of energy	0.386 €	0.352 €	- 8.80%
Cost of abating per kg of CO_2	1.34 €	1.13 €	- 15.67%

It is important to note that the KPI values in the table above are measured over a period of 7 months. In G, it is seen that by increasing the duration of the run these values may vary. For example, the value of energy obtained per tonne OFMSW has shown to increase to 350 kWh , when the duration of the model run is 24 months. Therefore, with the increase in model duration the potential of energy generated from OFMSW may increase as well.

9. Conclusion

This chapter concludes the research conducted by providing answers to the main research questions & its sub-questions. Furthermore, the research relevance (Section 9.1) , limitations of this research (Section 9.2) and the recommendations for future research (Section 9.3) are presented as well. The chapter ends with recommendations (Section 9.4) for the stakeholders of Havenstad to help establish a Waste-to-Energy system.

SQ1 What are the characteristics of the commonly used WtE technologies to treat OFMSW ?

The first sub-question can be answered with the help of Table 9.1, which is based on the data found from literature in Chapter 4 and its calculations in Appendix D.

Table 9.1: Characteristics of the Waste-to-Energy (WtE) technologies

	Technological Route	Carbon dioxide abated per unit	Electricity Biomethane generated per tonne	Cost of abating per kg of CO_2	Cost of generating per unit
1	Biogas to electricity	335 gCO_2 / kWh	204 kWh	2.03 €	0.68 €
2	Biogas to biomethane	1.766 $kgCO_2$ / m^3	65.10 m^3	1.21 €	2.15 €
3	Biomethane to electricity	335 gCO_2 / kWh	392.55 kWh	1.02 €	0.34 €
4	Waste incineration	335 gCO_2 / kWh	300 kWh	1.30 €	0.39 €

As seen from the table above, generating biomethane from the biogas obtained from OFMSW and using it to generate electricity is economically and environmentally the most favourable technological route. This is because the cost of generating per unit & cost of abating per kg of CO_2 is the lowest.

SQ2 How does distribution of households and SMEs in a neighbourhood influence the energy generated from their OFMSW, its economics of energy generation and the economic efficiency of CO_2 abatement ?

Higher proportion of households to SMEs result in a higher waste separation rate. While increasing the number of inhabitants per household decreases the waste separation rate.

Depending on the WtE technology to treat source separated OFMSW and waste separation rate, the distribution of households & SMEs influences the energy generated from their OFMSW. In case of the WtE technology to treat source separated OFMSW in the baseline scenario (i.e. *Biogas to electricity*), high proportion of SMEs to households is preferred. But in case of the second technological route (i.e. *Biomethane to electricity*), high proportion of households to SMEs is preferred.

The economics of energy generation is shown to vary for different proportion of households & SMEs. For different household types, this value does not vary alot. Whereas, the economic efficiency of CO_2 abatement is shown to vary more as compared to the previous indicator.

SQ3 What is the influence of different types of interventions on the energy generated from OFMSW, its economics of energy generation and the economic efficiency of CO_2 abatement?

Structural intervention is more influential than informational intervention on the energy obtained from OFMSW and other key indicators. Structural intervention involves changing the operating state or conditions of the Waste Management System and Informational intervention is the implementation of an awareness campaign aimed at increasing the personal norm values of the households & SMEs.

Structural interventions such as increase in central bin size & increase the frequency of waste collection, contribute towards a higher waste separation rate. Although increasing the bin capacity is environmentally & economically more desirable than increasing the frequency of waste collection.

SQ4 What is the influence of different behaviour values on the energy generated from the OFMSW,its economics of energy generation and the economic efficiency of CO_2 abatement ?

Presence of high biospheric and high altruistic values did not significantly influence the energy obtained from OFMSW. While presence of high egoistic and high hedonic values can have a stronger influence on the energy obtained from OFMSW.

The economics of energy generation has shown to be sensitive to the presence of each and every behaviour value. While the economic efficiency of CO_2 abatement is shown to be only sensitive to hedonic & egoistic values.

Additionally, the waste separation rate due to the presence of biospheric & altruistic values is shown to be dependent on the central bin size. In order to get a high waste separation rate, a larger bin is required in addition to the presence of these two values.

SQ5 How do different WtE technologies, that treat source separated OFMSW, influence the contribution of interventions and behaviour values on economics of energy generation & economic efficiency of CO_2 abatement ?

Among the three WtE technological routes to treat source separated OFMSW, *Biomethane to electricity* is economically & environmentally the most desirable.

In case of the technological route, *Biogas to electricity* low waste separation is preferable because waste incineration is economically & environmentally more desirable. For the second route,*Biomethane to electricity*, high waste separation is preferable beacause waste incineration is economically & environmentally less desirable. In the figure below a list of factors to realise the desirable outcomes for the two technological routes are presented.

Biogas to electricity	Low waste separation	Small central bin (240 L)	Presence of high egoistic & hedonic values	High proportion of SMEs to households
Biomethane to electricity	High waste separation	Large central bin (480 L or 3000 L)	Presence of high biospheric & altruistic values	High proportion of households to SMEs

To conclude, the choice of WtE technological route can play a big role in determining the contribution of (structural) interventions and behaviour values on economics of energy generation & economic efficiency of CO_2 abatement.

What is the potential of energy generation, its net operating costs and CO2 abated from per tonne Organic Fraction of Municipal Solid Waste(OFMSW) generated by households and Small-Medium Enterprises(SMEs) ?

Based on the system proposed in Section 8.4, the potential of energy generated from one tonne of OFMSW, over a period of 7 months, is 322 kWh, at a rate of 0.352 € per kWh and results in the abatement of 100 kg of CO_2 per tonne of OFMSW processed.

Compared to the baseline scenario, the waste separation rate increases by nearly 7 times. The energy generated per tonne of OFMSW incrased by 16.24%. Furthermore, the cost of generating per kWh of energy decreased by 8.80% and the amount of CO_2 abated increases by 25.32%.

9.1 Academic and societal relevance

The academic relevance of this thesis is that it examines the link between the waste separation behaviour & Waste Management System (WMS) on the energy output from OFMSW. The results of this thesis highlight the importance of aspects such human behaviour, waste bin sizes and urban planning when studying a WtE system. Furthermore, it opens the avenue for future research to examine systems not only from their technical perspective, but also from a social perspective.

The societal relevance of this research is that it highlights the importance of Pro-environmental behaviour and WMS on realising the viability of WtE as a renewable source of energy. The results show that the presence of high waste separation behaviour not only reduces the cost of the waste management process, but also contributes towards a cleaner environment.

9.2 Research reflection & limitations

In this section, a personal reflection is provided by the author on assumptions made, exclusion of certain concepts and research limitations. The main reason for most of the assumptions made or concepts excluded is that it helped reduce the complexity of the thesis, which is important due to a short time period for carrying out the thesis research. Also, the author acknowledges struggling with time period allocated.

The section is divided in such a manner that it addresses each element of a system, starting from the description of the OFMSW.

The composition of the OFMSW, presence of impurities & the moisture content of OFMSW is not considered in this research. As discussed in the previous chapter, these aspects can influence the energy output from a technological route & subsequently the model KPIs. To avoid increasing the complexity of this thesis project and due to a lack of time, they are left out.

Within the technological routes, concepts like transportation of biogas/biomethane, waste contamination, energy losses and capital costs are not addressed. The inclusion of these concepts could reduce the energy output from processing organic waste and increase the costs of the whole system. Thus, affecting the choice of the technological route, specially in case of the route *Biomethane to electricity.*

Next, in the model the choice of Value-Belief Norm(VBN) as the social theory to capture & predict the waste separation behaviour stems from the fact this theory has been employed by researchers in the past to explain pro-environmental behaviours successfully

It's use of behavioural values as an input to describe the pro-environmental behaviour, made it easier to implement and quantify in a Agent-Based Model. But this does not close the door to other behavioural theories like Theory of Planned Behaviour(TPB).

The results of the model could be different if the VBN theory is replaced by TPB. An agent based on TPB would work towards utility maximization. This would make the model more sensitive towards parameters such as : distance of the bin or the bin convenience, for that matter.

Apart from the exclusion of TPB, the concept of social norms is left out of this research and the ABM. Social norms can play a major role in forming of waste separation behaviour. The inclusion of such a concept may introduce more 'emergent patterns' in the model.

Lastly, the coefficient values of the variables of the VBN theory are estimated by calibrating the model based on literature available about the behavioural values of Dutch households and waste separation rate of Amsterdam. But this estimation could have been more accurate if a Schwartz Value Survey (SVS) could have been conducted on Amsterdam households & SMEs. This would provide an accurate measure of the behavioural values and subsequently the regression coefficient values that relate the variables of VBN theory.

In case of the structural intervention, more settings could have been examined. Such as employment of a door-to-door service to collect organic waste or the provision of insinkerators to collect organic waste from households. Inclusion of these settings could have resulted in wider variety of choices for the system.

Furthermore, the influence of hygiene levels of the central bins on the waste separation intent of the agents is not examined. Especially for a large bin size (like 3000 L), this aspect can play a role in determining the waste separation rate.

Lastly, the CO_2 emitted during the transportation of OFMSW from the central bins to the WtE infrastructures is not considered. Inclusion of this may result in lower abatement of CO_2 from processing OFMSW into energy.

9.3 Recommendations for future research

Based on the research results and limitations, a list of recommendations for future research are given in this section.

First, aspects like capital costs of the technological routes and waste composition should be considered in future research when evaluating different WtE systems or technological routes. Additionally, the impact of novel subsidies or financial instruments in increasing the economic viability of the technological routes should be examined.

Second, the relationship between Pro-environmental behaviour and the level of contamination in the source separation organic waste should be more closely examined. Also, the presence of contaminants or other losses during the WtE process should be studied for their influence on the energy outputs of different WtE technologies.

Third, the ABM can further be improved by inclusion of concepts of bin convenience and socio-demographic factors.

Concepts like hygiene level of the bin, its design, ergonomics and its subsequent influence on the waste separation intent of the agents should be examined. Especially in case of a large central bin.

Socio-demographic factors, apart from internal & external factors. are said to influence waste separation as well. In future studies it is recommended to include these factors, especially when comparing the results for countries with different cultural & economic backgrounds. Moreover, according to Meng et al. (2019), there is a need for more research on the influence of these factors on the waste separation.

Lastly, different social theories (like TPB) should be employed in future ABMs to predict waste separation behaviour and compare their results with that of VBN theory.

Fourth, different waste collection infrastructures or strategies should be examined. For example, the use of insinkerators & door-to-door collection should be compared with the centralized waste collection infrastructure.

Additionally, financial incentives for individuals to separate waste or use of persuasive games should be examined for their influence on the waste separation behaviour of the individuals.

Fifth, future research should look at the feasibility of realising the system proposed from a process management & stakeholder perspective.

9.4 Recommendations for Havenstad

In this thesis, the planned city of Havenstad is used as a case study to construct a baseline scenario. By varying the elements & parameters of the baseline scenario, a new scenario or system for Havenstad is proposed. The proposed system is shown to be economically & environmentally more desirable for processing OFMSW into energy. In order to realise this system the following recommendations are made:

Firstly, it is environmentally and economically more benefical to generate electricity from biomethane rather than biogas. But the implementation of the required WtE technological infrastructures would require financial support from the government.

Secondly, the central bin size should be increased from 240 L to 480 L to increase the waste separation rate. Furthermore, the bin size should gradually increase from 480 L to 3000 L. During this gradual increase, there should certain informational interventions in place that increase the pro-environmental behaviour of the residents. This gradual increase in bin size along with the informational intervention in turn helps in the gradual increase in the waste separation rate. Also, it helps check the hygiene of the bin during this gradual increase.

Thirdly, from a urban planning perspective of Havenstad, having less number of inhabitants in a neighbourhood results in higher waste separation. But practically it might not be possible.

Although, the equal distribution of households and SMEs in a block is fine. But, if possible, a higher proportion of households over SMEs is environmentally & economically more desirable.

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Appendices

A. Organic waste of Amsterdam households & SMEs

A.1 Households

The distribution of the households types in Amsterdam is given in Figure A.1. The households types planned in Havenstad can be classified according to the following types:*Single bedroom apartment, Two-bedroom apartment, Three-bedroom apartment and Four-bedroom apartment* (Gemeente Amsterdam, 2019a). By assuming per captia organic waste generation in Amsterdam to be 92 kg, table gives the organic waste generated by the different household types in Amsterdam

Figure A.1: Distribution of household types in Amsterdam(Gemeente Amsterdam, 2018)

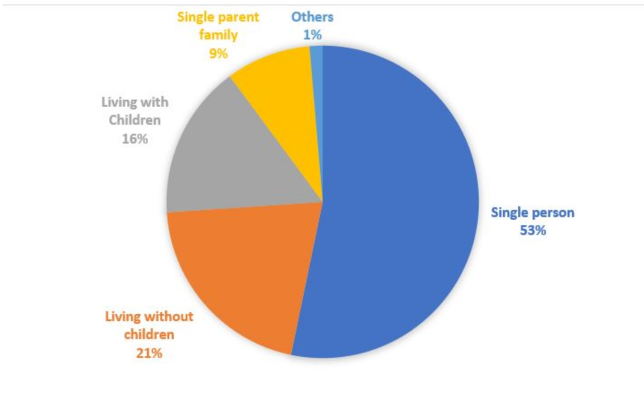


Table A.1: Organic waste generated by Amsterdam households per year

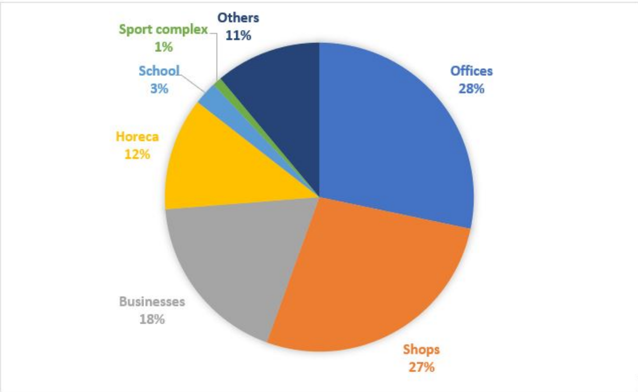
Type	No. of inhabitants	Waste generated
Single person	1	92 kg
Living without children	2	184 kg
Single parent family	2-3	184 kg to 276 kg
Living with children	3-4	276 kg to 368 kg
Others	5	460 kg

A.2 Small-Medium Enterprises

According to the report by Gemeente Amsterdam (2017b) SMEs in Amsterdam can be classified into the following types: Offices, Shops, Businesses, Horeca, School, Sport complex and

Others. Figure A.2 gives the distribution of the commonly found SMEs in Amsterdam. The waste generated by SMEs is composed of paper & cardboard, organic waste, plastic waste and other residual waste(Gemeente Amsterdam, 2017b). The Organic fraction of municipal solid waste(OFMSW) of SMEs mainly consists of fruits & vegetables and their cuttings, bread, garden waste and other organic residues. But distribution of these types of organic wastes can vary among the SMEs(Goossensen, 2017).

Figure A.2: Distribution of SMEs in Amsterdam(Gemeente Amsterdam, 2017b)



In Table A.2 the OFMSW generated by the different types of SMEs is given. Only a quarter of the total number of SMEs dispose their waste through *reinigingrecht* or through the waste bins meant for households(Gemeente Amsterdam, 2017b).Out of which 'Offices' and ' Shops' tend to use the waste bins meant for households more frequently than other types of SMEs(Gemeente Amsterdam, 2017b, pp.8).

Table A.2: Organic waste generation of SMEs in Amsterdam(Gemeente Amsterdam, 2017b)

Type	**Distribution(%)**	**Organic waste generated per year(kg)**
Offices	28%	730 kg
Shops	27%	310 kg
Businesses	18%	410 kg
Horeca	12%	860 kg
Others	11%	25 kg
School	3%	1520 kg
Sport complex	1%	6050 kg

B. Operation cost or OPEX of conversion technologies

B.1 OPEX for anaerobic digester

The OPEX or operating costs of an anaerobic digester are mainly concerned with the processes that enable the extraction of biogas from organic waste. According to Haddad (2014) the following parameters contribute towards the operating costs of an anaerobic digester.

- Raw material
- Personnel
- Process maintenance
- Material costs
- Electrical costs
- Insurance, amortization, depreciation, taxes and interest
- Cost of R&D, monitoring and safety procedure
- Cost of distribution

These parameters are not fixed for all types of anaerobic digesters. They may or may not be considered when calculating the operating costs of a digester. The size of the digester or the amount of organic waste that it processes can influence its operating costs.Lagen and Mitchinson (2010) mentioned that the operating costs of anaerobic digester can decrease when the processing capacity of the digesters increase. The separate collection of organic waste can amount to 15 €(Veeken, Hamminga, & Mingshu, 2005) to 100 € per ton of OFMSW (NVRD, 2016). Table B.1 provides the different operating costs of anaerobic digesters from literature sources. From the values given in the table below, the operating cost considered for this thesis research is the one deduced by Olivard (2017). The reason behind choosing this value is because a)the author provides performs a detailed calculation of the operating costs and b)the processing capacity of waste and type of digester process that is considered is similar to the BIOCEL digester.

Table B.1: Operating costs of anaerobic digesters

Source	Operating costs (Per ton of OFMSW)	Specifications
Goossensen (2017)	40 € to 75 €	Specifications not given
Olivard (2017)	61.22 €	Processing 50,000 tons of food waste per year
Heeb (2009)	32.81 € to 38.61 €	Processing 91.25 t/y of MSW
European Commission (2016)	12 €	Biogas from mono-digestion
Lagen and Mitchinson (2010)	35 €	Processing 180000 t/y of MSW
Lagen and Mitchinson (2010)	29.7 €	Processing 310000 t/y of MSW
Mutz, Hengevoss, Hugi, and Gross (2017)	10 € to 15 €	Cost for developing nations

Figure B.1: OPEX summary provided by Olivard (2017)

	DRY PROCESS		
	Number of units	Price	Total price (€/year)
STAFF	**16 staff**	**40,000 €/y**	**640,000**
Exploitation chief	1		
Administration staff	1		
Technical officer	1		
Shift chef	1 x 4 shifts		
Engines driver	2 x 2 shifts		
Unqualified workers	1 x 2 shifts		
Maintenance officer	1		
Mechanical officer	1		
Electrical officer	1		
Electrical Energy			**56,250**
Connection	1.5 MW	2,500 €/m/MW	45,000
Consumption	50 h	225 €/h	11,250
Maintenance			**651,250**
Civil work	7,500,000 €	0.5%	37,500
Equipments	16,750,000 €	2.5%	418,750
Generators	13,000 MWh	15 €/MWh	195,000
Water	**4,000 m^3**	**2 €/m^3**	**8,000**
Gasoil	**50,000 L**	**1.3 €/L**	**65,000**
Air treatment reagents	**50,000 t**	**1.5 €/t**	**75,000**
Water treatment reagents	**22,000 m^3**	**3.0 €/m^3**	**66,000**
Dehydration reagents	**8 t**	**4,000 €/t**	**32,000**
Others (Insurances, environmental plans, etc.)	**50,000 t**	**2.5 €/t**	**125,000**
Refuses to landfill	**14,000 t**	**80 €/t**	**1,120,000**
Hazardous water treatment	**750**	**250**	**187500**
TOTAL			3,026,000

C. Interview and email transcriptions

The transcripts of the semi-structured interview and the emails with the experts are presented here. Their personal details are not shared in this report, but they are available on request.

C.1 Semi-structured interview

Date: 18th December '19 Duration: 45 mins

A semi-structured interview was carried of an Urban planner/ Sustainability advisor for Havenstad. The interviewee works for the Gemeente Amsterdam (Municipality of Amsterdam). The aim of the interview was to discuss the urban planning scenarios for Havenstad and validate the data and other scenarios analyzed in the model. The model is a simulation of a waste-to-energy system, that processes organic waste to energy. The questions posed to the interviewee are given below. Few of the questions were posed by the interviewee during the discussion.

How many households and SMEs do you expect to be a neighborhood block?
At the moment there are no fixed number of households or SMEs for a central bin or block. Instead, it would be interesting to see the numbers from the model.

What is the ratio of households and SMEs?
40,000- 70,000 households ;120,000 people. Number of employees 60,000. The number of SMEs would be high in the total.

Are you interested to evaluate the total number of households and SMEs set up in whole of Havenstad ?
Yes, in addition to that it is interesting to analyze the phase-wise construction of households and SMEs in Havenstad. Particularly Sloterdijk south region where 4500- 5000 households are planned to be set up.Also, this region represents how Havenstad might grow in the future. Scaling up households to 750, 4500,25000, 40000, 70000 in the model and identifying the tipping point for the system in the model would be an interesting insight.

Can you use the same model to check for other systems like shredders or different systems?
Yes, it is possible but would require changes in the model.

Why assume centralized collection? (*Question posed by Interviewee*)
The reason of choosing a central bin is that it is an existing system so makes it easier to implement. Also, there are not many organic waste bins in Amsterdam as compared to those for plastics and paper, so there is a lack of insight of having such a system in place.Therefore, it would be interesting to look at a case when a centralized collection system is used to collect organic waste in Havenstad.

What is the basis of having centralized electricity production over a decentralized one?

According to a research conducted by a Masters student on the anaerobic digestion of organic waste in Amsterdam, a city level anaerobic digestion of organic waste in a centralized manner is advantageous and feasible as compared to decentralized anaerobic digestion of waste at a neighborhood scale.

Are awareness campaigns to increase waste separation a relevant policy to analyze?

Yes, it would be a relevant to look at such a policy.

Are different waste management systems interesting to analyze?

Yes, it would be interesting to identify the optimum mix between the size of the bin and the block based on the influence of households and SMEs. Especially regarding the influence of bin size on the households and SMEs that are covered. Also, the distance of the bin from households is interesting to analyze.

So would the distribution of households and SMEs in a neighborhood block be interesting to analyze?

Yes, it would be interesting to look at the outcome of the waste management system for a varying distribution of households and SMEs as compared to having an equal distribution. For example, if there are 70

Financial incentives can be given to households and SMEs to separate their waste properly. Would that be an interesting policy to look at?

It is not interesting to analyze financial incentives as a policy because of the complex nature of implementing or involving them. It is more interesting to look at more influential policies.

Lastly, there were few questions stated by interviewee which could be answered based on this research

- What is the difference in running the waste-to-energy system with and without subsidies for the operation costs?
- Is the influence of waste contamination of organic waste higher as compared to other parameters?
- Is it a good solution to generate energy out of waste, given that is the least favored option? Given that in general making energy out of waste is not highest priority in a circular economy design.
- What is the influence of a spatial policy as compared to other forms of policies?

C.2 Email correspondence

To gather empirical data and details about the validation of the model, two waste management experts in the Municipality of Amsterdam and a lecturer from the Hogeschool van Amsterdam are contacted via email. A transcription of the email conversations is shared below.

C.2.1 Expert 1

Below is the transcript of the email conversation with an expert in the *Afval en Grondstoffen* department in the Municipality of Amsterdam.

Date: 16^{th} December 2019

(Jereon) :Hereby the answers to your questions
Size and capacity of waste bins that collect the organic/or
residual waste from households and SMEs.
Organic waste (GF): 240 liter, circa 100 kg
Residual waste (restafval): 5m3, circa 500 kg
Organic waste (GF) is collected by 6.500 households
Distance of the organic waste bin/ or residual waste bins from households and SMEs.
Residual waste (restafval): 75 meter Organic waste (GF): there isn't data available

C.2.2 Expert 2

Date: 28^{th} February 2020

A set of questions are posed to a waste management expert in the Municipality of Amsterdam, to evaluate the validity of the model and its results. The transcript of the email, containing the set of questions posed (in bold) and their answers by the expert, is given below:

What is the influence of the central bin size on the waste separation % ? If the capacity is increases, does the waste separation % increase?

No. Unless the capacity enables quick overflow (because of low capacity and a fast speed of waste disposal. If there is overflow people cannot dispose their waste.What is important though is the design of the central bin. It should be visible and distinctive, making it obvious that it is thé location for organic waste. Size could matter.

How does the frequency of waste collection influence the waste separation% ?

Little. Unless low frequency increases the chance of overflow, in which you'd have the same "problem" as the prior question.

It is proven that the longer you keep organic waste stored, the faster it loses it caloric value. Rotting will make the organic waste smelly and unhygienic. For a user it is then not inviting to use the bin for disposal. However: I don't know if there are usability researches done on this item, and how significant this problem could be.

The same could be said for nuisance of rodents. The longer you store waste, the bigger the chance rodents can get into it. But you can avoid that with design and solid construction of the bin.

How does the distance of a household from the central bin influence waste separation% ?

Very much. Location and distance are of great influence. The closer the bin is, how higher the effect on waste separation. See the images below of an example of Paper.

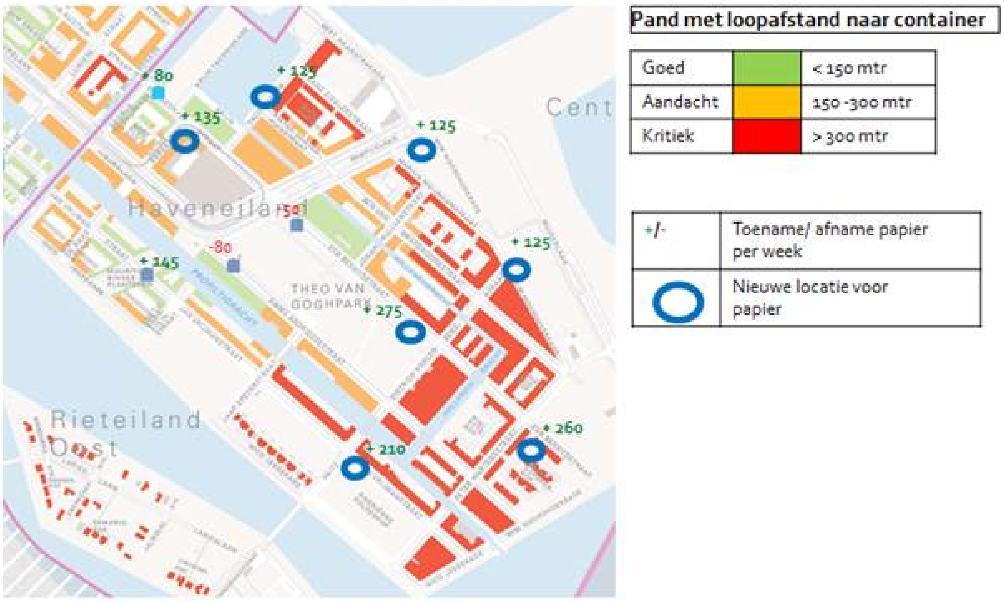
You could easily say that for organic waste the distance is even more important. Paper and glasses are two waste fractions that could easily be stored indoors, in the house. So the necessity to get rid of these waste fractions is lower than with organic waste. Smell, insects and moisturizing makes it unattractive to "store" organic waste at home. It is really important then, if you want to enable waste separation, that bins are located closeby housing. This is for me the reason to investigate and try out kitchen garbage disposals / grinders for organic waste. It is thé waste type that you want to get rid of immediately. If distance and effort increase it is unlikely that many citizens will participate in the waste separations of organics.

Don't forget that apart from distance, location is very important. If you don't put the containers on "spontaneous" or strategic routes, it is unlikely that citizens will find their way.

For paper, glass and textile bins you could use locations closeby bus stops, super markets, crossroads. For organic waste it is even more important to get into the neighbourhood and get close the houses.

The same is to be said about placemaking. If you make the bins attractive (design) and meaningful (story about what happens with it, and why it is important), you create conditions for citizens to participate in waste separation.

Figure C.1: Email attachment



C.2.3 Expert 3

Date: 15thNovember 2019

Below is a rephrased email from a lecturer in Hogeschool van Amsterdam. The recipient is asked questions about the bin size and the distance of the bin from households over an email.

What is the size and capacity range of the central bins?

Central bins (underground ones) that are used for household waste and "reinigingsrecht" (i.e. small enterprises that are allowed to use the household waste system in return for paying a fixed fee to the municipality) have a capacity of 5 to 8 m3, depending on the location.

What is the distance of the central bin from the households?

In general I think the municipality calculates with 160m walking distance maximum.

D. Calculations for technological routes

Here the calculations of the components presented in Table D.1 for the four different technological routes(TR) are discussed.

Table D.1: Characteristics of the different technological routes

	Technological Route	Carbon dioxide abated per unit	Electricity / Biomethane generated per tonne	Carbon dioxide abated per tonne	Operating cost per tonne
1	**Biogas to electricity**	335 gCO_2 / kWh	204 kWh	68.34 $kgCO_2$	139.09 €
2	**Biogas to biomethane**	1.766 $kgCO_2$ / m^3	65.10 m^3	114.96 $kgCO_2$	140.14 €
3	**Biomethane to electricity**	335 gCO_2 / kWh	392.55 kWh	131.50 $kgCO_2$	134.45 €
4	**Waste incineration**	335 gCO_2 / kWh	300 kWh	92.01 $kgCO_2$	119.86 €

D.1 Electricity/ Biomethane generated per tonne

For TR 1, the calculations are discussed in Section 4.8. For TR 4, the value is based on literature discussed in Chapter 4. The calculation for TR 2 is fairly straight forward. From literature 1.536 m^3 of biogas is required to generate 1 m^3 of biomethane. One tonne of OFMSW results in 100 m^3 of biogas. Therefore, dividing 100 by 1.536 results in 65.10 m^3 , that is the biomethane generated per tonne of OFMSW.

The electricity generated from 1 m^3 of biomethanae is 6.04 kWh. Multiplying this value with amount of biomethane obtained per tonne of OFMSW, results in a value of 392.55 kWh per tonne of OFMSW, which is also the electricity generated from TR 3.

D.2 Carbon dioxide abated per tonne

To calculate the carbon dioxide abated per tonne for the first three technological routes, the values in first column are multiplied with that in the second column.

In case of TR 4, a similar calculation is carried out. This results in a value of 100.5 $kgCO_2$ per tonne. But as discussed in Chapter 4, the process of incineration releases emissions due to a) combustion of fossil carbon in organic waste (7.34 kg per kg) b) use of natural gas from the gas grid (1.766 $kgCO_2$ / m^3). By subtracting appropriate 100.5 by the emissions caused, a resultant value of 92.01 is obtained.

D.3 Total operating cost per tonne

Table D.2: Total operating costs

	Technological Route	Electricity Biomethane generated per tonne (w)	Cost of Anaerobic digestion per tonne (A)	Cost of waste collection per tonne (B)	Cost per m^3 of biomethane produced (C)	Cost of per kWh generated (D)	Revenue generated per unit(E)	Total operating cost (per tonne) (A + B + w x C + w x D - w x E)
1	Biogas to electricity	204 kWh	61 €	85 €	-	0.0169 €	0.0507 € per kWh	139.09 €
2	Biogas to biomethane	65.10 m^3	61 €	85 €	0.1113 €	-	0.2012 € per m^3	140.14 €
3	Biomethane to electricity	392.55 kWh (Biomethane = 65.10 m^3)	61 €	85 €	-	0.0213 € (including cost of biomethane)	0.0507 € per kWh	134.45 €

The breakdown of the operating costs and the revenue generated per tonne is given in Table D.2. These costs are based on the literature discussed in Chapter 4. In the table each variable is assigned a letter, which is used in the equation for calculating the total operating cost for each technological route. The equation used is given below, along with an expansion of its components:

$$Total\ operating\ cost = (A + B + w \times C + w \times D - w \times E) \tag{D.1}$$

A = Cost of anaerobic digestion (EUR / tonne)

B = Cost of waste collection (EUR / tonne)

C = Cost per m^3 of biomethane produced (EUR / m^3)

D = Cost per kWh generated (EUR/ kWh)

E = Revenue generated per unit (EUR / unit)

w = Electricity / biomethane generated per tonne (unit / tonne)

Components A,B,C,D are the operating costs associated with a technological route. Component E is the revenue generated. In all the routes the operating costs is greater than the revenue generated. Therefore, the former components are subtracted by latter to give the total operating cost.

A example is given about calculating the total operating cost for the first route: *Biogas to electricity*. Firstly, the value for each component in Equation D.1 is noted down from Table D.2.

$$\begin{aligned} A &= 61 \\ B &= 85 \\ C &= 0 \\ D &= 0.0169 \\ E &= 0.0507 \\ w &= 204 \end{aligned}$$

The value of each component in put in Equation D.1 to get a total operating cost of 139.09 €. Similarly, the operating costs for the rest of the technological routes are found out in similar manner.

The operating cost of TR 4 (Waste incineration) can be broken down based on the components as follows:

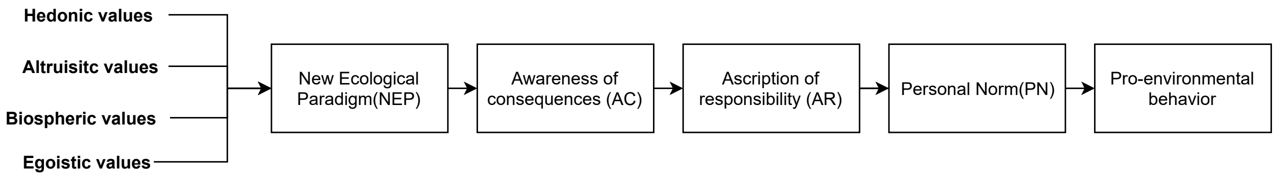
$$\begin{aligned} A &= 70 \\ B &= 65 \\ C &= 0 \\ D &= 0 \\ E &= 0.0507 \\ w &= 300 \end{aligned}$$

When these values are put into Equation D.1, the value comes out to be 119.79. There is an additional cost to it and that is the cost of purchasing natural gas to combust organic waste. Combusting one tonne of organic waste requires 0.368 m^3 of natural gas and based on the price of natural gas from the gas market it would cost a total of 0.07€ . Adding this to the previous value leads to a resultant value of 119.86€

E. Formalization of variables of Value-Based Norm (VBN) theory

The Value-Based Norm theory states that its variables are related to each other and tend to directly influence each other. The chain of variables begins with the input of the four behaviour values and the rest of the variables are related to each other by regression coefficients. For example, in Figure 3.1, the variable 'Awareness of consequences(AC)' can be related to the preceding variable 'New Ecological Paradigm(NEP)' by a coefficient. Similarly, each variable can be related to its preceding variable by a certain coefficient.

Figure E.1: Value-belief Norm (VBN) model



The NEP can be determined based on the values held by an agent.NEP is a scale to measure environmental attitudes, which according to the theory are influenced by values.Therefore, NEP is be represented by a summation of values held by an agent along with certain weight for the values.Bigospheric(b) and alustric(a) values are allocated postive weights of +1.2 and +1 respectively. While egoistic(eg) and hedonic(h) values are allocated negative weights of -1.2 and -1 respectively, owing to their negative influence on pro-environmental behavior(Davis, 2014; Lind et al., 2015; Namazkhan et al., 2019). Thus, for each agent NEP can be calculated with the help of the following Equation E.1.

$$NEP = 1.2 \cdot b + 1 \cdot a - 1 \cdot h - 1.2 \cdot eg \tag{E.1}$$

E.1 Regression coefficients

The other variables of the VBN model can be related by coefficients, uptil the personal norms. 'Pro-environmental behavior' is not considered as a variable because usually high personal norms values here would translate to increased chances of having a pro-environmental behavior.

$$PN = (\alpha \times AR).(\beta \times AC).(\gamma \times NEP) \tag{E.2}$$

Equation E.2 gives the relationship between the PN value and the other variables along with their coefficients. There are three coefficients in the equation (α, β, γ) and each of these coefficents have a value ranging from 0.5 to 1.0. The choice of this range is based on the observations made in literature.

Usually the regression coefficients are determined by conducting a survey. But due to the large sample size a survey could not have been carried out in the given time period of the thesis.

Instead a parameter sweep is carried out to determine the value of the three coefficient values in Equation E.2.Also, the aim of the parameter sweep is to calibrate the model to socio-demographics associated with waste separation in Amsterdam. There in the model contains the necessary parameters required to roughly mimic the demographics of households and SMEs engaging in waste separation in Amsterdam. The algorithm and logic used in this model is same as the model used for the rest of the research, its only the parametric values like household type and their distribution and size of the block is changed.

E.1.1 Socio-demographics of Amsterdam

Namazkhan et al. (2019) carried out a survey among 1461 Dutch households to determine the behaviour values associated with them, using a 9-point scale. The results of the survey are presented in Table E.1

Table E.1: Results of the value survey carried out on Dutch Households

Value	Mean	Standard Deviation	Maximum value	Range
Biospheric	5.17(0.4)	1.27 (0.1)	7.00	7.75
Egoistic	1.94(0.2)	1.23 (0.1)	6.40	7.40
Hedonic	4.62(0.4)	1.38 (0.1)	7.00	7.00
Altruistic	5.14(0.4)	1.18 (0.1)	7.00	7.00

The mean and standard deviation values are scaled down to the 6-point scale used in the model. In Table E.1 scaled down values are presented in brackets along with the original values found by Namazkhan et al. (2019). Also, the numerical values of behavioural values in the table above are used in the case of Havenstad.

According to current demographics of Amsterdam there are 5 types of households and 7 types of SMEs[1]. A central bin in a block is set-up for 60 households and/or SMEs. The distribution of these agents , their waste generation and size of the block are captured in the model. The socio-demographics of Amsterdam captured in the model can be summarized with help of Table E.2.

[1]For more information on the demographics refer Appendix A

Table E.2: Socio-demographics for waste management in Amsterdam

Parameter	Value
Duration of one model run	7 months
Biospheric value	0.4
Altruistic value	0.4
Hedonic value	0.4
Egoistic value	0.2
Capacity of central bin	240 L
Collection frequency	Once in two weeks
Size of block	60 agents (30 households & 30 SMEs)

E.1.2 Determination of coefficients

The waste separation obtained is a function of personal norm values of SMEs and households. The coefficients for the variables of the VBN theory play a role in controlling their personal norm value. Thus, waste separation can be indirectly considered as function of these coefficients.

$$Waste\ separation \approx f(\alpha, \beta, \gamma) \tag{E.3}$$

In Equation E.2 it is seen that personal norm is function of the product of the three coefficients. Therefore one way to ascertain the values of these coefficients is to use their product to measure the waste separation %.

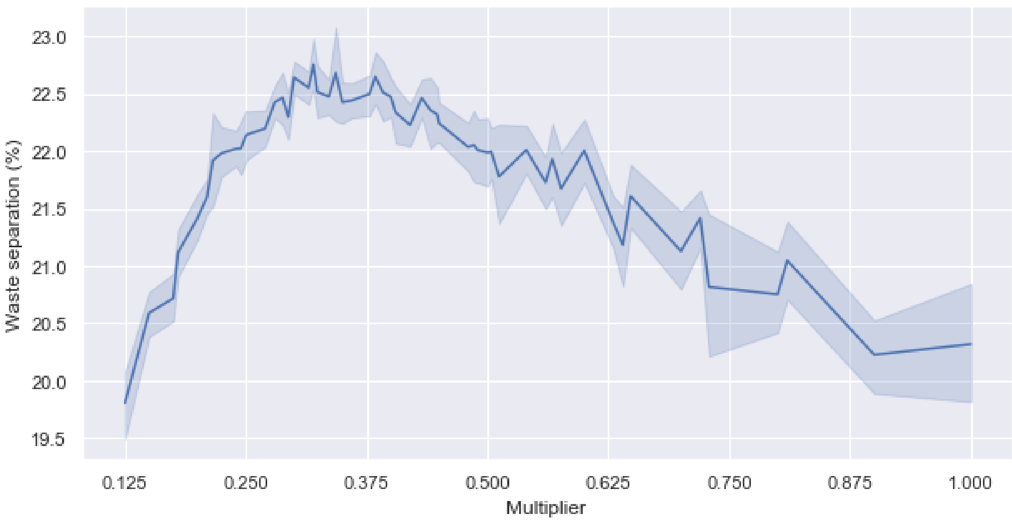
This is accomplished by carrying out a parameter sweep, wherein model runs are carried out with the different set of combination values (216 combinations) for the three coefficients. In combination set is repeated 30 times to take into account the randomization in the model. Therefore, in total 6480 runs are carried out.

In each run the waste separation rate is measured and compared with the waste separation rate in Amsterdam. The waste separation in Amsterdam according to literature is between 16-19%. The combination of coefficient values that give a waste separation rate equal to (or close) to that of Amsterdam are chosen.

The results of the parameter sweep are presented in **??**. The waste separation is measured in the y-axis for different product of coefficients. Based on the examination of the line plot, it is observed that lowest waste separation rate is between 19 to 20% and it occurs at a product value equal to 0.125.

This waste separation value is also the closest to the waste separation rate observed in Amsterdam. Therefore, based on the product of the coefficient of 0.125, the rest of the three coefficients are calculated to be equal to 0.5.

Figure E.2: Waste separation %



F. Verification analysis

The model code is available on https://bit.ly/3baAdyE

F.1 Recording and tracking of agent behavior

Model interface
All the output values are equal to the input values specified in the model interface, except the number of houses in the block and their distribution. The number of houses in the model environment are usually less by a value of 1 or 2 than specified in the slider. Also, the distribution of the households types is based on the approximation of the input values.

To setup

1. Set up model environment
   (a) patches are set grey in color[Verified]
   (b) patch in the center is green in color[Verified]
2. Setup globals
   (a) capacity of household local storage bin is 11.95 kg
   (b) capacity of SME local storage bin is 35.85 kg
   (c) set capacity of central bin in kg
   (d) limiting the % of household distribution to 100%
   (e) define the ratio between the total agents and agents in a block
   (f) setting up the value of the coefficients of VBN theory
   (g) setting up the value of the threshold for pro-environmental behavior
3. Globals output[Verified: Setup globals]
   (a) All the outputs are equal to the inputs
   (b) A message is displayed when the % distribution of households exceeds 100%
4. Positioning the agents[All items verified]
   (a) Shape of the houses is in the form of a "house"
   (b) Shape of the SMEs is "house colonial"
   (c) First 28 houses are positioned at a radius of 4 from the center. Rest are positioned at a radius of 8 from the center.

   (d) First 30 SMEs positioned at a radius of 6 and rest positioned at a radius of 12.
   (e) No positioning of SMEs when their number is 0.

5. Behavior profile inputs
   (a) Biospheric (0.4) , Alustric(0.4), Hedonic(0.4) and Egoistic(0.2) specified at start.

6. Behavior profile outputs[Verified]
   (a) All four values normally distributed. Maximum value 1 and minimum is 0.
   (b) The NEP, Awoc and Ascor values proportional to the behavior profile inputs and are as per their specific equations.

7. Waste value and appearance of houses
   (a) For households 'house' = TRUE and SMEs 'house' = FALSE [Output verified]
   (b) Specific color for each household type [Output verified]
   (c) Waste generated by agents specified [Output verified: Randomized for certain agents]

8. Distance from central bin.
   (a) Input: Distance of an agent from central bin between 0 to 160m.
   (b) Output: The distance of each agent from the central bin is randomized between 0 to 160m. [Verified]

9. Collection frequency
   (a) Input: "once a week" and "once in two weeks"
   (b) Output: In case of "once a week", waste is collected once in every 35 ticks. "twice a week", waste is collected once in every 70 ticks

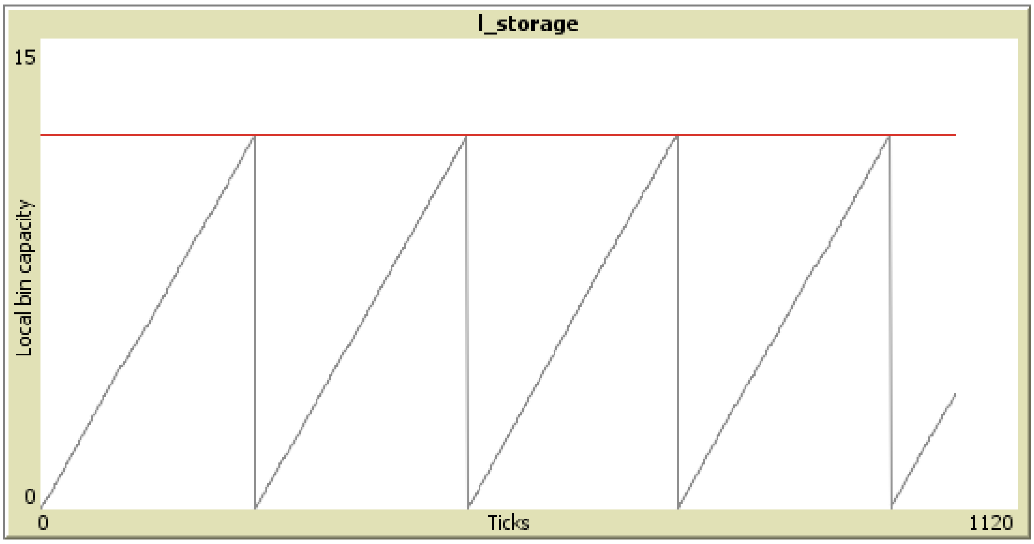
To go

1. The model stops after 1050 ticks [Verified]
2. Energy conversion processes carried out after the central bin is cleared [Verified]
3. Local separation of waste
   - Input: pn value of agents greater than or equal to their threshold
   - Output: Pro-environmental behavior = TRUE[Verified]
   - Input: pn value between positive and negative threshold
   - Output:Pro-environmetnal behavior = TRUE or FALSE;Randomized based on its pn value [Verified]
   - Input pn value less than negative threshold
   - Output: Pro-environmental behavior = FALSE [Verified]
   - Input: Pro-environmental behavior = TRUE
   - Output: Waste in local bin [Verified]

- Input: Pro-environmental behavior = FALSE
- Output: Waste in residual waste bin [Verified]
- All other outputs are equal to the inputs[Verified]

4. Separation at central bin
   (a) Input for decision to separate at central bin: l_storage ≥ l_storageMax
   (b) Output: dispose = TRUE for input condition. In Figure F.1 a bin of an agent is shown to clear when it reaches its maximum capacity. This means that the waste is disposed off in the central bin.

Figure F.1: Local bin clearing



   (c) dist≥ 75 m results in willwalk = FALSE [Verified]
   (d) pn≥ positive threshold results in willwalk = TRUE or FALSE(Randomised)[Verified]
   (e) cc_storage ≥ c_storage results in full = TRUE [Verified]
   (f) Bin experience. Input: bin_fullness;Output:bexp = TRUE when bin_fullness ≤ 80 and dist ≤ randomized value greater than 80 m [Verified]
   (g) waste separated in central bin when bexp = TRUE and full = FALSE and willwalk = TRUE [Verified]

G. Sensitivity analysis

The sensitivity analysis is performed to examine the influence of model duration on the three KPIs for the baseline scenario and the system proposed at the end of Chapter 8. The default model duration is 7 months and in this sensitivity analysis it is increased to 24 months. The results are presented in the form of bar plots in Figure G.1, Figure G.2 & Figure G.3.

By analysing the plots, it is observed that values for KPI 1 & KPI 2 increase as the model duration increases for baseline scenario and the system proposed. But this increase is for both the runs in the x-axis and does not influence the qualitative analysis made for the default model duration of 7 months.

Figure G.1: Energy generated per tonne - KPI 1 (Sensitivity analysis)

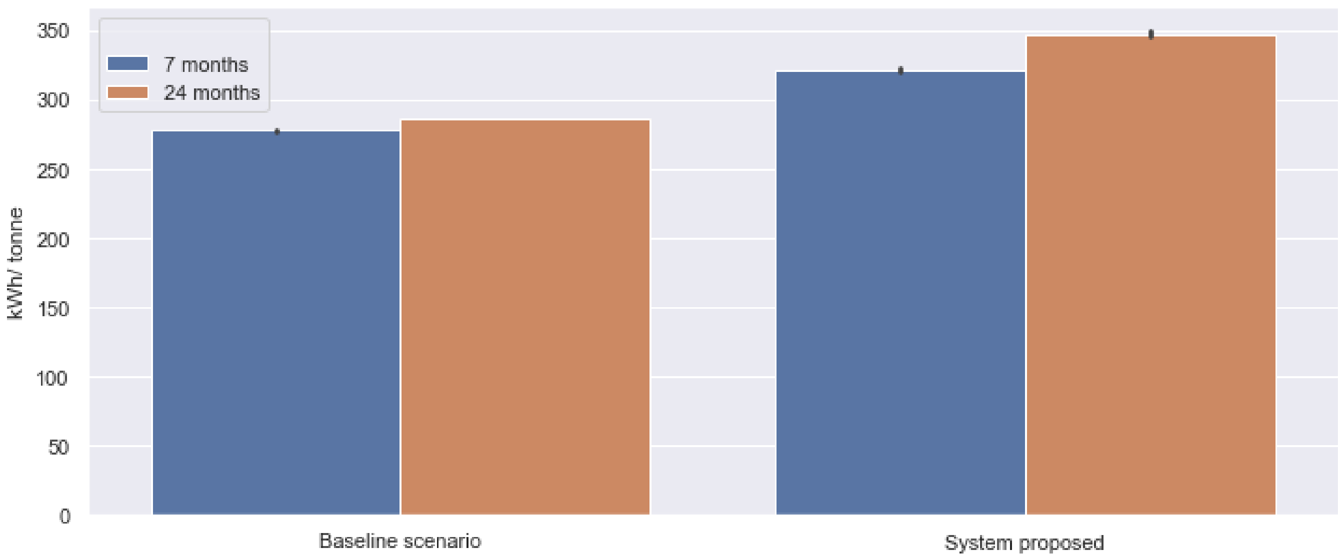


Figure G.2: Cost of generating per kWh energy - KPI 2 (Sensitivity analysis)

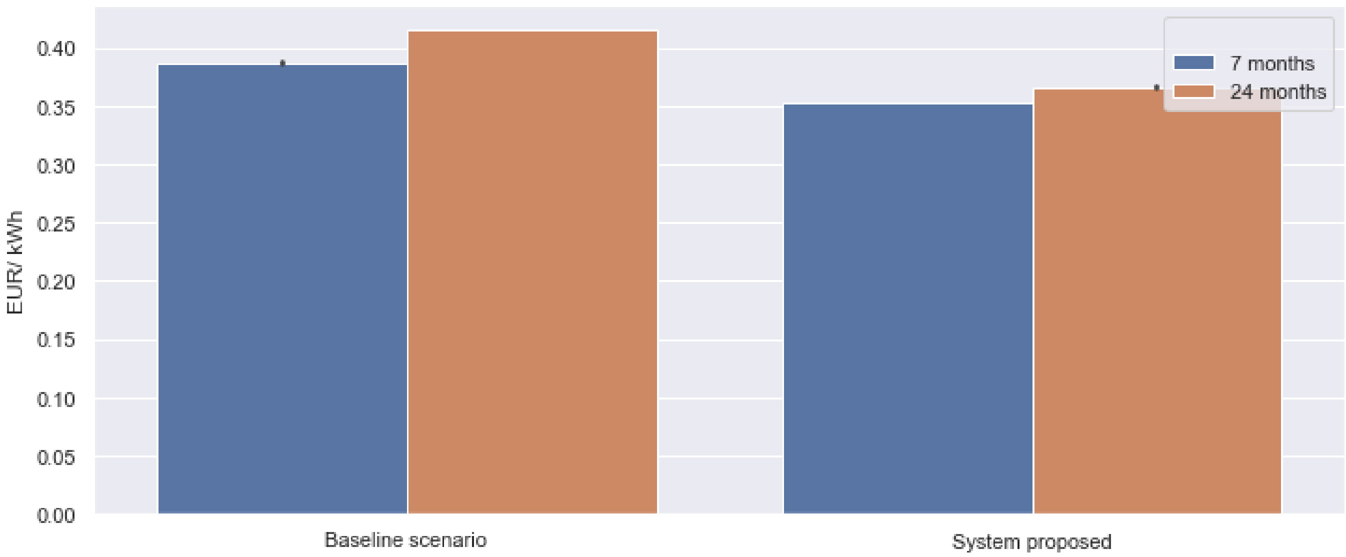


Figure G.3: Cost of abating per kg of CO_2 - KPI 3 (Sensitivity analysis)