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Optimizing Solid Waste Management in Semi-Public Spaces

A Case Study of the Efteling Theme Park

TU Delft

Efteling

Optimizing Solid Waste Management in Semi-Public Spaces

A case study of the Efteling Theme Park

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MASTER THESIS

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Preface

Waste tells us so much about ourselves. Not only the quantity and quality of our waste are significant, the attitude that we have towards waste may be even more characteristic. If there is one thing that I learned, it is that viewing waste as an opportunity instead of something to be marginalized and hidden can really make the difference in this time of global warming.

This report is the result of eight months of research into the hidden world of solid waste management (SWM). The research was conducted while being inside the even more hidden world of the Efteling organization. This report is also the result of my Master thesis, with which I complete my Master Transport, Infrastructure and Logistics at Delft University of Technology (TU Delft). During my research, the COVID-19 pandemic unfolded which created some challenges but, in the end, these have been overcome. My thesis started with the Efteling department of administrative affairs asking me to do research into improving the sustainability of the SWM of the Efteling park. They gave me complete freedom when it comes to the research approach. With the help of my TU Delft knowledge, I designed an approach that allows holistic decision-making and that enables an easy adaptation to many other organizations.

I would like to thank some people who have helped me tremendously during my research journey. First of all, Wyke Smit and Matthijs Spruyt, you have been the best mentors I could wish for. You have introduced me to the complex world of administrative affairs in the context of theme park operations and to corporate culture in general. Wyke, thank you for providing me with all the resources I ever needed within, but also outside of, the Efteling organization. Matthijs, if there is one person that is dedicated to making solid waste management more sustainable, it is you. Thank you for your never letting go of that ideal and for showing me the great potential that waste has to offer. Much appreciation also goes to the other 'colleagues' of 'Bestuurlijke Zaken' who have made me feel very much at home. Finally, I would also like to thank the Efteling, in particular Ad van Kempen and Karolien Baden (who have not been mentioned yet), for giving me the opportunity and trust to do a graduation project at the company I dreamed of working for ever since my childhood.

Of course, I could not have completed this thesis without the help of my TU Delft supervisors. Jaap Vleugel and Mark Duinkerken, my daily supervisors, have always given me the feedback I needed to improve my research and report. Thank your for your critical view and motivational words. My chair supervisor, professor Rudy Negenborn, has provided me with valuable comments during the different meetings. Thank you for that. I would also like to thank my former teachers from Wageningen University for showing me the value of integrated thinking. Finally, I would like to thank my friends and family for their continuous support and, seemingly contradictory but true, the distraction they provided to help me keep going.

At the end, my thanks go to you reader, for giving waste management the attention it deserves.

Stefan van Lier
Delft, October 2020

Abstract

The worldwide production of solid waste is rapidly increasing along with its environmental footprint. While much research has focused on the sustainable solid waste management (SWM) of residential waste, the SWM of commercial waste and especially waste from (semi-)public spaces has received less attention. This category does however prove to be relatively problematic when it comes to reducing shares of mixed (unrecyclable) waste. Sectors that manage waste from semi-public spaces are culture, sport, recreation, transport and government. The subsector with one of the highest percentages of mixed (unrecyclable) waste is the theme and amusement park sector. Therefore, this research has focused on identifying and evaluating ways to improve the sustainability of solid waste management in theme parks and semi-public spaces in general. The Efteling, a major theme park in Europe located in the Netherlands, is used as a case study.

To overcome the shortcomings of simply applying the hierarchy of waste management, an integrated waste management approach was applied which enables reducing the overall environmental burdens of the theme park SWM system as far as possible, within an acceptable level of costs. To the best of the author's knowledge, this study is the first to apply an integrated waste management approach to optimize SWM in theme parks and semi-public spaces in general. The approach consists of assessing the integrated environmental and economic burdens of the collection, transportation, sorting and treatment processes of a SWM strategy using a life-cycle assessment (LCA).

Using requirements engineering and general morphological analysis techniques, approximately 10 alternative high potential SWM strategies were composed and selected out of a very large pool of possible SWM strategies. The environmental and economic impact of these high potential SWM strategies for the Efteling case was subsequently assessed using the WARM LCA model and a custom economic assessment model. Each strategy distinguishes behind-the-scenes (BTS) waste management interventions from public/semi-public (PSP) waste management interventions, as these are generally different regimes in the theme park sector. The results reveal that emission reductions of up to 190 ton CO_2 equivalents (TCO_2E's) per year, relative to the current strategy, can already be achieved by separating and recycling more fractions from BTS waste. This corresponds to an increase in yearly avoided SWM system emissions of about 25% for the Efteling case (from a life-cycle perspective). When PSP waste is also included, emission reductions of up to 800 TCO_2E's per year can be achieved for single-fraction separation (e.g. PMD, plastic or PET) and up to 960 TCO_2E's per year for two-fraction separation (e.g. PMD + paper or PMD + cups). This corresponds to major increases in avoided SWM system emissions of 110% and 131% respectively. It was also found that small interventions in the transport and/or treatment waste management components can make a big difference in the environmental and/or economic impact of a SWM strategy. A majority of the alternative SWM strategies has an eco-efficiency (emission reduction cost-effectiveness) ranging from €39 to about €140 per TCO_2E saving.

The results show that there is great potential for improving the sustainability of SWM practice in theme parks and (semi-)public spaces in general. Furthermore, the eco-efficiency of many of the alternative SWM strategies proves to be (much) higher than that of a range of benchmarks in the sustainable electricity production and sustainable building sector. These benchmarks include the eco-efficiency of solar-pv panels at a non-industrial scale, wind turbines at sea and the eco-efficiency of office building insulation. This indicates that optimizing waste management should be given more priority in (scientific) research as well as in practice.

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List of Abbreviations

Abbreviation	Description
Avg.	Average
BTS	Behind-The-Scenes
CCA	Cross-Consistency Assessment
EEA	Eco-Efficiency Analysis
ETS	Emissions Trading System
EU	European Union
GHG	GreenHouse Gas
GMA	General Morphological Analysis
GWP	Global Warming Potential
HDPE	High-Density PolyEthylene
IWM	Integrated Waste Management
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low-Density PolyEthylene
LLDPE	Linear Low-Density PolyEthylene
Manf.	Manufacturing
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
MWh	MegaWatt Hour
OSS	Offices, Stores and Services
PE	PolyEthylene
PET	Polyethylene Terephthalate
PP	PolyPropylene
PS	PolyStyrene
PSP	Public/Semi-Public
RDF	Refuse-Derived Fuel
SWM	Solid Waste Management

Chapter 1

Introduction

This chapter introduces the research to be conducted. First a general introduction to the subject of waste (management) and sustainability will be provided. After that, the problem at hand will be introduced, starting at the national level and zooming in to specific business sectors. The objectives and research questions are stated in section 1.3 while their scope is finally discussed in section 1.4.

1.1 Introduction

Globally, more than 1.3 billion tonnes of Municipal Solid Waste (MSW) is being produced every year. MSW consists of (solid) household and commercial waste [1]. To make matters worse, MSW production is rapidly increasing to about 2.2 billion tonnes per year by 2025 (World Bank, 2012). This comes down to approximately 1.42 kg of MSW per person per day in 2025. Depending on region, country and/or city, this number may deviate. The amount of MSW produced seems to increase with economic development and rate of urbanization. This means that regions such as Europe and North America have a far higher average MSW production of about 2.2 kg per person per day and counting (World Bank, 2012). The Netherlands has a MSW production close to the average of the 'high income countries' with 2.12 kg per person per day. While MSW production continuous to increase, climate change has become a serious global concern. The MSW production generally is the final result of the extraction, processing and use of natural resources. This, in turn, directly contributes to climate change through the burning of fossil fuels (Turner et al., 2016). Furthermore, the MSW itself also poses a serious concern in the light of sustainability as almost all regions in the world (including Europe) are exceeding the ability of the planet's natural sinks to absorb and convert MSW into harmless compounds (McDougall et al., 2001). On top of that, renewables such as water, soil, forests, fish stock and biodiversity are being disrupted due to the sheer presence and processing of MSW and the possible emissions of greenhouse gases (GHG) resulting from it (McDougall et al., 2001; Turner et al., 2016). These phenomena are often referred to with the generic term 'pollution'.

It is clear that the through the improvement of Solid Waste Management (SWM), in terms of sustainability, a considerable climate benefit can be achieved (UNEP, 2010). Improving SWM is, in many cases, complicated. Especially household waste is one of the hardest sources of waste to manage as it consists of a wide range of materials mixed together (McDougall et al., 2001). Commercial and industrial waste is often more homogeneous which makes it easier to manage effectively. Waste produced in semi-public spaces takes a unique position in this sense as its composition is more homogeneous than household waste but also less homogeneous than strictly commercial waste (Rijkswaterstaat, 2016a). Furthermore, SWM of waste produced in semi-public spaces comes with specific challenges that have barely been addressed by current literature. These challenges will be described later. Still, many companies that manage semi-public spaces have recently committed to improving SWM to the extent of almost eliminating waste destined for incineration or landfilling (dumping). This type of waste is often called 'residual waste' (Rada et al., 2009). Examples of such commitments can be found at NS (2019), which wants to re-use 75% of its waste in 2020, at RAI Amsterdam (2020) and at Efteling, which wants to eliminate residual waste by 2030. The Efteling commitment will be used as a case study for this research into optimizing solid waste management in semi-public spaces.

[1] The literature provides different, and often conflicting, definitions of MSW. Most authors agree on the notion that MSW consists of household and commercial solid waste although others may also include industrial waste or even all solid waste depending on material type.

1.2 Problem Definition

In line with policy (European Commission, 2010) and legislation (Directive 2008/98/EC, 2008) of the European Union (EU) and subsequent national legislation (Wet MB, 2019) and policy (LAP3, 2019), SWM is more and more adhering to the principles of the hierarchy of waste management. This waste hierarchy will be described into more detail in section 2.1. In short, it calls for the prevention, re-use, recycling and recovery of solid waste, in that order of priority, which shall minimize waste disposal. This waste hierarchy is not only applicably to household waste but to all types of waste. Companies also have to optimize their SWM towards the principles of the waste hierarchy. On top of that, many companies, including Efteling, have an intrinsic motivation to make their SWM more sustainable.

1.2.1 Solid Waste in the Netherlands

The Netherlands		**Total Waste**		**Mixed waste**				**Recyclable waste**				**Organic waste**			
Year	**Population**	Household waste	Offices, stores and services waste	Household waste		Offices, stores and services waste		Household waste		Offices, stores and services waste		Household waste		Offices stores and services waste	
	million	x1000 ton	x1000 ton	x1000 ton	%	x1000 ton	%	x1000 ton	%	x1000 ton	%	x1000 ton	%	x1000 ton	%
2008	16,41	9331	5884	4696	50%	2622	45%	2146	23%	1410	24%	1718	18%	1287	22%
2010	16,57	8989	5645	4436	49%	2438	43%	2053	23%	1347	24%	1708	19%	1272	23%
2012*	16,73	8434	5579	4251	50%	2428	44%	1957	23%	1288	23%	1768	21%	1240	22%
2014*	16,83	8098	5586	3992	49%	2475	44%	1844	23%	1276	23%	1806	22%	1215	22%
2016*	16,98	8107	5662	3960	49%	2644	47%	1819	22%	1250	22%	1874	23%	1123	20%

* Provisional numbers

Table 1.1: Dutch waste statistics (CBS, 2018, 2019a)

To get an idea of the current and historic amounts of solid waste in the Netherlands and the composition of this solid waste, table 1.1 shows some key waste statistics that are relevant to this research. The table shows, among others, the total amount of household waste and offices, stores and services (OSS) waste in the Netherlands. OSS waste includes all waste that is collected by non-industrial and non-agricultural companies. More specifically, this refers to companies in the G up and to and including the U category of the SBI 2008 (standardized company classification system). The table also shows percentages of mixed waste, recyclable waste and organic waste relative to the total amount of waste. Note that these percentages do not fully add up to 100% since a small fraction may also be chemical waste, mineral waste or discarded equipment (vehicles, electronics and machines). The following consecutive conclusions can be drawn from these statistics:

- The total amount of household waste in the Netherlands has decreased or at least stabilized since 2008 even though the population has increased with approximately 600.000 in the period between 2008 and 2016. This shows that the principle of waste prevention seems to pay off.
- The amount of waste from offices, stores and services has also decreased in the same period, however the relative decrease is only 3,7% versus 13,1 % for household waste.
- The share of total waste that is not collected separately or separated afterwards to be eligible for recycling (mixed waste) is about half of the total waste. Whereas this share has remained stable for household waste, it has increased for offices, stores and services in the last years.
- The share of recyclable waste has remained relatively stable for both household waste and OSS waste, yet it tends more towards a decrease.
- The share of (separately collected) organic waste, which can be composted, has increased in the household waste domain while it has decreased in the OSS domain.
- Given that OSS (commercial) waste is generally more homogeneous than household waste, which has been mentioned earlier, these observations are quite remarkable as it should be easier to prevent, re-use or recycle homogeneous waste.

1.2.2 Solid Waste Management at offices, stores and services

To zoom in on the SWM of OSS waste, that is appearing to be quite problematic in terms of waste hierarchy standards, table 1.2 provides a more detailed insight in waste quantities of specific OSS sectors. The quantities of private households are also included in the table to give some reference. As can be seen in the table, the shares of mixed waste, recyclable waste and organic waste differ strongly per OSS sector. Especially culture, sport and recreation and financial services seem to be doing poorly when it comes to waste hierarchy standards, they have high shares of mixed waste and low shares of waste deployed for useful applications (recycling + composting of organic waste).

Origin	**Total Waste**	**Mixed waste**		**Recyclable waste**		**Organic waste**		**Useful Applications**
	x1000 ton	x1000 ton	%	x1000 ton	%	x1000 ton	%	%
Private households	8107	3960	49	1819	22	1874	23	46
Retail, transport and hospitality	1902	724	38	562	30	204	11	40
Financial services	117	86	74	25	21	4	3	25
Business	1154	575	50	263	23	262	23	45
Government, education and healthcare	2094	1006	48	274	13	641	31	44
Culture, sport, recreation and others	**160**	**98**	**61**	**48**	**30**	**10**	**6**	**36**

Table 1.2: Waste quantities per origin in 2016 (CBS, 2018)

Table 1.3 gives an overview of the percentage of residual waste[2] per subsector. All of these subsectors belong to the offices, stores and services (OSS) category. This time, the numbers are based on a desk study of waste data of 580 companies, additional web research into public waste company information, waste quick scans at relevant companies and interviews with companies and organisations (Stichting Stimular, 2016a). The numbers are not exact but indicative.

From the table, one can conclude that for almost all sectors a majority of waste is still processed as residual waste. The only sector that manages to re-use and recycle more than 50% of waste is the retail sector. Note that 50% is the actual target value that the EU has set for 2020 for waste re-use and recycling (Directive 2008/98/EC, 2008). The worst sectors in terms of sustainable SWM are: transport, education, 'culture, sport and recreation' and business. The worst subsectors, about which sufficient (residual) MSW data is available, are: festivals (79%), theme and amusement parks (86%), sport clubs (85%), bungalow parks (85%) and camping sites (79%). All of these subsectors have in common that they 'collect' (mixed) waste that is mainly being produced by third parties, being customers, guests or visitors in semi-public spaces. In other words, the main source of the waste within these subsectors does not lie with staff members or processes that are executed by staff members. Whereas staff members can easily be conditioned or trained to properly separate waste and thereby to reduce residual waste, this is much more difficult to achieve with third parties. This effect can also be seen in the numbers in table 1.3.

As Stichting Stimular (2016a) describes, there are two main bottlenecks in the successful waste separation in (semi-)public spaces. Firstly: "*Visitors are not concerned with waste separation, they just want to get rid of their waste quickly. They do this on autopilot, as quick and easy as possible. As a result, waste often ends up on the street or in the wrong bin" (Stichting Stimular, 2016a, p.16)*. Secondly, *The choice of bins varies across organisations, this makes it unclear which types of waste are to be separated and how (Stichting Stimular, 2016a, p.16)*. Furthermore, waste separation is not yet self-evident in (semi-)public spaces. Finally, there are also a lot of interconnected behavioural factors that may negatively affect public waste collection and separation, leading to litter and impure waste streams (Bolsius et al., 2017). These factors include attitude (knowledge), perceived behavioural control (estimation of one's effectiveness) and subjective norms (social environment), but also automatic behaviour (Berends, 2003; Bolsius et al., 2017). The subsector with the absolute highest percentage of residual waste is theme and amusement parks which makes Efteling a good choice for a case study into SWM improvements for semi-public spaces.

[2]Waste that is unsorted and that is being incinerated or dumped.

Sector	Subsector	Residual Waste %	Source
Culture, sport and recreation		**68**	Stichting Stimular (2016c)
	Theatres and pop stages	62	
	Event halls	53	
	Festivals	79	
	Museums	63	
	Zoos	62	
	Theme/amusement parks	**86**	
	Sport clubs	85	
	Swimming pools	55	
Retail		**18**	Stichting Stimular (2016f)
	Chain stores food	12	
	Chain stores non food	15	
	Other stores	72	
Hospitality industry		**61**	Stichting Stimular (2016d)
	Restaurants, cafes and cafetarias	62	
	Hotels	57	
	Bungalow parks	85	
	Camping sites	79	
Education		**74**	Stichting Stimular (2016e)
	Primary education	77	
	Secondary education	76	
	Higher education	60	
Government		**42**	Stichting Stimular (2016b)
	Offices	46	
	Public space	42	
Transport		**85**	Stichting Stimular (2016g)
	Public transport: Train and bus	51	
	Transport over water	High*	
	Aviation	65	
Business		**68**	Stichting Stimular (2016h)
	Offices	67	
	Film, TV and sound recordings	High*	
Healthcare		**59**	Stichting Stimular (2016i)
	Hospitals	72	
	Nursing, disabled care and GGZ	47	
	Childcare	High*	
	Ambulance	59	
	Laboratory	23	
	Veterinary services	39	

* Qualitatively assessed to be high %, insufficient data for quantitative assessment

Table 1.3: Residual waste per OSS (sub)sector

1.2.3 Solid Waste Managment at Efteling

The Efteling is, by far, the most visited (tourist) attraction in the Netherlands with more than 5 million visitors per year (Respons, 2018). It is open 365 days per year and has more than 3000 employees. The so-called 'World of the Efteling' consists of a large themepark, a theater, multiple hotels and resorts and a golf park. On top of that, the Efteling organises approximately 300 large events and 600 smaller (business) events per year (Efteling, n.d.). All in all, this concerns a huge amount of semi-public space where lots and lots of waste is being produced on a daily basis. Note that visitors are allowed to bring their own food and drinks which means that the Efteling also processes waste from third parties. On the waste prevention and procurement side, a lot of sustainable developments like the elimination of plastic disposables, are already taking place. Therefore, the focus will be on the SWM side. Two separate waste streams can be distinguished in the Efteling. On the one hand, you have waste that is being produced and collected 'behind the scenes', this includes kitchen waste and inventory packaging waste. On the other hand, you have waste that is produced and collected in semi-public guest areas. Whereas the 'behind the scenes' waste is mostly collected separately and processed for recycling and re-use, this is not the case for the waste collected in guest areas. The latter waste stream is almost[3] completely processed as residual waste which explains the high residual waste percentage.

There are different reasons for not collecting this waste separately yet. One of them is that pilot projects at other companies that collect waste in (semi-)public space have revealed that separate collection is not quite successful (Bolsius et al., 2017). These companies include Schiphol and NS. At both companies, separately

[3] Only a portion of the PET bottles in the residual waste is being extracted by hand and recycled.

collected waste streams are often so impure that they have to be manually sorted afterwards in order to be eligible for recycling (Bolsius et al., 2017). Another reason is that separate waste collection is also partly a design problem for the Efteling. Rijkswaterstaat (2018b) has developed strict guidelines for 'recognizable waste separation'. The use of these guidelines for bin design is strongly advised. However, the guidelines possibly jeopardize the very essence of a theme park namely: "*a symbolic microcosm with a distinctive identity that proposes a complete emotional experience, a place of entertainment which has been provided with its own homogeneous semiotics*" (Anton Clave, 2007, p.21). To give an example: having standardized bright orange bins in the Efteling for the collection of plastics removes part of its distinctive identity and it interferes with the established homogeneous semiotics (theming harmony). In other words, it puts you back in the 'real world'.

Finally, there is one more major problem, related to a lack of knowledge, that has prevented full separate waste collection in (semi-)public (theme park) spaces and that is the logistics of it. Every additional bin that is added has to be purchased and then monitored (filling rate), emptied and cleaned on a regular basis. Separate waste streams also have to be transported, stored and processed separately. Additionally, they may also have to be checked and sorted again to make sure that they are pure enough to be re-used or recycled. All of this requires additional resources in the form of money, time and energy (emissions). A thing that is often overlooked is that it also requires more behind-the-scenes space, which is scarce (Stichting Stimular, 2016c). On the other hand, money and energy (emissions) can also be saved if relevant waste streams are separately collected, sorted or if the composition of waste is changed (Renewi & Efteling, 2018). This way, huge amounts of CO_2 and other greenhouse gas emissions can potentially be avoided. As Stichting Stimular (2016a) describes, there are a lot of negative stories about SWM in (semi-)public spaces which create the image that waste separation does not work there. However, now that all problems have been described and analyzed, it is time to look at solutions and success stories.

1.2.4 Research Gap

Given that separate waste collection, additional waste sorting and alternative means of waste treatment may have different interrelated effects on the economic as well as the environmental sustainability of the SWM system, the ultimate challenge is to optimize resource usage in the entire life cycle of waste. Combining "*waste streams, waste collection, treatment and disposal methods with the objective of achieving environmental benefits, economic optimisation and societal acceptability*" is referred to as Integrated Waste Management (IWM) (McDougall et al., 2001, p.15). To the best of the author's knowledge, optimizing SWM in semi-public spaces in an integrated manner is something that has never been done before in scientific literature. The only existing literature that partly approaches the problem at hand can be divided in two categories. The first category entails studies about waste generation, prevention and separate waste collection at hotels, festivals and events (Martinho et al., 2018; Radwan, 2009; Rafiee et al., 2018). These studies do not evaluate or optimise the integrated SWM system that is necessary to process all of the waste from festivals and events. The second category entails studies that do consider the entire life cycle of (semi-public) waste (collection, transport, sorting and treatment) but only for specific materials (TNO & WFBR, 2018). This study will focus on optimizing the SWM system of semi-public spaces according to the principles of IWM instead, considering all operational waste types. The research gap is more elaborately defined in figure 2 of the literature overview chapter.

1.3 Objective & Research Questions

The **overall objective**, which has been introduced in previous sections, is:
To identify and evaluate ways to improve the sustainability of solid waste management in semi-public spaces, using the Efteling as a case study.

The **main research question** that has to be answered by the proposed research to be able to fulfill the objective is:
How can the sustainability of solid waste management in semi-public spaces be improved?

The main research question can be divided into several sub questions that facilitate a clearer and more manageable research structure. The scope of the sub research questions is discussed in the next section. The **sub**

research questions are:

1. What are the operational, environmental and economic characteristics of the current solid waste management system at the Efteling?
2. What requirements and KPI's for solid waste management at the Efteling can be identified?
3. What strategies can be designed to improve the sustainability of solid waste management systems in semi-public spaces?
4. How can the environmental and economic impact of different solid waste management strategies for semi-public spaces be estimated?
5. What is the environmental and economic impact of different strategies to improve the sustainability of solid waste management at the Efteling?

The answering of the research questions requires the use of several research methods. These are described in the next chapter about methodology. Table 1.4, which is displayed below, links all of the sub research questions to specific methods to answer these questions. The section numbers of the respective method descriptions are provided in the rightmost column. The table also indicates whether a sub research question has a more generic character or a more case study specific character. Note that although a sub research question may be answered case study specific, there will be many similarities to other theme parks and semi-public spaces. Below the table, a flow chart of the research framework can be found. This flow chart indicates the relations between the different sub questions and chapters. More information about these relations can be found in the methodology chapter (chapter 3). The sub questions have also been placed into the different DMADV process steps. DMADV stands for define, measure, analyse, design and verify. This is a frequently used framework for implementing high-quality new strategies and therefore relevant for this research. DMADV is part of the Six Sigma initiative but can be used as a standalone process improvement procedure (Selvi & Majumdar, 2014).

Research Question		Method	Method Section
1	*Current Efteling SWM characteristics*	*Case Study Data Analysis*	*3.1*
2	*Identifying SWM requirements and KPI's for the Efteling*	*Requirements Engineering*	*3.2*
3	*Designing SWM strategies for semi-public spaces*	*General Morphological Analysis*	*3.3*
4	*How to estimate impacts of SWM strategies*	*Life cycle assessment and Economic Assessment*	*3.4*
5	*Assessing SWM strategies for the Efteling*	*Life cycle assessment, Economic Assessment and Uncertainty Analysis*	*3.4* *3.5*

Case Study specific
Generic

Table 1.4: Research method(s) per sub research question

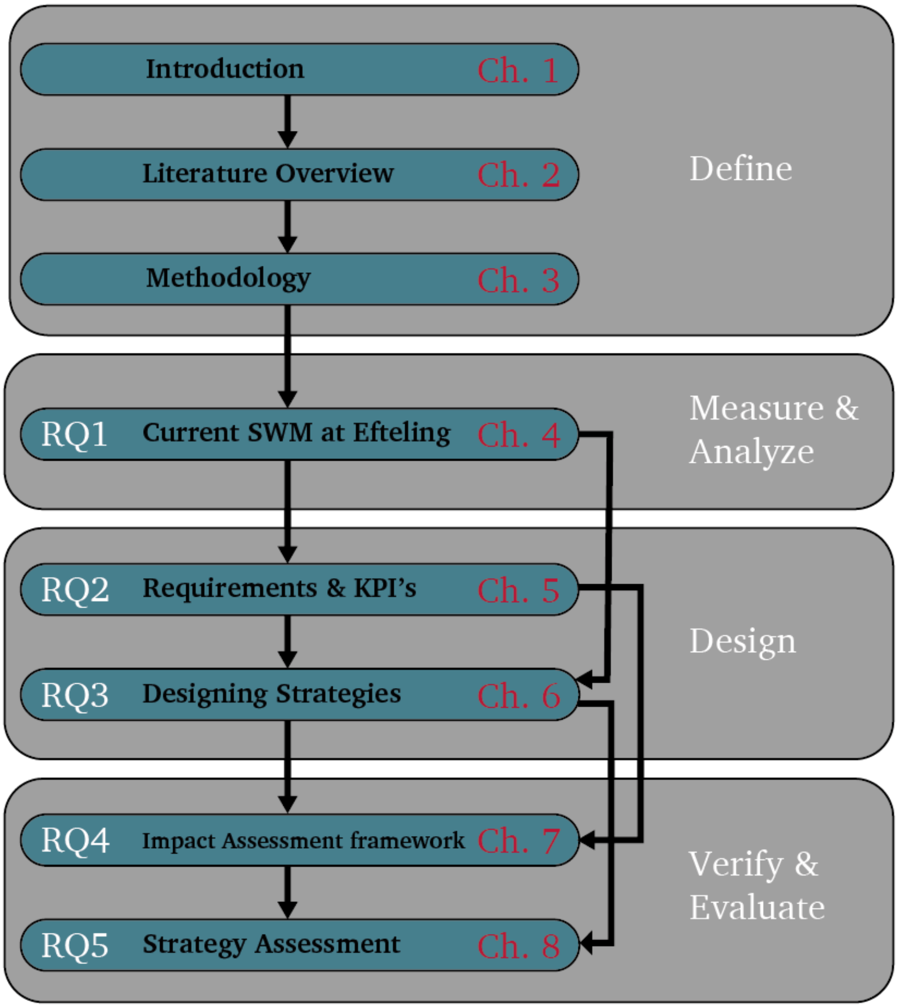

Figure 1.1: Research framework

1.4 Scope

The scope of this research with respect to various terms and concepts that have been mentioned in the previous section is clarified using the definitions below:

- **Efteling:** Depending on the data provided by the Efteling, the focus will be on the Efteling theme park as much as possible. Other Efteling business units (hotels and resorts, golf park etc.) will be disregarded (if possible). Furthermore, only the SWM belonging to the regular operation will be analyzed and optimized extensively. This concerns everything except the SWM of waste types that are released during maintenance and construction activities. Excluding these activities is done for the following reasons:
  - Maintenance and construction activities are often very park-specific and ad hoc in nature and therefore hard to generalize to other parks and semi-public spaces.
  - Whereas transport plays a significant role for waste types that are released in large quantities, this is not the case for some waste types that are released in small quantities on an irregular basis. These latter waste types are picked up only a few times per year by the waste management company and are sometimes even picked up together (using the same vehicle).
  - The separate collection and recycling of many maintenance and construction waste types such as metals result in large environmental benefits compared to incineration. However, these benefits can be seen as a constant since there is no reason to assume that these materials are deposited as residual

waste at any time. This means that different strategies will not result in additional environmental benefits from these materials which makes modelling them unnecessary.

- **Sustainability:** Refers to sustainability according to the IWM approach ("*to reduce the overall environmental burdens of the waste management system as far as possible, within an acceptable level of cost.*" (McDougall et al., 2001, p.44)). As stated in chapter 5, environmental burdens will mostly be defined in terms of CO_2 emissions and Global Warming Potential which is measured in CO_2 equivalents. Economic optimisation is measured in terms of business economic costs.
- **Environmental Impact:** As stated in chapter 5, environmental burdens will mostly be defined in terms of CO_2 emissions savings and avoided Global Warming Potential which is measured in CO_2 equivalents. The environmental impact of SWM systems is calculated using a SWM Life Cycle Assessment (LCA) as described in section 3.4. This also means that, as opposed to a product LCA, a 'zero burdens' LCA approach (McDougall et al., 2001) is utilized which assumes zero burdens for incoming waste to be managed. More information about the LCA system boundaries can be found in section 3.4.
- **Solid Waste Management System**: Refers to SWM according to the IWM approach (see also section 2.2). This means that the system entails the collection, sorting, transportation and treatment of all types of solid waste provided to it.
- **Source Separation vs. Central Sorting (post-separation)**: Two main types of collection schemes can be found in worldwide household SWM practice: one that involves the source separation of waste fractions (per household) to be able to recycle fractions other than residual waste and one that involves the central sorting of mixed waste to allow the recycling of mechanically post-separated fractions (Cimpan et al., 2015). In this report, source separation (in combination with manual sorting) is assumed as the means of enabling the recycling of certain waste fractions. The post-separation of mixed waste from semi-public spaces is not considered for the following reasons:
  - The post-separation of mixed waste from semi-public spaces is deemed to be infeasible in the foreseeable future for the reasons mentioned in section 4.3.3.
  - The costs of the post-separation of mixed waste for companies, and thus also for the case study, are unknown. However, they are expected to be considerable higher as the total costs of operating a post-separation scheme for household waste (which is subsidized) are also higher compared to a source separation scheme (Cimpan et al., 2015).
  - Although detailed information on the process efficiency and output quality of central sorting plants that separate recyclable fraction from mixed waste is very scarce, there are some signs that central sorting may be less beneficial than it may seem (Cimpan et al., 2015). Although post-separation schemes may recover more recyclable materials from the total waste stream, these materials result in comparable amounts of secondary products (as in the case of source-separation schemes) because the quality of these recovered materials is lower due to increased cross-contamination. This also translates into market value differences. "*In the Netherlands, the initial plastic concentrates recovered in post-sorting have little or no market value. The polymer products sorted from these concentrates are also sold for lower prices than their counterparts coming from separate collection*" (Cimpan et al., 2015, p.196). This, of course, makes successful recycling much more difficult.

Chapter 2

Literature Overview

A lot of (scientific) literature that is relevant to answering the research questions as stated in section 1.3 has already been covered by the problem definition section or will be covered by the methodology section. Relevant literature that is not fully addressed in the problem definition or methodology sections is included in this chapter. First, the hierarchy of waste management will be described. Then, the integrated waste management (IWM) approach, which is a counterpart to the hierarchy, will be introduced. After that, current literature on optimizing the sustainability of solid waste management will be listed and sorted based on the approach that was utilized. Finally, some key principles of waste logistics will be described based on an integrated waste management flow chart.

2.1 Hierarchy of Waste Management

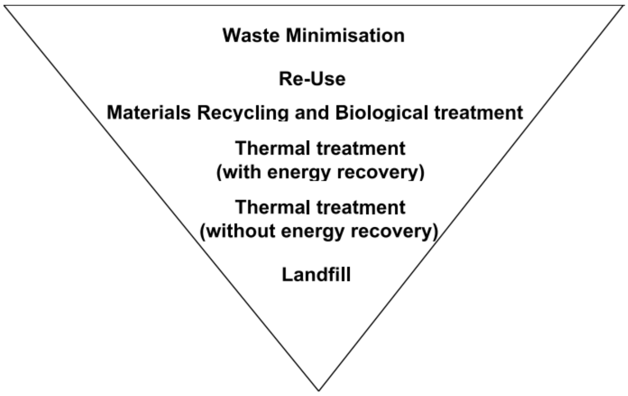

Figure 2.1: Hierarchy of waste management
(McDougall et al., 2001)

The hierarchy of waste management, which is displayed in figure 2.1, is a concept that is widely used in international as well as national policy and legislation about SWM. It provides a priority list for waste management options where options at the top of the hierarchy such as waste minimisation and re-use are to be prioritized over thermal treatment and landfill. The clarity and ease of use of the hierarchy explains part of its popularity. However, despite its wide application, the hierarchy has quite some limitations. Most importantly, it has no scientific basis and does not incorporate costs (McDougall et al., 2001). The hierarchy always prefers recycling over thermal treatment (with energy recovery) while in some cases, thermal treatment may be more sustainable for particular waste streams. Furthermore, the hierarchy cannot asses a system that combines several waste treatment options while many waste streams require sequential treatments. Therefore, this research utilizes the Integrated Waste Management (IWM) approach instead of the hierarchy of waste management. IWM is holistic and able to asses all kinds of waste treatment combinations. This will be further explained in the next section.

2.2 Integrated Waste Management

Integrated Waste Management (IWM) as a concept was first defined in the United Nations Environmental Programme of 1996 as: "*a framework of reference for designing and implementing new waste management systems and for analysing and optimising existing systems*" (UNEP, 1996, p.9). As mentioned earlier, IWM is a holistic approach to SWM striving for environmental effectiveness, economic affordability and social acceptability. The principles of IWM are extensively documented in the book 'Integrated solid waste management: A Life Cycle Inventory' by McDougall et al. (2001). Since the three objectives of IWM are difficult to maximize simultaneously, there will be a trade-off. "*The balance that needs to be achieved is to reduce the overall environmental burdens of the waste management system as far as possible, within an acceptable level of cost*" (McDougall et al., 2001, p.44). As the term IWM already implies, this approach revolves around two key principles: all types of solid waste materials and all sources of this solid waste are considered. The reason for this is that focusing on specific materials or sources is likely to be less effective. Instead of making minor changes to the old system, the whole (interconnected) system is being looked at. Two more ways in which IWM is an integrated approach are that all collection and all treatment methods are considered. Furthermore, IWM is market-oriented and flexible in the sense that it recognizes that effective recycling and composting depends on markets for these output products and that, therefore, these waste treatment options may be varied in time. As opposed to the 'hierarchy of waste management', which is often referred to by policy and legislation, IWM does recognize that all waste management options can play a role in optimizing the whole system, depending on the local situation. This is illustrated by figure 2.2.

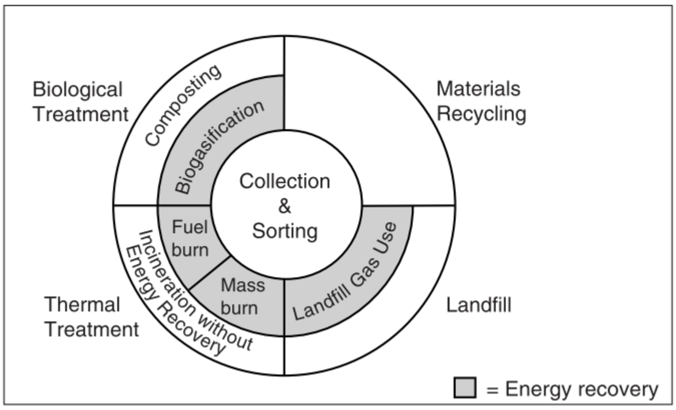

Figure 2.2: Elements of IWM (McDougall et al., 2001)

IWM is all about balancing the elements of figure 2.2 in a way that is optimized for a given context. This can be done using LCA, which will be described in the next chapter, as an assessment method. The step that precedes effective IWM, in reality, is waste minimization or waste prevention. This is, therefore, not part of the IWM framework but a precursor to it (McDougall et al., 2001).

2.3 Solid Waste Management Optimization

There are many previous studies into solid waste management optimization with respect to sustainability. These studies can be divided based on the approaches that have been described in the previous sections. This division is visualized in tables 2.1 (condensed overview) and 2.2 (elaborate overview). On the one hand, there are studies that take the hierarchy of waste management as a starting point. These studies generally analyze SWM systems based on the components of the waste hierarchy and aim at optimization towards (higher) hierarchy standards. These studies do usually not include a LCA to quantify environmental burdens. On the other hand, there are studies that implicitly or explicitly apply the concept of integrated waste management. These studies generally compare the (life cycle) environmental burdens of different SWM strategies based on a LCA without prior assumptions on the hierarchy of management options. Tables 2.1 and 2.2 also organize SWM optimization studies based on their application area. Most studies focus on (household) waste collected by municipalities. Furthermore, there are also quite some studies that focus on the environmental burdens of individual (packaging) products. A more niche research area relevant to this research is SWM in (semi-)public spaces or SWM of recreational waste. There are only few studies with this application area and all of them are currently done according to the hierarchy of waste management approach. This creates the research gap that is indicated in the bottom right corner of table 2.2. The research gap has also been described in section 1.2.4.

	Approach		*Application*		
	Hierarchy of Waste Management*	Integrated Waste Management**	Individual Product Supply Chains	Municipalities / Residential Waste	(Semi-)Public Spaces / Recreational Waste
Kopicki et al. (1993)	●		●		
Radwan (2009)	●				●
Annepu (2012)	●			●	
Pirani & Arafat (2014)	●				●
Martinho et al. (2018)	●				●
Rafiee et al. (2018)	●				●
CE Delft (2007)		●	●		
Parkes et al. (2015)		●		●	
Turner et al. (2016)		●		●	
TNO & WFBR (2018)		●	●		
This Article		○			○

* Optimization towards hierarchy standards

** LCA approach, no assumptions on best SWM strategy

Table 2.1: Condensed literature overview ordered by approach and application area

Approach / Application	Hierarchy of Waste Management Optimization towards hierarchy standards		Integrated Waste Management LCA approach, no assumptions on best SWM strategy	
Municipalities / Residential waste	Annepu (2012)	To find ways to reduce the quantity of solid wastes currently disposed in India by recovering materials and energy from wastes, in a cost effective and environmental friendly manner.	Parkes et al. (2015)	LCA of 10 integrated waste management systems for 3 potential post-event site design (mostly residential) scenarios of the London Olympic Park.
			Turner et al. (2016)	Evaluating the environmental performance of a local authority SWM system and to compare it with alternative systems
Individual Product Supply Chains	Kopicki et al. (1993)	Guide for planning and implementing waste reduction, reuse and recyling programs for supply chains	CE Delft (2007)	Assessing the life-cycle environmental burdens of individual packaging materials
			TNO & WFBR (2018)	Evaluating the environmental burdens of two different SWM strategies for processing cardboard cups
(Semi-)Public Spaces / Recreational waste	Radwan (2009)	Evaluating the state of waste hierarchy implementation at small hotels and identifying corresponding challenges	**Research gap** (see section 1.2.4)	
	Pirani & Arafat (2014)	Examining the current status of waste management in the hospitality sector and proposing a general waste management procedure for this sector		
	Martinho et al. (2018)	Analyzing waste prevention and management measures implemented at the Andanças festival, Portugal.		
	Rafiee et al. (2018)	Investigating the effects of different events and festivals in Tehran on quantity of recyclable fractions to optimize recycling rate		

Table 2.2: Elaborate literature overview ordered by approach and application area, including research gap

2.4 Key principles of waste logistics

To illustrate the key logistic principles, elements and system boundaries of an integrated SWM system, the IWM-2 model by McDougall et al. (2001) will be used as an example. This model is displayed in figure 2.3. The model is able to calculate the size of different waste (processing) streams and the environmental burdens associated with these. In this research, the exact IWM-2 model will not be used for performing scenario analysis. However, the principles and elements of the model used will be similar to those in IWM-2. The IWM-2 model contains all of the elementary processes that have to be considered when optimizing SWM systems using the IWM approach. These processes are: waste generation, collection, sorting, transportation and treatment. Several treatment options including recycling, biological treatment, thermal treatment and landfill are modelled next to each other. The exact applications and properties of the different sorting and treatment processes will be described later. For now, it is important to observe that the inputs to the model are: waste, energy (which may be the burning of fuel) and raw materials. The outputs are: energy, recovered materials, compost, air emissions, water emissions and residual solid waste. Furthermore, it should be noticed that second-level burdens are not included in the model. These are the environmental effects of building and decommissioning facilities, equipment and infrastructure for the SWM system. An example of a second-level burden would be the production of a garbage truck. Previous studies have shown that second-level burdens are insignificant when spread over the life cycle of the equipment, facility or infrastructure (McDougall et al., 2001). However, as these assets may require significant capital investments, they should be included in the economic assessment in addition to operating costs. Finally, to be able to determine the in- and outputs of each (treatment) process in the model, given its efficiency, the composition of each waste stream (represented by arrows) has to be known. This means that although materials may be physically mixed together, the material fractions have to be kept separate in the model. Therefore, on a practical level, residual waste cannot be an input to the system. The residual waste has to be artificially divided into several material fractions, based on for example sorting tests.

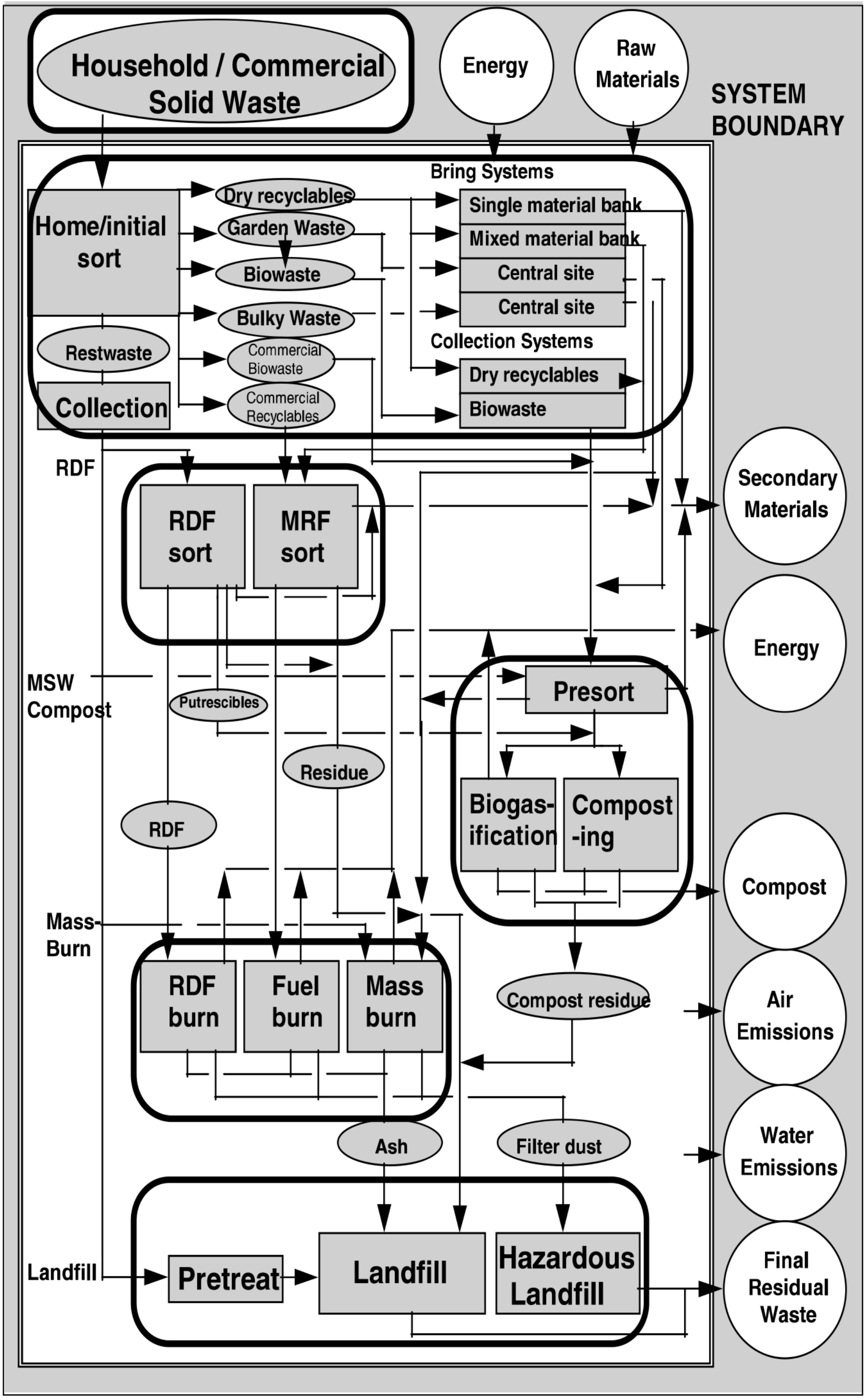

Figure 2.3: Elements, logistic flows and system boundaries of the IWM-2 model (McDougall et al., 2001)

Chapter 3

Methodology

The overall approach that will be used to answer all of the research questions is that of Integrated Waste Management (IWM). The main principles of IWM are discussed in the literature overview (chapter 2.2). This chapter describes the methods that will be used to answer the research questions as formulated in chapter 1.3. A case study data analysis will be used throughout this research to perform the case study. This method will be described first in section 3.1. However, some of the case study data requirements mentioned in this section are derived from the life cycle assessment method which is described in section 3.4. The second method that will be described is requirements engineering which will be used to answer sub research question 2. Subsequently, general morphological analysis, which will be used to design the SWM strategies of sub question 3, will be introduced. In line with the IWM approach, a Life Cycle Assessment (LCA) method will be used to compare the different SWM strategies (sub questions 4 and 5). LCA will be explained in subsection 3.4, it consists of an environmental as well as an economic analysis. The LCA('s) should provide an objective basis for strategic decision making regarding SWM strategies. Finally, uncertainty analysis will be used to check the robustness of the estimated impact of different SWM strategies, this will be described in section 3.5.

3.1 Case Study Data Analysis

Doing a case study enables to go really in-depth when it comes to, for example, analyzing SWM data and operations (Flyvbjerg, 2006). This is important since SWM systems are really complex and consist of a lot of interrelated processes (as shown in section 2.4) that may differ per location and sector. Generalizing these systems would mean that a lot of significant nuances that result in very different impact numbers would be overlooked. By focusing on a specific type of SWM system, the impact of such a system can be analyzed much more accurately. In the case of the Efteling, detailed data about waste quantities, waste compositions, transport distances and collection and processing costs is available and can be used to do an in-depth impact analysis of different possible strategies for the Efteling as well as for the sector. This is mainly done using an LCA (see section 3.4). Performing LCA's and more specifically LCI's requires lots of data. This data can be divided into two categories: specific data and generic data. Generic data are often averages that can be used for any LCA. Specific data consist of data that is specific to the system being assessed. Generic data can be replaced with specific data if it is available. While generic data is becoming widely available, specific data, especially on SWM, is scarce (McDougall et al., 2001). Data can also be classified into the following categories, note that these are general and thus also applicable to product LCA's (ISO, 2006):

- Energy inputs, raw material inputs, ancillary inputs, other physical inputs
- Products, co-products and waste
- Emissions to air, discharges to water and soil
- Other environmental aspects

The advantage of doing a case study is that, for some of these categories, specific data can be used instead of generic data. Data about the MSW collection, transportation, sorting and treatment processes can for example be derived from the Efteling itself and its waste processing company. For some data about emissions caused by waste treatment processes 'down-the-line' generic data may be used. This data is available from LCA databases that can be downloaded online. For the overall data management process, there are software tools specifically designed for LCA's such as 'OpenLCA', which is open-source, WARM and WRATE. These tools may be used depending on their usefulness during the actual research.

For the economic assessment, waste processing costs as provided by the waste processing company can be used. In addition, operational processes within the Efteling regarding waste transport and sorting may have to be analyzed to be able to asses the (potential) costs of staff and energy for these processes.

3.2 Requirements Engineering

Before starting to design and model (alternative) SWM strategies, it is important to define what the stakeholders need from these strategies and what the underlying systems must do in order to satisfy these needs. This can be done using requirements engineering. As Hull et al. (2011) describes, formulating requirements is the basis for every project, there are many examples of systems that failed because requirements were not properly organized. Requirements engineering enables better communication and accountability between stakeholders and projects and it improves the traceability of design choices. The latter can contribute to a greater confidence in meeting objectives and to a better ability to assess the impact of change (Hull et al., 2011).

A classic model that is widely used in the context of requirements engineering is the V-model. This model will also be (partly) applied in this research. The model is displayed in figure 3.1. As the model already indicates, requirements engineering is not a single phase. It is applicable throughout the complete development process of a system. Different types of requirements can be distinguished based on the state of the development process. The V-model starts with the formulation of stakeholder requirements, these state what the stakeholders want to achieve through use of the system. These can subsequently be used to define system requirements that state abstractly how the system will meet the stakeholder requirements (Hull et al., 2011). The system requirements may be broken down into subsystem requirements and component requirements that state how the specific design will meet the system requirements. In this research, the focus will be on identifying requirements in the problem domain. This mainly refers to stakeholder requirements as these should not contain any reference to particular solutions. In other words, requirements in the problem domain state no more than necessary to define the problem in order to find the best solution without preconceived ideas (Hull et al., 2011). Finding concrete solutions or scenarios is done using morphological analysis which will be described in the next section (3.3). These solutions can be tested (implicitly) against system and subsystem requirements in the cross-consistency assessment (that is part of the morphological analysis) or the eco-efficiency analysis that follows. The testing is displayed at the right side of the V-model.

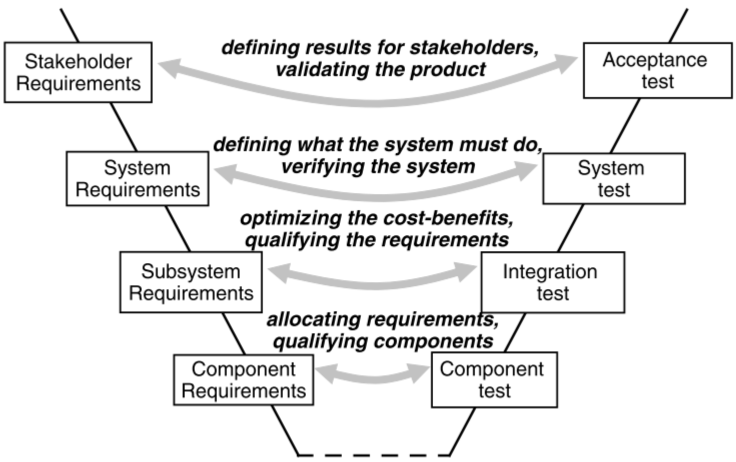

Figure 3.1: The V-model: Requirements Engineering in layers (Hull et al., 2011)

As described by Bahill and Dean (2009), different types of requirements can be distinguished. Some requirements are non-negotiable, these are also called mandatory requirements or constraints. Others requirements that are negotiable are called trade-off requirements or objectives. A requirement can also be both a constraint and an objective. For the latter category, several performance values such as mandatory lower or upper limits, desired values and/or best values may be provided in both constraints and objectives. Requirements can also be divided into functional and non-functional requirements. Functional requirements state things that a system has to do while non-functional requirements state attributes (performance, usability etc.) that a system must have. Finally, all requirements and requirement sets should meet the criteria mentioned in table 3.1.

Requirement criteria	Requirement set criteria
Atomic	Complete
Unique	Consistent
Feasible	Non-redundant
Legal	Modular
Clear	Structured
Precise	Satisfied
Verifiable	Qualified
Abstract	

Table 3.1: Criteria for writing requirements (Bahill & Dean, 2009; Hull et al., 2011)

3.3 General Morphological Analysis

Since SWM systems are fairly complex and consist of a chain of interrelated processes such as collection, sorting, transportation and treatment processes (see also section 2.2), composing relevant strategies has to be done in a systematic way. General Morphological Analysis (GMA) is a widely used method in this context and will also be used in this research for composing strategies. GMA was developed by Zwicky (1967) for investigating problem complexes. It is a method for "*identifying and investigating the total set of possible relationships or "configurations" contained in a given problem complex*" (Ritchey, 2002, p.3). The GMA method consists of broadly two steps:

1. Constructing a morphological box
2. Cross-consistency assessment (reduction)

A morphological box can be constructed by identifying the parameters of the problem (SWM in this case) and by assigning a relevant range of conditions to these parameters. These parameters and conditions are then combined in a matrix where each cell represents a condition for a certain parameter. This is illustrated in figure 3.2. The combination of blue cells in this figure represents a single strategy or configuration. One can imagine that complex problems result in morphological boxes with a very high number of possible configurations. Therefore, a cross-consistency assessment is carried out as a second step. In this assessment, the number of possible configurations is reduced by crossing out configurations that are internally inconsistent. This can, for example, be done using a pair-wise comparison as described by Ritchey (2002). Three types of inconsistencies can be distinguished (Ritchey, 2002, p.6):

1. Logical contradictions: Based on the nature of the concepts.
2. Empirical inconsistencies: Combinations that are highly improbable on empirical grounds.
3. Normative constraints: Combinations that are excluded based on ethical or political grounds.

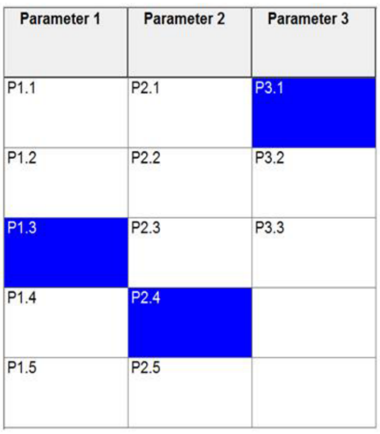

Figure 3.2: Morphological box in morphological field format

A major advantage of the use of the GMA method for composing strategies is that it represents a fairly clear 'audit trail' (Ritchey, 2002). In other words, it makes the strategy formation traceable. Additionally, GMA helps to discover new and non-obvious configurations that may have been overlooked otherwise. After the formation of strategies using GMA, these strategies still have to be assessed in terms of sustainability. This is done using life cycle assessments and an economic assessments which will be described in the next section.

3.4 Life Cycle Assessment & Economic Assessment

Life Cycle Assessment (LCA) is, as the name implies, a tool to understand and evaluate environmental burdens of a product, process or service during its entire lifetime ('from cradle to grave'). It is considered to be one of the most effective management tools for assessing the environmental impacts of different SWM systems (Cherubini et al., 2009). The LCA has become so important in decision making processes that ISO standards on its principles and implementation were developed around 1997. The current ISO standards on LCA are ISO14040:2006 and ISO14044:2006. These ISO standards are not prescriptive, they leave a lot of flexibility for organizations to implement LCA according to their requirements as long as all steps are completed (ISO, 2006).

The difference between a LCA for a product or service and a LCA for SWM is that the latter can be characterized as a LCA 'in reverse', in the sense that the product (waste) remains constant (after waste minimization) while the disposal method changes to influence environmental impact (McDougall et al., 2001). In a product LCA, the product itself is changed to influence environmental impact. Whereas a product LCA takes the source of raw materials as 'the cradle' and the final disposal of the product into the environment as 'the grave', a SWM LCA takes the bin as 'the cradle' and the final disposal into the environment as 'the grave'. This means that both applications overlap. However, they have different functional units and therefore also a different purpose. The definition of functional unit will be explained later. Another way to characterise the difference between a product LCA and a SWM LCA, which will used in this case, is that a product LCA utilizes a vertical approach whereas the SWM LCA utilizes a horizontal approach (McDougall et al., 2001). In other words, the product LCA considers raw materials extraction, manufacturing, distribution, use and waste management of a single product whereas the SWM LCA only considers waste management but does this for all products present in the waste. This difference makes that a SWM LCA is way more useful in this case as a theme park or semi-public space has considerable influence on its SWM system and infrastructure while it has way less influence on products that are disposed. In short, a LCA works in the following way. The LCA calculates the inputs (raw materials, resources, energy) and outputs (emissions to air, water and solid waste) for every operation in the life cycle (McDougall et al., 2001). After aggregating these inputs and outputs over the entire life cycle, the environmental consequences of these can be evaluated in the Life Cycle Impact Assessment (LCIA). The different stages or steps of a LCA, based on ISO (2006) are illustrated in figure 3.3.

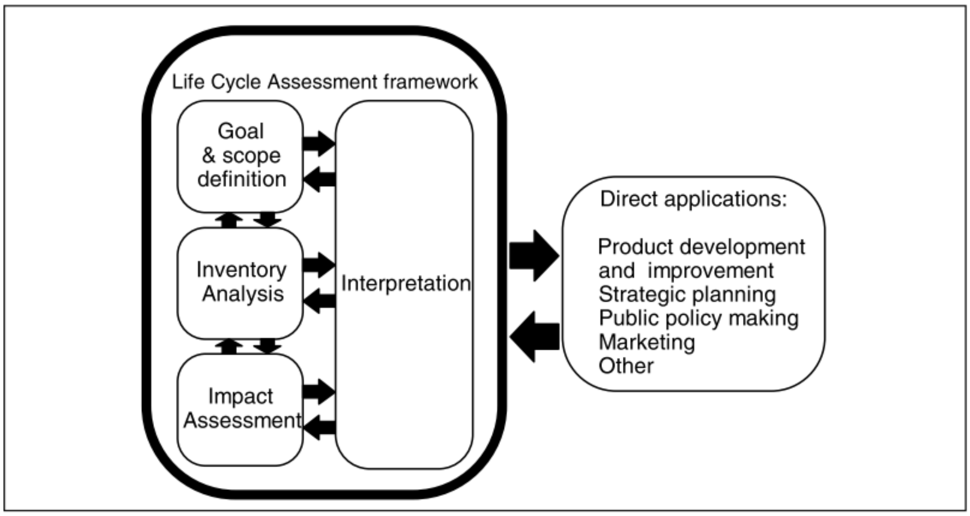

Figure 3.3: Stages of a LCA (ISO, 2006)

Each stage will now be briefly discussed. A LCA starts with the 'goal and scope definition' phase. In this phase, the intended use of the LCA and its system boundaries (technical, geographical and time) are defined (McDougall et al., 2001). Furthermore, this phase includes describing the product system, the functional unit and all assumptions and limitations. The product system is, in this case, the complete SWM system and all of its processes. The choice of a functional unit, which is the focus of the study, is very important. For a product LCA, the functional unit usually is the product (per kg, liter or unit of product), this is the output of the system. For a SWM LCA, the functional unit is the input of the system (waste). This means that the functional unit is, for example, the total waste of a defined geographical area over a certain time period (Cherubini et al., 2009). During the 'goal and scope definition' phase, one may also define different SWM scenarios to be assessed.

The next step is the Life Cycle Inventory Assessment (LCI). This is where all of the energy and material in- and outputs for each stage in the life cycle are calculated. It involves a lot of data manipulation. The acquisition of this data is discussed in subsection 3.1. When all in- and output data has been related to the functional unit and aggregated, the final stage can be initiated. This final stage is the Life Cycle Impact Assessment (LCIA). This stage is "*aimed at evaluating the significance of potential environmental impacts using the LCI results. In general, this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts*" (ISO, 2006, p.14). Examples of category indicators are: 'Global Warming Potential' in CO_2 equivalents and 'depletion rate of resources'. The final result of the LCIA is the indication of the contribution of the life cycle to the selected environmental issues (McDougall et al., 2001).

As can be seen in figure 3.3, all stages are linked to the interpretation stage. This involves checking that all assumptions are consistent and that the data throughout the whole LCA process is reliable enough. It also includes checking the sensitivity of the indicators of the significant issues. This should ensure that the conclusions are valid. Along with the LCA, a parallel economic assessment with the same system boundaries has to be executed since the environmental burdens of a SWM system have to be compared to its economic sustainability in the end, in line with IWM principles. This is especially relevant in this case since we are mostly dealing with companies and semi-public spaces with high costs for collection. Economic inputs include costs for collection, sorting, various forms of treatment, transport and final disposal but also revenues from the sale of reclaimed materials, compost and energy (McDougall et al., 2001).

In order to compare the environmental burdens of different SWM systems, the LCA indicator results of different impact categories may have to be weighted to obtain an overall score. This is the most subjective phase of a LCA as the weighing is specific for one organisation (ISO, 2006). This emphasizes that LCA is a decision support tool, it does not replace decision-making. Finally, the environmental burdens of different systems also have to be compared to their respective economic costs. This can be done using an eco-efficiency key performance indicator. This concept will be described in chapter 5.

3.5 Uncertainty Analysis

Since the results of the LCA modelling process, which has been described in the previous section, may be affected by different sources of uncertainty, doing an uncertainty analysis is deemed to be important. As Björklund (2002, p.64) describes, "*uncertainty arises due to a lack of knowledge about the true value of a quantity*". This may be true for many inputs to the LCA model. Uncertainty is not the same thing as variability, the latter is attributable to the natural heterogeneity of values. In the context of LCA, different types of uncertainty can be distinguished (Björklund, 2002; Huijbregts, 1998):

- Parameter Uncertainty: Related to possible empirical inaccuracy, unrepresentativeness or lack of inventory analysis (background) data.
- Model uncertainty: Related to aspects that cannot be modelled within the LCA structure due to simplifications. These include the loss of temporal and spatial characteristics due to the aggregation of emissions.
- Uncertainty due to choices: Choices are unavoidable in performing a LCA. There is often not one single correct choice when choosing a functional unit, system boundary or allocation rule for multi-waste processes. This leads to uncertainty in choice.

These different types of uncertainties may be dealt with in different ways. Parameter uncertainty can be controlled by using standardised life cycle inventory data from databases which may also include uncertainty ranges. Furthermore, expert judgement can be used to estimate uncertainty ranges of parameters (Huijbregts, 1998). Model uncertainty is less relevant for this case as temporal and spatial variability are of less importance to the (time) scale at which the LCA is performed and to the global warming potential indicator. Finally, uncertainty due to choices is considered to be the most relevant source of uncertainty in this case. This source of uncertainty can be reduced by applying standardised procedures and models. One of these standards is ISO (2006), which has already been mentioned. Following a standard may increase credibility because it makes it easier to communicate how a study was done (Björklund, 2002). Furthermore, it also decreases the risk of making mistakes. In addition to using standard procedures, a scenario analysis is considered to be a very relevant tool to address uncertainty due to choices in this case.

Scenario analysis or modelling involves calculating different scenarios to analyse the effect of corresponding input parameters on output values (Björklund, 2002). Scenarios in this context are descriptions of possible future situations, based on certain assumptions about the future. A scenario analysis is sometimes also called a sensitivity analysis and can be visualised using a tornado diagram (Björklund, 2002).

Chapter 4

Current Solid Waste Management at the Efteling

This chapter describes the current operational, environmental and economic characteristics of SWM practice in the Efteling. This is done for all of the elements that are commonly distinguished within a SWM system in scientific literature (Gentil et al., 2010; McDougall et al., 2001). These elements are waste collection, waste transportation, waste sorting and waste treatment. The structure of this chapter is also based on these elements (see figure 4.1). Whereas the operational characteristics are discussed throughout the chapter, the economic characteristics of SWM operations are provided at the end of each subsection. Finally, the environmental implications of SWM are mainly discussed in section 4.4 about waste treatment. Before going into the actual SWM system, some general information about the case is provided in section 4.1.

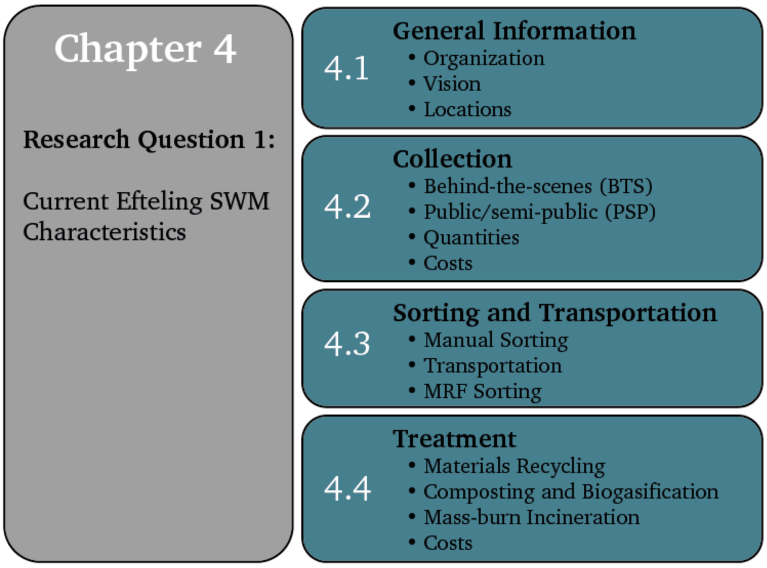

Figure 4.1: Structure of chapter 4

4.1 General Information

Before analyzing the current SWM practice of the Efteling, this section will provide some general information that is relevant to understanding the organization, its vision and its geographical structure.

4.1.1 Organization

The Efteling B.V. is organized into three different business units that can operate relatively independent and a support division that supports these business units. Together these are referred to as the 'World of the Efteling'. The business units are further divided into divisions that work closely together. The business units are listed below. Corporate support, which advises on all kinds of matter including sustainability and SWM, has also been added although this is not necessarily a business unit but a supportive unit. This research is commissioned by the corporate support division of administrative affairs.

- Corporate Support
- Park
- Hotels & Resorts
- Events

The most relevant divisions with respect to SWM, besides administrative affairs, are Park Food and Beverage and Park Maintenance and Service. Park Food and Beverage is the main waste generator of the park. Park Maintenance and Service has a specific subdivision that takes care of SWM and the operation of a large waste sorting facility ("milieustraat"), this subdivision is called the environmental service ("milieudienst"). The environmental service employs dozens of people and operates every day of the year from 6AM to after park closing time. The SWM-related tasks of the environmental service are:

- Picking up litter
- Swapping bins[1]
- Cleaning cocoons (casing for a wheelie bin)
- Cleaning benches
- Cleaning waste bins and baskets
- Transporting waste streams other than residual waste to specific collection locations
- Separating and sorting bulky waste including construction waste
- Cleaning paths by means of (leaf) blowing and sweeping
- Providing adequate waste bins and baskets to all divisions

All in all, more than 40 different types of waste are being collected separately by the environmental service. Most of these waste streams are relatively small. The exact types and amounts of waste that are being collected are described in section 4.2.

4.1.2 Vision

The long term vision and strategy of the Efteling is described in the 'Meerjarenvisie 2030', which is largely confidential. However, one of the main pillars of the vision is sustainability and the corresponding target to be climate neutral in 2030 (Efteling, 2020b). Besides the vision for 2030, the Efteling has always had a focus on nature and on preserving the Efteling for current and future generations. This is rooted in its history. The Efteling opened in 1952 as a park with a small fairy tale forest and some sport and play facilities. This early Efteling was owned and operated by 'Stichting Natuurpark de Efteling' (Efteling Nature Park Foundation) which, as the name implies, has a focus on recreation in combination with nature (Efteling, 2020a). Although management and operations have been taken over by 'De Efteling B.V.' in 1985, the foundation is still the sole owner and shareholder of the Efteling. This means that the importance of nature conservation and sustainability is deeply intertwined in the organisation.

4.1.3 Locations

A map with of the Efteling park can be found in appendix B. This map also shows the different realms ('Rijken') into which the park has been divided. This realm division also plays a role in the organisation of staff and operations. The central waste sorting facility ('milieustraat') is not visible on this map. This facility is located adjacent to the west edge of the main parking lot.

4.2 Collection

Waste collection forms the contact point between waste generators (guests, staff members, operations) and the SWM process chain. This means that collection also has a major impact on subsequent steps in the SWM

[1]Only a small portion of the bins in the park is swapped by the environmental service, others are swapped by the Attractions, Entrance and Entertainment division and the Food and Beverage division.

process chain. As McDougall et al. (2001) describes, the collection determines which waste management options can be used and whether these are economically and environmentally sustainable. Furthermore, the collection method also influences the quality of possible recovered materials, compost and/or energy and thereby also their market potential. From a pure recycling point of view, the ideal collection process would result in purely separated homogeneous waste streams. Looking at it in a more integral way, this is unlikely to be optimal as both the collection processes and the subsequent handling processes of purely separated waste streams require a lot of effort and energy. The reason for this is that benefits from economies of scale and synergies between different waste treatment options are (partly) lost (McDougall et al., 2001).

The quality of waste separation in the collection phase is dependent on the characteristics of the waste generators. Different models and theories exist for explaining this waste separation behavior. One of the most widely used theories in this context is the theory of planned behavior by Ajzen (1991). The structural diagram of the theory of planned behavior is displayed in figure 4.2, this diagram is sometimes also referred to by the name 'Triad Model'. A central assumption of the theory of planned behavior is that people act rationally and that they systematically use the information that is provided to them (Berends, 2003). In short, the theory of planned behavior states that intentions influence behavior. "*The stronger the intention to engage in a behavior, the more likely should be its performance*" (Ajzen, 1991, p.181). Intentions are, in turn, influenced by attitudes, subjective norms and perceived behavioral control. In the context of (separate) waste collection, this means that the willingness of people to correctly separate their waste (intention) depends on (Berends, 2003):

- Their attitude towards separate waste collection. This attitude is related to their knowledge, feelings and ideas about separate waste collection.
- Their impression of relevant other people's attitude towards separate waste collection.
- Their estimation of their own effectiveness with regards to separate waste collection. This estimation is based on experience, observation of others and observation of the situation.

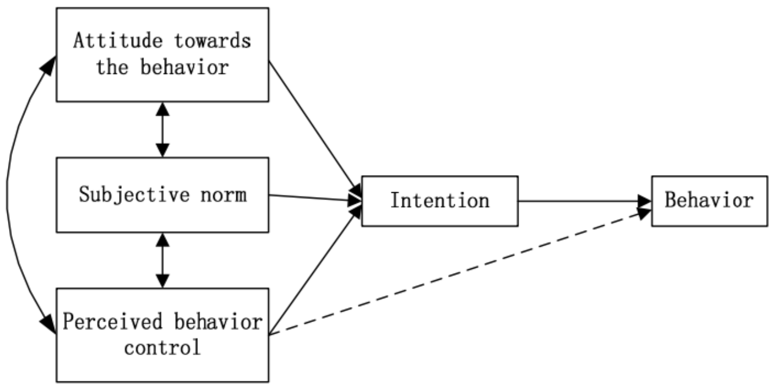

Figure 4.2: Schematic representation of the theory of planned behavior (Ajzen, 1991)

The model that is used by McDougall et al. (2001) to predict the amount of correctly sorted waste in the collection phase follows the logic of the theory of planned behavior to a large extent. It is simpler in the sense that it only models degree of sorting as a function of sorting ability and sorting motivation. Ability corresponds to perceived behavioral control and motivation to attitude and subjective norms within the theory of planned behavior. Both sorting ability and sorting motivation influence the participation rate and the separation efficiency which are the factors that can be used to theoretically calculate the recovery rate of of waste materials (rate of correctly sorted waste). The formula for the total amount of recovered waste material (e.g. paper or plastic) is given below (formula 4.1):

$$\text{Amount of material recovered} = \text{Amount of material in waste stream} \times \text{Participation rate} \times \text{Separation efficiency} \quad (4.1)$$

The participation rate is the percentage of, in this case, guests and staff members that participate in separate waste collection. The separation efficiency refers to the percentage of material that is correctly sorted and separated. This percentage (for one type of material) is equal to 100 minus the contamination level. Four different types of contamination can be distinguished (McDougall et al., 2001):

1. Wrong material type for that part of the system
2. Right material but in the wrong form (plastic packaging in plastic bottle bin)
3. (Dirty) leftover waste material (of the wrong type) after emptying
4. Non-recyclable material

The combination of participation rate and separation efficiency results in the material recovery rate. This rate can differ significantly for different collection systems. A property of waste collection in the culture, sport and recreation sector is that it is often done using multiple types of collection systems next to each other. This is also true for the Efteling.

Two types of SWM operations can be distinguished in the Efteling: behind-the-scenes (BTS) SWM and public/semi-public (PSP) SWM. The first type (BTS SWM) refers to the collection of MSW as well as other types of waste in spaces that are only accessible to staff members. This includes waste collected in kitchens, sculleries, warehouses and workshops and waste from construction sites. The second type (PSP SWM) refers to the collection of waste in areas that are accessible to guests and visitors. The waste collection processes will now be described into more detail.

4.2.1 Behind-the-scenes collection

BTS waste collection in the Efteling park happens at many different locations throughout the park. These are mainly linked to catering (food and beverage) locations. There are, however, also other types of BTS collection locations such as the Raveleijn office (corporate headquarters) and the Dienstencentrum (service center). Waste that is collected inside buildings is brought to the nearest BTS waste cluster site where it remains until it is picked up by the waste management company or internal Efteling transport. Cluster sites are mostly permanent but can also be temporary to facilitate seasonal/temporary food and beverage locations. This is for example the case for the ice tent which is usually present during the 'Winter Efteling' season. The types of waste that are currently being collected separately at nearly all BTS collection locations in the park are listed in table 4.1. The table also includes information about the types of bins that are used for the collection and a description of the different waste types. Note that the the listed bin types are those that are used at the waste collection cluster sites and not necessarily the ones that are used in (rinse) kitchen environments.

Waste type	Bin type(s)	Description
Residual Waste	240 liter and 1100 liter black bins	Waste that does not belong to any other category
Paper	1100 liter blue bins and compressed bales	Paper and cardboard
Glass	660 liter blue bins with yellow cover	All types of (hollow) glass
PET Bottles	240 liter orange bins	Only all types of PET Bottles
Swill	120 liter green bins	(Cooked) food scraps including sauces and soups
Fat and Oil	120 liter blue bins with grey cover	Waste (frying) fat and oil
PMD[2]	1100 liter blue bins with orange cover	Plastics, metal packaging and drink cartons
Foil (LDPE)	400 liter transparent foil bags in a holder	Low-density polyethylene: packaging film
Cardboard Cups	Tubes and yellow bags	Cardboard cups with polyethylene (PE) coating
Garden Waste	Depots at 'Milieustraat' and 'Tuinhuys'	Garden and sweeping waste

Table 4.1: BTS collection waste types (park)

Since BTS waste collection is handled by staff members, the extent to which the Efteling can control the collection process is higher compared to PSP collection. This means that both the participation rate and the separation efficiency can be influenced more directly. By means of staff education, motivation and management, the participation rate and separation efficiency are increased relative to PSP collection. This also explains why the number of separately collected types of waste is higher compared to PSP collection. Information about the

[2] BTS PMD collection is currently being rolled out to all park food and beverage locations

quantities of waste collected in the Efteling over different periods of time is provided later in this chapter in section 4.2.3. The separately collected waste streams (everything except residual waste), that are also present in the data, are almost completely the result of BTS collection. Still, there is also a major fraction of BTS waste that is being processed as residual waste.

Legal Framework separate waste collection

The Environmental Protection Act (Wet MB, 2019) and elaborations thereof in the National Waste Management Plan 3 (LAP3, 2019), state specific requirements for separate waste collection that are mainly applicable to the BTS collection of the Efteling. First of all, annex 15 of the LAP3 contains a list of waste types that have to be kept separate. In principle, this list applies to all types of waste collection and storage. However, it is stated that a less strict working method may be applied to the collection of household waste or small amounts of non dangerous waste within organizations. Waste types that have to be kept separate according to annex 15 and that are relevant in the Efteling case are: garden waste, separately collected organic waste, paper and cardboard, packaging glass and waste oils. On top of that, there is another LAP3 guideline specifically for companies (B.3.5.) that states that it is forbidden to mix waste with other types of waste if separation can reasonably be demanded. This reasonability is further defined using specific thresholds. The following waste types are collected in quantities above the threshold which means that they have to be collected separately: paper and cardboard, foil and other plastics, swill, garden waste, and glass packaging. However, even for these waste types, separate collection may not be reasonable if, and only if, the costs for separate collection and processing of a specific waste type are more than €45 higher than the costs for the collection and processing of residual waste (per ton). The costs of SWM are further discussed in section.

BTS residual waste composition

To get insight into the composition of BTS residual waste, the Efteling performed a sorting test of residual waste in cooperation with Renewi in 2018. The sorting test was executed by means of hand picking. To make sure that this sorting test is representative for all of the BTS collected residual waste in the park, the sorting test was performed on 6 samples coming from BTS locations spread over the park. The samples also cover a wide variety of food and beverage formulas present in the park (fast service, table service etc.). The results are largely confidential, some conclusions are discussed below. In total, 421 kilograms of residual waste was sorted into 9 different types of waste. Note that the total weight of the sorted waste was slightly higher than 421 kilograms due to measuring inaccuracies.

From the results, it can be concluded that the largest fraction of BTS residual waste is 'real residual waste', meaning that it could not be categorized as one of the other 8 (recyclable) waste types. However, this also means that a majority of the waste could be classified as a distinct type of waste. Especially food waste turned out to be a major component. This is remarkable as swill bins, that are actually meant for food waste, are present at all of the sampled BTS locations. The same goes for paper and card, which was found to be a smaller but still significant component of the BTS residual waste. For the other types of waste, no separate BTS bins were available at the time of the test. The results indicate that plastics such as plastic packaging and PET bottles also are a major component of BTS residual waste. The fraction of drinking cans is relatively small but this fraction can have a major impact on CO_2 emission as we will see later. Bulky waste, which also forms a relatively large fraction, includes wood, metals and manufactured items such as umbrellas and bags.

4.2.2 Public/semi-public collection

PSP waste collection in the Efteling is less complicated in the sense that it mainly involves the collection of residual waste in the guest accessible areas throughout the park. However, this type of collection is responsible for a major part of the total residual waste quantities collected in the Efteling park. Data about quantities is provided in section 4.2.3. The PSP collection waste types and bins are listed in table 4.2. Note that for the collection of residual waste, a variety of bins is used. When a 240 liter roll container is used for PSP collection, this roll container is always placed into a themed cocoon. Such a cocoon is displayed in figure 4.3.

Waste type	Bin type(s)	Description
Residual Waste	• 240 liter black/green bins in a themed cocoon • Holle Bolle Gijs • Waste baskets • Smaller waste bins	Waste that does not belong to any other category
PET bottles (bin)[3]	240 liter black/green bins in a themed PET cocoon	Only all types of PET bottles
PET bottles (RVM)[3]	Return Vending Machines (see main text)	PET bottles are sorted by barcode

Table 4.2: PSP collection waste types (park)

Figure 4.3: PET cocoon (left), residual waste cocoon (middle) and PET return vending machine (right)

There are hundreds of residual waste cocoons placed throughout the park. The spacing between these cocoons depends on the location, but ranges between 5 and 30 meters. On top of that, lots of waste baskets and smaller bins also collect residual waste in PSP areas. Finally, there are 11 'Holle Bolle Gijs' attractions that playfully collect residual waste. The total numbers of bins per cluster site are not provided in this public version of the report. Note that only the 'spare 240 liter' bins, cocoons and 1100 liter PSP bins are relevant to PSP collection. The cocoons contain 240 liter roll containers that are swapped with 'spare 240 liter' containers when they are full. When all of the spare containers are also full, they are emptied into the 1100 liter bins. The 1100 liter bins remain at the cluster site and do not move into the PSP areas.

The current PSP PET bottle collection is a pilot project meant to test the purity of PET collected waste streams. The pilot consists of two PET bottle bins and two return vending machines (RVM's) that are placed on two main squares in the park. Pictures of the bins and RVM's can be seen in figure 4.3. The intermediate results of the pilot show that the PET bins provide a waste stream that is quite pure. A small fraction of the collected waste stream consists of cans, cups, sticks and trays (contamination type 1 and 2). The RVM's, which can sort waste into two fractions based on barcodes, manage to collect a PET bottle waste stream that is almost completely pure. While the latter stream is eligible for recycling, the PET bin waste stream can currently only be used as a source for manufacturing of PET-based materials (no PET bottles). The total quantities of PET bottles that are collected through PSP collection are however very low compared to the quantities of sold PET bottles.

[3] Current PSP seperate PET collection is a small scale pilot project to test its effectiveness

PSP residual waste composition

To get insight into the composition of PSP residual waste, the Efteling also performed a sorting test of this residual waste in cooperation with Renewi in 2018. This sorting test was performed on 12 samples coming from many different PSP locations throughout the park. The locations include outdoor terraces as well as avenues and squares. In total, 109 kilograms of residual waste was sorted into the same 9 waste types as those in the BTS sorting test. The composition of the PSP residual waste turned out to be quite different as compared to the BTS residual waste. The PSP residual waste contains significantly more PET bottles, bulky waste, coffee cups, cans and beverage cartons. It contains relatively less 'real residual waste', food waste and plastic packaging. The fraction of paper and card is quite similar.

4.2.3 Quantities

This section contains information about the collected waste quantities of the Efteling park regarding all relevant waste types. The exact numbers can not be provided in this public version of the report because they are confidential. Furthermore, note that BTS collection and PSP collection quantities are aggregated since PSP (residual waste) bins are moved to BTS areas when they are full. As mentioned earlier, PSP bins may also be emptied into 1100 liter BTS bins if necessary. All of the (residual waste) bins are also emptied by the 'waste collection company' at the same time. To get insight into the historic development of waste quantities, historic information is presented first. This information is also used to illustrate certain trends regarding different types of waste. After that, data of the year 2019 is studied extensively.

Historic

The collected waste quantities are registered separately for all business units. From this, it can be concluded that the Efteling Park is still by far the largest producer of solid waste. In the analysis of historic waste quantities, the numbers of visitors per year are used to determine the amount of waste per visitor (per person). Besides the absolute quantities and quantities per person, the analysis also includes the calculation of Beta values and Rho square values per waste type based on linear regression. These values can tell whether waste quantities of a specific type have shown an increasing or a decreasing trend over the years (or no trend at all). The Beta and Rho square linear regression values were also calculated for the waste quantities per person.

From the analysis, it can be concluded that absolute quantities of collected waste have strongly increased in the last 15 years along with an increasing number of visitors per year. Residual waste has always been the largest stream and is more than three times as large as the second largest stream, which is swill. When the number of visitors continues to develop as it did in the past and the SWM system remains the same, the amount of residual waste is expected to increase with dozens of tonnes per year. Although this is a large absolute increase, the amount of residual waste per person has remained relatively stable over time. A strong linear trend could not be found in the residual waste numbers per person. Swill is more remarkable in this sense as it has, by far, the largest Beta and Rho square values per person. The values indicate that the amount of swill waste per person has increased over the years. In other words, the increasing amount of swill waste is larger than can be explained by growing visitor numbers, assuming that each visitor causes a more or less fixed amount of waste. A very strong increase in swill waste per person can be noticed between the years 2009 and 2012. This may be related to the increased use of fresh products in food and beverage assortments that started around 2010. The collected quantities of paper per person have not increased significantly although the absolute quantities have.

Current

Another data analysis was conducted using only the most recent data about collected waste quantities in the Efteling park. This data is more detailed in the sense that it includes collected quantities per month. These quantities are subject to strong seasonal variations. This is especially true for residual waste. The variations are, of course, related to the variations in the number of visitors per month. The data also includes 'newer' types of separately collected waste streams. The numbers show, for example, that the separate BTS collection of PMD and cardboard cups has started in the course of 2019. Some important statistical measures including the average waste quantities per month and the standard deviation and coefficient of variation related to these averages have also been calculated.

The statistical measures reveal that residual waste has a monthly standard deviation as high as tens of tonnes. This has, of course, also consequences for waste management processes further down the line. However, looking at the coefficients of variation, which express the extent of variability in relation to the average waste quantities per month, residual waste is overshadowed by PET, glass, foil and garden waste. Collected quantities of PET have the highest coefficient of variation. This variability may be caused by the unfamiliarity with BTS PET collection due to its recent introduction in the Efteling. The relative high variability in garden waste, which also includes sweeping waste, can be explained by the seasonality of plants and trees. In the fall season, a lot of leaves that fall from the trees have to be swept off of the paths and end up as garden waste. Another thing that stands out is the relative stability of the amount of produced swill waste (compared to the stability of the production of other waste types). This may be due to excessive food preparation in less busy months to be able to keep the same assortment. Note that PMD and cardboard cup collection have not been analysed statistically since the separate collection of these waste types has only started in the course of 2019.

BTS/PSP Ratio

Since operational processes have prevented the capture of separate quantitative data for BTS and PSP collected (residual) waste, all of the waste data that was analyzed in this section is aggregated for BTS and PSP collection. To be able to still provide an estimate of the ratio between the amount of residual waste that is collected in PSP areas and the amount of residual waste that is collected BTS, the aggregated volumes of BTS and PSP bins may be used. These are known since all bins at all cluster sites are registered (confidential). However, the 1100 liter bins are used for both BTS and PSP residual waste. Therefore, the 1100 liter bins have been divided into bins that are mainly used for BTS waste and bins that are mainly used for PSP waste. The division is purely based on expert knowledge from employees of the Efteling environmental service subdivision.

The calculation of the ratio between BTS and PSP collected residual waste based on bin volumes shows that a majority of the total residual waste of the Efteling park originates from PSP collection and a minority from BTS collection (exact percentages are confidential). Although it is very convenient to have this estimate, it must be noticed that bin volumes are not directly related to waste quantities in terms of weight. Some bins may have to be emptied every day while others are only full after several days. However, the numbers of bins per cluster site have been optimized over a long period of time to make sure that the released waste quantities per day match the available bin capacity for every site. Therefore, the total available bin volume can be assumed to be representative of the total quantity of residual waste on the busiest days and the BTS/PSP ratio as calculated may be used as an approximation.

4.2.4 Collection costs

The costs of collecting waste consists of costs for the purchase or the rent of bins and collection facilities and the maintenance of these facilities. Note that costs for waste transportation and treatment are discussed later in this chapter. The collection cost values, which differ per bin and waste type, are not included in this public version of the report because they are confidential. Some types of bins have been purchased while others are being rented. The costs per year for bin cleaning are also taken into account as these form a major part of the total collection costs. Note that only bins that are used for the collection of 'dirty' (mixed) waste types have to be cleaned on a regular basis. This refers to residual waste and PMD bins. Swill bins are also cleaned but this is not done on-site. The Swill bins are replaced with fresh bins whenever they are full. The costs for cleaning the Swill bins is therefore included in their transportation costs. For bins that are cleaned on-site, it is assumed that this happens a fixed amount of times per year as is currently the case.

4.3 Sorting and transportation

Sorting and transportation processes are key in the total SWM chain. They connect the collection of waste to the different treatment processes for waste. Since sorting and transportation processes may be present at different places in the SWM chain, depending on the type(s) of waste collected and the availability of treatment facilities, they are jointly addressed in this section. An overview of the main types and methods of waste sorting is provided in table 4.3. Note that these sorting types can also be combined in certain SWM chains. Only the sorting types that are relevant to the SWM chain of the Efteling are described in this section. This means that refuse-derived fuel (RDF) sorting will not be addressed. Manual sorting will first be described since this process occurs at the beginning of the Efteling SWM chain (even before transportation). After that, the transportation of different types of waste will be described. Finally, materials recovery facility (MRF) sorting, which occurs later in the chain, is addressed.

The different sorting methods that are listed in table 4.3 are often combined in a single sorting facility to be able to recover many different types of materials. The methods will not be described into more detail but can be found in McDougall et al. (2001). MRF sorting utilizes the same methods as RDF sorting but with a very different goal. RDF sorting will not be described in detail since it is a very uncommon sorting type for residual waste in the Netherlands. In short, RDF sorting refers to the mechanical separation of the non-combustible fraction from the combustible fraction of MSW. The combustible fraction is subsequently shredded and possibly also pelletised to allow efficient transportation. As the name already implies, the combustible RDF is finally used as fuel in a thermal treatment plant.

Sorting Type	**Method(s)**
Separate Collection	*See collection (section 4.2)*
Manual Sorting	Hand picking
Materials Recovery Facility (MRF) Sorting	Screening
	Air classification
	Air knife
	Sink/float separation
	Flotation
	Magnetic separation
	Electromagnetic separation
	Electrostatic separation
	Detect and route systems
	Roll crushing
	Shredding
	Baling
Refuse-Derived Fuel (RDF) Sorting	*See MRF sorting*

Table 4.3: Overview of sorting types and methods (based on McDougall et al. (2001))

The sorting types that are applied to the different types of waste of the Efteling are listed in table 4.4. Note that many types of waste are not sorted but separately collected. This is the best way to reduce cross contamination, especially by organic material (McDougall et al., 2001). However, the application of separate collection is limited by the factors mentioned in section 4.2 such as attitude (motivation) and ability. This explains the need for sorting procedures.

Waste type	**Sorting Type**	**Sorting company - location**	**Sorted fractions**
Residual Waste	Manual Sorting	Efteling - Kaatsheuvel	PET Bottles
Paper	Separate Collection	-	
Glass	Separate Collection	-	
PET Bottles	Separate Collection	-	
Swill	Separate Collection	-	
Fat and Oil	Separate Collection	-	
PMD	MRF Sorting	*Confidential*	LDPE, HDPE, PP, PET, metal, drink cartons
Foil (LDPE)	Separate Collection	-	
Cardboard Cups	Separate Collection	-	
Garden Waste	Separate Collection	-	

Table 4.4: Sorting details per Efteling waste type

4.3.1 Manual Sorting

Manual sorting refers to hand picking by humans. This may take place before, after or during mechanical sorting processes. In the case of the Efteling, manual sorting is currently applied to separate PET bottles from residual waste. The residual waste remains in its own bin during this process so only PET bottles that are easily accessible are separated. This is mostly done at the different cluster sites throughout the park after park closure.

Manual sorting rates vary widely depending on the type of material(s) being sorted. The sorting rates are also affected by the setting in which the sorting takes place, the position of the sorter, the tiredness of the sorter and lighting conditions. Sorting rates that have been found in literature are listed in table 4.5. Note that these sorting rates apply to sorting operations in an (industrial) MRF setting. Materials that can be sorted in large quantities (weight) per hour include glass, PET bottles and cardboard. Paper and plastic foil are harder to sort. Materials that are not listed in table 4.5 are generally not sorted using manual sorting because sorting rates are too low or because mechanical sorting is superior. In the table it can be seen that sorting rates differ even for sorting the same type of material. PET bottle sorting rates range from 160 to 31,25 kilograms per person per hour. Since the sorting conditions in a MRF are better compared to the decentralized sorting operations at the Efteling. The sorting rate of PET bottles in the Efteling is expected to be in the lower range or even lower than 31,25 kilograms per person per hour.

Waste type	**Sorting rate (kg/h)**		
	McDougall et al. (2001)	Pascoe (2000)	Kutz (2018)
Paper	12	-	-
Cardboard	100	-	-
Glass	500	-	-
PET bottles	160	50-100	31,25
Film plastic (foil)	20	-	-

Table 4.5: Manual sorting rates per person

4.3.2 Transportation

Transportation refers to the transport of waste types from collection sites to treatment facilities via possible intermediate facilities such as sorting facilities and transfer stations. The amount of waste transport depends on the amounts and types of waste collected, the storage capacity, the vehicle capacity, the distance between facilities and (company) waste policy. For the Efteling, many waste transports are planned in a predefined schedule based on expected numbers of visitors. Two main periods can be distinguished in this schedule namely the peak and the low season. The peak season includes July, August and holiday periods such as the Christmas holidays, fall break and spring break. The low season covers all other periods. An overview of transport types and transport frequencies during the peak and low season for all waste types can be found in table 4.6. The locations to which all waste types are finally being transported are listed in table 4.8.

Waste type	**Transport type**	**Transport freq./week peak season**	**Transport freq./week low season**
Residual Waste	Decentralized cluster pick up	7	3-5
Paper	Decentralized cluster pick up	2	2
Glass	Centralized pick up	0.5	0.5
PET Bottles	Return to supplier	2	2
Swill	Decentralized cluster pick up	2	2
Fat and Oil	Decentralized cluster pick up	2	2
PMD	Decentralized cluster pick up	2	2
Foil (LDPE)	Centralized pick up	1	1
Cardboard Cups	Centralized pick up	0.5	0.5
Garden Waste	Centralized pick up	2	2

Table 4.6: Transport types and emptying frequencies for all Efteling (park) waste types

Pick Up

As can be seen in the table, three main transport types can be distinguished for the Efteling. The two most important ones are: decentralized pick up and a centralized pick up. The terms centralized and decentralized refer to the pick up by external waste management companies and not to the internal waste transport of the Efteling. In case of decentralized pick up, an external waste management company picks up specific waste from all of the cluster sites in the Efteling park where this waste is being collected. This is mostly done in a fixed route which is not included in this report because it is confidential. Analysis of the pick-up route has revealed that the total length of this route within the boundaries of the Efteling park is approximately 7 kilometers due to the path structure with many curves and dead ends. Centralized pick up, on the other hand, means that an external waste management company picks up specific waste at a central location , being the 'Milieustraat' or the 'Tuinhuys', that has previously been brought to this location from relevant cluster sites by internal Efteling transport.

Waste types that are collected in large quantities or that have a large volume, such as residual waste, paper and PMD, or that require special handling, such as Swill and fat, are picked-up by waste management companies at the decentralized cluster sites. Other waste types such as glass are picked up centrally because this is more economical.

Return to Supplier

Another type of transport that is becoming more popular is 'return to supplier'. This means that materials are taken back by the suppliers of these materials after they have been used and disposed. This type of waste transportation is mainly employed in the retail sector as described by Stichting Stimular (2016f). A major advantage of this transport type is that it prevents unnecessary transport kilometers since the delivery return trips, that used to be empty, are now used for waste transport. This way, the waste of many customers can be collected at a central distribution location where it is picked up at once by a waste management company. The disadvantage of 'return to supplier' is that you are dependent upon the supplier for the transport of waste, this may not be sufficient. This type of transport is only relevant for specific waste types due to its legal context. Waste return logistics are explicitly addressed in the 'National Waste Management Plan 3' (LAP3, 2019) which is a framework for waste policy and legislation. Normally, the (professional) transport of waste requires all kinds of legal documents and procedures. An exception has been made for waste return logistics of packaging materials, pallets and materials that have been collected as imposed by law or Order of Council. The latter category concerns (among others) PET bottles subject to a deposit. Note that the implementation of a mandatory deposit for small PET bottles is currently being prepared in the Netherlands (CE Delft, 2019). For the reasons mentioned above, the following waste types of the Efteling can potentially be 'returned to the supplier': Paper, foil and PET bottles.

Transportation Costs

The costs of the different types of transport are not provided in this version of the report because this information is confidential. The cost structure however is as follows. For a decentralized cluster pick up of waste, a transportation fee per hour is being charged. This fee only applies to the time that a transport vehicle spends on the Efteling terrain and not to time spend on public roads. Note that a different fee applies to Saturdays and Sundays, which is only relevant for residual waste transports as these are the only transports required during weekends. Furthermore, the transportation costs for waste types that are picked up centrally differ per waste type. This type of transportation is not charged per hour but per container instead. However, for most types of waste, additional internal transport is necessary to facilitate a centralized pick up. The costs of internal (Efteling) transport have been calculated separately for this research. The calculation of these internal transport costs is not provided in this version of the report because this information is confidential. Finally, the most economical form of waste transportation is returning it to the supplier, which is generally free. However, this type of transportation also has a lot of limitations as described in the previous section.

4.3.3 MRF Sorting

Materials Recovery Facility (MRF) sorting refers to the separation of materials that have enough value to make their recovery worthwhile in a MRF (McDougall et al., 2001). Although some separately collected waste types such as glass and paper may also receive some limited kind of manual or mechanical sorting to remove contamination, this is not referred to as MRF sorting. In this case, MRF sorting applies to PMD which is a mix of different kinds of recyclable materials that have to be separated to be eligible for materials recycling treatment. There is no standard procedure for MRF sorting, the sorting methods as listed in table 4.3 are combined and adapted based on the process inputs and desired final outputs. Every sorting method can be associated with a certain recovery efficiency. This is the extent to which target materials are successfully separated from the mixed waste stream. The recovery efficiency for most sorting methods is between 60% and 90% (McDougall et al., 2001). The overall recovery efficiency has to be taken into account when calculating the environmental burdens of recycling via MRF sorting as the mixed residue is usually still treated using thermal treatment.

Although MRF sorting is widely applied for the recycling of household (seperately collected) PMD, it is a much less accessible means of sorting and recycling for companies. This means that PMD recycling is also much less common among companies and thus theme parks. There are three reasons for this (Rijkswaterstaat, 2018a; Royal HaskoningDHV, 2019). These reasons also apply to the MRF sorting of mixed waste from companies:

- Only two MRF's in the Netherlands have a limited capacity for sorting company PMD. These are located in Amsterdam and Wijster. The other capacity is reserved for household PMD. This means that waste management companies do barely offer company PMD recycling as a service.
- There are no general (shared) collection routes for transporting company PMD to a MRF which makes transport very expensive.
- It is difficult to sort household PMD and company PMD at the same time (in one MRF) as the sorting and recycling of household PMD is subsidized via the 'Afvalfonds verpakkingen' regulation while this is not the case for company PMD. This means that manufacturers and importers of household packaging materials have to pay a fee for the recycling of these materials. This makes household waste recycling much cheaper compared to company waste recycling.

It is expected that the accessibility of MRF sorting for company PMD recycling will improve in the future. The capacity of MRF facilities for PMD sorting is currently being expanded (Rijkswaterstaat, 2018a). Still, the average transport distances to MRF's are likely to remain higher as compared to thermal treatment facilities.

4.4 Treatment

Waste treatment processes are the final step in the integrated SWM chain. After (consecutive) treatment, waste materials have either become inert material, emissions to air and water or they have regained value as compost, secondary material or fuel (McDougall et al., 2001). Waste treatment processes are responsible for large parts of the total environmental burdens of the total SWM system. At the same time, the types of treatment processes that are applied are very much dependent on earlier steps in the SWM chain such as collection, sorting and transportation processes. Four main types of waste treatment can be distinguished. These are listed in table 4.7. Within each treatment type, different methods are employed to treat (different types of) waste. Only treatment types and methods that are relevant to the SWM system of the Efteling will be described in detail. Table 4.8 lists the treatment types and methods that are applied to each (operational) waste type of the Efteling. The table also includes information about the company that treats each waste type and its location.

Treatment Type	Method	Prerequisite(s)
Thermal treatment	Mass-burn Incineration	None
	Burning Refuse-Derived Fuel (RDF)	RDF sort
	Pyrolysis	RDF sort or MRF sort
	Gasification	RDF sort or MRF sort
Biological treatment	Composting (Aerobic)	Separate collection or RDF sort or MRF sort
	Biogasification (Anaerobic)	Separate collection or RDF sort or MRF sort
	Bio-drying / Bio-stabilization	None
Materials Recycling	Paper and Card manufacturing and recycling	Separate collection or MRF sort
	Glass manufacturing	Separate collection or MRF sort
	Ferrous metal manufacturing and recycling	Separate collection or MRF sort
	Non-ferrous metal manufacturing and recycling	Separate collection or MRF sort
	Plastic manufacturing and recycling	Separate collection or MRF sort
	Textile recovery and recyling	Separate collection or MRF sort
Landfill	Single-liner landfill	None
	Composite-liner landfill	None
	Double-liner landfill	None

Table 4.7: Overview of treatment types and methods

Thermal waste treatment encompasses the valorisation of solid waste by recovering energy from it using (intense) heat. The main thermal treatment method used in the Netherlands is mass-burn incineration. This method will be described in section 4.4.3. Burning RDF is less common in the Netherlands and also requires RDF sorting which is also uncommon as mentioned in section 4.3. Possible advantages of RDF burn over mass-burn are that RDF has a higher calorific value and less non-combustible material than mixed MSW. This results in more uniform combustion characteristics and less leftover ashes (McDougall et al., 2001). In other words, the overall efficiency of RDF burn is higher although it also produces a stream of poorly combustible material such as organic material that has to be treated using other treatment methods.

Other thermal treatment methods that will not be discussed in detail because they are not applied at industrial scales in the Netherlands (yet) are pyrolysis and gasification. Pyrolysis refers to the "*thermal degradation of waste in the absence of air to produce gas (often termed syngas), liquid (pyrolysis oil) or solid (char, mainly ash and carbon)*" (Zaman, 2010, p.227). Pyrolysis, which takes place at temperatures between 400 and 100 degrees Celsius, has a lot of resemblance to gasification which takes place at higher temperatures between 1000 and 1400 degrees Celsius. Gasification also produces syngas by means of thermochemical conversion. However, this is done using a gasification agent as opposed to pyrolysis which can be oxygen or steam (Seo et al., 2018). The amount of oxygen is only a fraction of the amount used for mass-burn incineration. The products of pyrolysis and gasification are mostly used to produce energy from. According to comparative research by Zaman (2010), the global warming potential (GWP) of pyrolysis and gasification is similar to the GWP of mass-burn incineration. However, pyrolysis and gasification have significant benefits in other environmental impact categories such as eutrophication and toxicity.

Another main type of waste treatment is biological treatment. It refers to the treatment of the biodegradable components of waste using naturally occurring micro-organisms. The main objective of biological treatment is to valorise organic waste by producing compost, biogas and/or energy (McDougall et al., 2001). Two main biological treatment methods are composting and biogasification. The difference between the two is that composting happens in the presence of oxygen while biogasification occurs in the absence of oxygen. In other words, composting is an aerobic process while biogasification is an anaerobic process (also called fermentation). Composting and biogasification will be described into more detail in section 4.4.2. Both processes are used to treat organic waste of the Efteling. Finally, bio-drying and bio-stabilization, which will also not be discussed in detail, are biological treatment types that are applied for the pre-treatment of mixed waste streams such as residual waste before incineration or landfill. They are both aerobic processes. However, their main goals are different. Bio-drying is aimed at exploiting the exothermic reactions during composting to evaporate as much of the humidity in the waste as possible without converting too much organic carbon. This bio-dryed fraction is very suitable as RDF. Bio-stabilization, on the other hand, is aimed at converting as much organic carbon as possible (mostly for landfill purposes) (Rada et al., 2005). Bio-drying and bio-stabilization are currently not used as a pre-treatment for residual waste in the Netherlands.

Waste type	Treatment Type	Processing Company - Location	Method	Dist. (km)
Residual Waste	Thermal treatment	*Confidential*	Mass-burn incineration	91 (avg.)
Paper	Materials Recycling		Paper and card manf. and recycling	*Confidential*
Glass	Materials Recycling		Glass manf.	
PET Bottles	Materials Recycling		Plastic manf. and recycling	
Swill	Biological Treatment		Biogasification	
Fat and Oil	Biological Treatment		Biogasification/refinement	
PMD	Materials Recycling		Plastic, paper & metal manf. and recycling	
Foil (LDPE)	Materials Recycling		Plastic manf. and recycling	
Cardboard Cups	Materials Recycling		Plastic & paper manf. and recycling	
Garden waste	Biological Treatment		Composting	

Table 4.8: Treatment details per Efteling waste type (manf. = manufacturing)

Materials recycling treatment can take many different forms depending on the type(s) of materials being recycled. This treatment type will be discussed in section 4.4.1. Finally, landfill (or dumping) is a treatment type that is forbidden in the Netherlands unless it concerns specific waste types for which a landfill permit has been granted because there are no other ways of treatment available (AMvB Bssaf, 2019). This means that residual waste can never be landfilled in the Netherlands because there are plenty of alternative treatment options for it. Globally however, there are still many countries that use landfill as a dominant waste treatment type. The main methods for the application of landfill are described by Hughes et al. (2005). The difference is the type of liner system used, which is meant to isolate the landfill and to protect the soil and groundwater from pollution.

4.4.1 Materials Recycling

Materials recycling refers to "*the reprocessing of recovered materials at the end of product life, returning them into the supply chain*" (Worrell & Reuter, 2014, p.10). As mentioned earlier, this can take many different forms depending on the material type(s). A recycled material is also called a 'secondary material' as opposed to a primary material which is produced from virgin (newly extracted) resources. The distinction between primary and secondary materials is important as it will be used to model the life cycle environmental impact of recycling. The sustainable character of recycling is derived from the fact that secondary materials can replace primary materials which may result in considerable energy and emission savings (McDougall et al., 2001). Note that primary and secondary does not refer to a difference in material quality. Just like MRF-sorting, which may proceed recycling processes for certain waste streams, recycling also involves material losses. These losses may be caused by quality, color or processing issues (Worrell & Reuter, 2014). These material losses can be expressed in the recycling efficiency which is the output of the recycling process divided by the input. Some recycling processes for relevant waste types of the Efteling will now be briefly described. Note that every recycling process requires transportation from the sorting or collection facility to the recycling facility. This has to be taken into account by the LCA model.

Paper

New paper is made using fiber pulp that is generated from wood and recovered paper (and/or board). Recovered paper can replace wood to a certain extent depending on the paper type. The wood used for paper production comes from tree parts that are left after it has been used for other manufacturing purposes (McDougall et al., 2001). Two types of fiber pulp can be distinguished namely mechanical pulp and chemical pulp. The latter represents 33% of all fibers used for worldwide paper production (Grossmann et al., 2014). Mechanical pulp consists of weaker and shorter fibers and is more used for newspapers whereas chemical pulp is more used for office paper and magazines (US EPA, 2019c). The difference between the two is important as chemical pulping is less efficient and requires more wood per unit of pulp which increases its environmental impact (US EPA, 2019c; Van Ewijk et al., 2018). This fact will be used in the LCA. Cardboard, which is one of the main types of paper used in the Efteling, consists of a relatively large share of recycled pulp which reduces the environmental impact of its production.

Glass

Almost all glass waste in the Efteling consists of container glass (hollow glass). This glass can be recycled indefinitely without any loss of performance by melting it in a furnace and forming it afterwards (Dyer, 2014). However, to be able to produce glass that is consistently colored, the recovered glass cullet has to be color sorted and supplemented with 10 to 40% of raw glass manufacturing materials (SiO_2, Na_2CO_2 and $CaCO_3$). The use of recovered glass cullet in glass manufacturing reduces the amount of energy necessary for the melting process (Dyer, 2014). Since the color of the glass to be produced determines the maximum share of recovered glass cullet, the color also determines the environmental benefits from glass recycling.

Plastic

Plastics are mainly produced from oil, natural gas, coal and salt using polymerisation (McDougall et al., 2001). Many different types of plastic can be distinguished. The following so-called thermoplasts are most relevant for the Efteling case and commercial waste in general: PET, PP, PS, HDPE, LDPE and LLDPE (see list of abbreviations). Two types of plastic recycling can be distinguished namely mechanical recycling, which is most dominant, and chemical recycling. Mechanical recycling involves sorting, shredding, washing, reprocessing (mainly extrusion) and finally molding. Whereas HDPE, PP and PET can be recycled into high-quality plastics using this process, this is much more difficult for plastic films and foils (LDPE, LLDPE) (Shen & Worrell, 2014). Chemical recycling is more expensive and only applied to PET plastic. However, it has the major advantage that the recovered PET can be recycled into polyester that is identical to virgin PET in terms of quality (Shen & Worrell, 2014). Both mechanically and chemically recycled polyester have a lower environmental impact than virgin polyester. The relative benefit of chemical recycling is slightly less but this type of recycling allows for a wider application of recycled fibers (Shen & Worrell, 2014).

4.4.2 Composting and biogasification

Both composting and biogasification processes involve the microbial decomposition of organic waste (fractions) using naturally occuring micro-organisms (McDougall et al., 2001). However, in the case of composting this happens in the presence of oxygen whereas in the case of biogasification, it happens in the absence of oxygen. The difference between the two is important as composting results in different types of emissions and useful products than biogasification. Therefore, both processes will also be modelled differently in chapter 7. During composting and biogasification, energy is released from the organic waste material to its surroundings. This energy is mostly lost in case of composting and partly lost in case of biogasification. With respect to the Efteling case, composting and biogasification are used for the treatment of different types of waste. Garden waste is treated using composting while food waste (swill) is treated using biogasification (Renewi, 2020b). There are multiple reasons for this. The costs and benefits of both processes differ for different types of waste. Food waste has a much higher biogas potential (amount of biogas production per ton of substrate) than garden waste (Agentschap NL, 2013). Furthermore, biogasification offers better conditions for the sterilisation of germs, which are more present in food waste, than composting (Alterra, 2000). The higher moisture content of food waste also favors the use of biogasification.

 

Figure 4.4: Composting (left) and biogasification (right) processes (Agentschap NL, 2013; van Iersel, n.d.)

Prior to composting or biogasification, there may be some form of pre-treatment. Nuisance materials (non-organic materials) may be removed from the waste stream. Additionally, the feedstock is usually shredded to make it better compostable (McDougall et al., 2001). Different types of composting can be distinguished namely windrow composting, which may be open or semi-enclosed, and enclosed vessel composting. The garden waste of the Efteling is treated using the most common and least expensive form of composting namely outdoor open windrow composting (see also figure 4.4). A disadvantage of this type of composting as opposed to (semi-)enclosed composting is that moisture content, temperature and fugitve emissions can be controlled to a lesser extent (McDougall et al., 2001). Especially temperature and oxygen presence are very important parameters in the composting process. Oxygen may be added through forced aeration as is the case for the Efteling garden waste. The average duration of the composting process in the composting facility where Efteling garden waste is being treated is 12 to 13 weeks (Renewi, 2020b).

The biogasification of Efteling food waste is handled by another company. Since it is an anaerobic process, biogasification always happens in an enclosed vessel (see also figure 4.4). This allows greater control over temperature, which is again very important, and over emissions (McDougall et al., 2001). It also enables the capturing of biogas which is released from the digesting substrate through bacteria. Biogas mainly consists of methane (CH_4), which is a very strong greenhouse gas, and CO_2. The biogas is first being cooled down, then desulfurized and finally burned in a combined heat and power generator. The main economic products of biogasification are therefore electrical energy and heat (Agentschap NL, 2013). These products will also be modelled in chapter 7. However, the organic residues of biogasification are also a product of the process. These residues need extensive treatment including drying and aerobic composting (which releases emissions to the atmosphere) before they are usable as compost (Agentschap NL, 2013).

4.4.3 Mass-burn incineration

Mass-burn incineration, which is the main thermal treatment method in the Netherlands as mentioned earlier, refers to the treatment of waste using 'mass-burn' technologies without much pre-processing (McDougall et al., 2001). In practice, this means that almost all (mixed) waste that is headed for mass-burn incineration is completely being burned in ovens. Only suspicious or dangerous waste parts that can be visually distinguished such as fire extinguishers, batteries and compressed containers are removed beforehand. All mass-burn incineration plants in the Netherlands recover energy from burning waste in the form of electricity and/or heat (Rijkswaterstaat, 2020a). This concept is also known as Energy from Waste (EfW) or Waste to Energy (WtE). The energy is usually recovered by means of steam generation. Water is heated to steam using the flue gasses coming from the oven(s). The steam is subsequently converted to electricity in a steam turbine and/or used for industrial or space heating applications (McDougall et al., 2001). An example of such an application is the heating of greenhouses. The full mass-burn incineration process including energy recovery as used by Attero Moerdijk is visualised in figure 4.5. Other plants may use slightly different processes. Overall, about 80% of the electricity generated by Dutch mass-burn incineration plants is delivered to the grid, the other 20% is used by the installations themselves, mainly for flue gas cleaning (Rijkswaterstaat, 2020a).

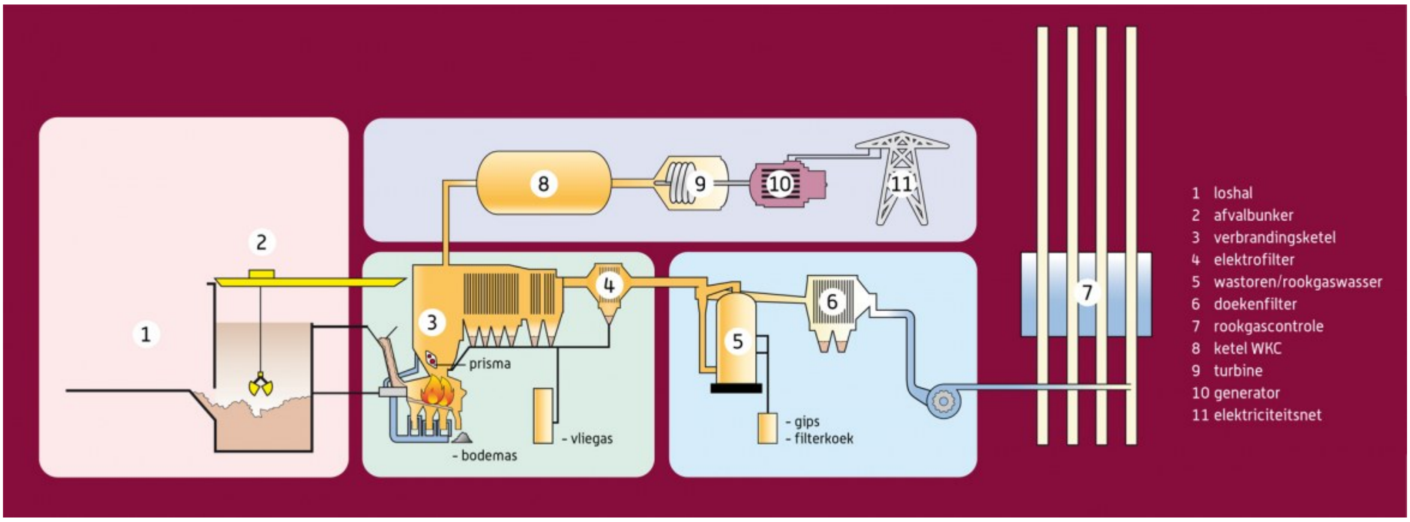

Figure 4.5: Mass-burn incineration process with energy recovery at Attero Moerdijk (Attero, n.d.)

Besides the oven and the energy recovery installation, other important parts of the process as displayed in figure 4.5 are: the (flue) gas cleaning installation and the treatment of incinerator bottom ash (IBA). These parts also have a major influence on the environmental impact of the incineration process. The flue gas cleaning system consists of three successive processes. First, particles are removed using electrostatic precipitators (number 4 in figure 4.5). After that, acid gases are controlled using a scrubber (number 5 in figure 4.5). The scrubber injects an alkaline reagent ($Ca(OH)_2$) into the flue gas to react with the acid gases. The reaction product is finally removed from the gas stream in the fabric filter (number 6 in figure 4.5) along with remaining dust. The fabric filter consists of filter bags through which the gas stream has to pass. The filters are cleaned regularly (McDougall et al., 2001). The incinerator bottom ash is treated in a separate process in which metals are removed from the ash using magnets. This way, a large share of the metals that were present in the burned waste stream can be recovered and recycled which has a positive effect on the total environmental burdens of the mass-burn incineration treatment. The remaining bottom ash is treated so that it can be deployed for useful purposes (building operations for example). In the Netherlands, about 2% of the bottom ash is ultimately being landfilled while the large majority is being deployed for useful purposes (Rijkswaterstaat, 2020a).

The residual waste of the Efteling is burned in different mass-burn incineration plants in the Netherlands. This has to do with contracting. The main plants treating the Efteling residual waste are located in the vicinity of the port of Rotterdam (Renewi, 2020b).

4.4.4 Treatment costs

The treatment cost values for all of the different types of BTS and PSP waste are not provided in this version of the report because they are confidential. Some general remarks about waste treatment costs can however be given. Waste treatment costs are usually charged per ton of waste. Treatment costs can also be negative for certain waste types which means that the processing (recycling) of these waste types actually generates money for the Efteling. This is for example the case for separately collected glass and PET bottles (provided that there is no excessive contamination). The market for recyclable paper has deteriorated significantly in recent years which has led to positive costs for the treatment of paper (instead of returns). Furthermore, recycling PMD is really expensive for companies compared to the treatment of other waste types. For swill, two different treatment cost values are used. This is related to the different means by which swill can be treated. The costs for local composting are based on a calculation specifically for the Efteling case. All of the unit costs for waste treatment will be used in a later stage to calculate the costs of different SWM strategies.

4.5 Conclusion current SWM characteristics

In this chapter, sub research question 1 has been answered. The question was: "*What are the operational, environmental and economic characteristics of the current solid waste management system at the Efteling?*" A schematic representation of the solid waste management system is provided in figure 4.6.

Operational: Two types of (theme park) waste collection can be distinguished: behind-the-scenes (BTS) and public/semi-public (PSP) collection. Since the participation rate and separation efficiency of separate BTS waste collection can be influenced more directly, the BTS waste is separated into 6 to 10 fractions versus 1 to 2 for PSP waste. Sorting tests of residual waste have revealed that residual waste of BTS locations has a very different composition than residual waste of PSP locations. Collected waste quantities have been analyzed in section 4.2.3, residual waste is by far the largest fraction. After collection, the different waste types are transported (and possibly also sorted) in different ways and with different frequencies. A main difference is the way in which waste is picked up by the waste management company: centrally or decentrally. The latter requires less internal transport. Finally, the waste is treated using three main types of waste treatment: thermal, biological or recycling methods.

Environmental: The environmental impact of the theme park SWM system is mainly dependent on the transportation and treatment steps. However, the collection and sorting methods that are applied determine which treatment type can be deployed. Generally, it can be said that separate collection followed by materials recycling results in less GHG emissions and depletion of resources than mixed collection followed by thermal treatment unless (separate) transport emissions become significant.

Economic: The total business economic costs of theme park SWM consists of different components which correspond to the different steps in the SWM process. First of all, waste collection facilities (bins, baskets etc.) have to be bought or rented and they also have to be maintained. Secondly, collected waste has to be transported to waste treatment facilities via possible intermediate facilities such as sorting and transfer stations. This involves transport costs for external transports (by waste management company) and possible also for internal transports (by theme park). Finally, the waste has to be processed which involves treatment costs per ton. These treatment costs are waste-specific. Some recyclable waste types may actually bring in money when offered for treatment.

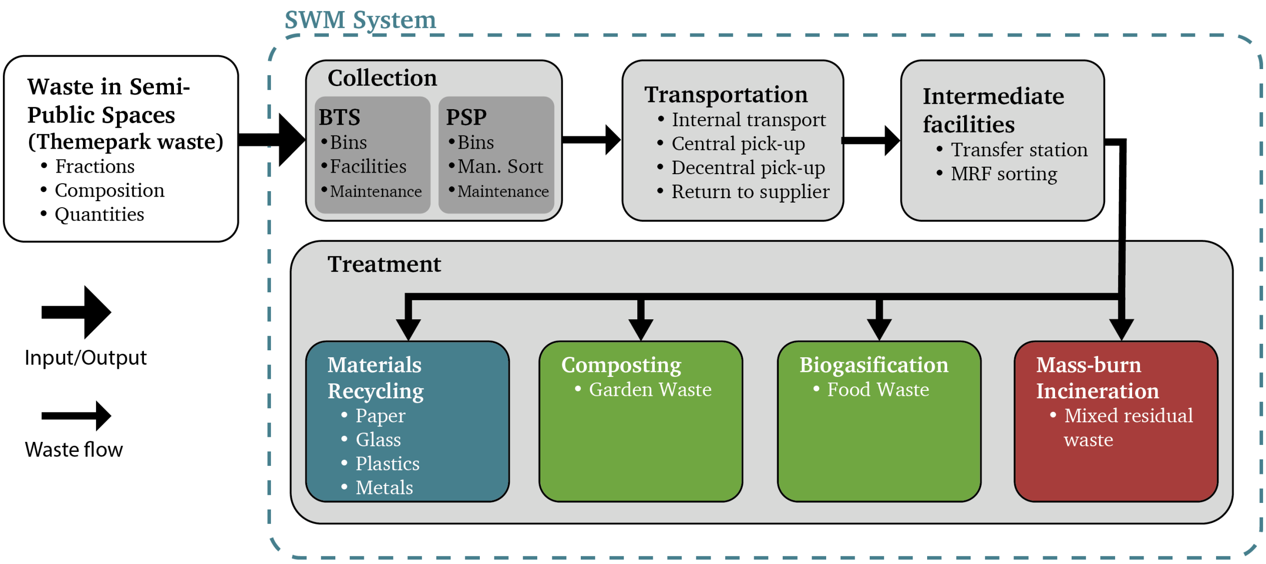

Figure 4.6: Schematic representation of the theme Park SWM System (outputs will be added in later chapters)

Chapter 5

Solid Waste Management Requirements and KPI's for the Efteling

This chapter provides an overview of requirements for an SWM system for the Efteling theme park. The requirements are based on an extensive analysis of the current characteristics of the SWM system at the Efteling as described in chapter 4 and many conversations with stakeholders to be able to identify the reasons for some key system characteristics. Furthermore, many documents including terms and conditions, policy and legislative documents have been studied to create a framework of requirements. The requirements are divided into constraints and objectives which are, in turn, divided into functional and non-functional constraints/objectives. The theoretical background of the requirements engineering method is described in method section 3.2. First, the constraints will be described. Secondly, the objectives are provided. Finally, some elementary key performance indicators (KPI's) are formulated based on the requirements that have been identified earlier.

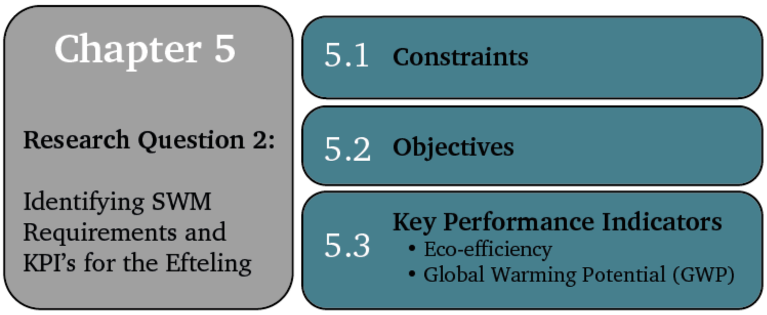

Figure 5.1: Structure of chapter 5

5.1 Constraints

The identified constraints to the SWM system of the Efteling are provided first since these are non-negotiable and therefore most limiting to a new SWM strategy. In other words, SWM strategies for the Efteling that do not comply to the formulated constraints are not viable. This is also evident from the way in which the constraint have been formulated using the words 'must' and 'shall'. Furthermore, it should be noticed that all constraints (and also all objectives) are formulated in the problem domain as much as possible. This means that the constraints describe what the SWM system must do and not how the system must do this (if reasonably possible). Describing how the SWM system should work is part of the solution domain (Hull et al., 2011). The solution domain will be discussed in the next chapter. Since constraints impose limits on the solution domain, each constraint has been carefully evaluated to make sure that there are no unnecessary constraints. As Hull et al. (2011) describes, too many unnecessary constraints can ruin a system or can, as a whole, make a development impossible.

Functional constraints are presented in table 5.1 while non-functional constraints are presented in table 5.2. The difference between the two is that functional constraints relate to functions that the system must provide while non-functional constraints relate to (quality) attributes that a system must have (Bahill & Dean, 2009). The most elementary functional constraint with respect to the top-level function of the Efteling SWM system is FC-01. The other functional constraints frame this function into more detail. Note that the different stakeholders that impose requirements on the system are also provided in the second column of the requirement tables. Most of the constraints imposed by Renewi are also mentioned in their terms and conditions (Renewi Nederland B.V., 2008).

Functional Constraints (FC)		
Code	**Stakeholder**	**Description**
FC-01	*Efteling*	*The SWM system must prevent the accumulation of solid waste outside of solid waste disposal facilities in theme park BTS and PSP areas*
FC-02	*Efteling*	*The SWM system must be able to process all types of solid waste produced in theme park BTS and PSP areas*
FC-03	*Efteling*	*Solid waste disposal facilities must prevent solid waste from being lost, spilt or blown away*
FC-04	*Efteling*	*Solid waste disposal facilities must prevent the contamination of solid waste with excessive amounts of rainwater*
FC-05	*Efteling*	*The SWM system must be able to process separately collected waste streams (other than residual waste) with any separation efficiency (see section 4.2) value and thus any contamination level*
FC-06	*Efteling*	*Solid waste disposal facilities in PSP and BTS areas shall only separately collect waste types that are produced in these respective areas and thus originate there*
FC-07	*Efteling*	*The number of separately collected waste types in PSP areas shall not be larger than 3 to prevent confusion (in line with JMA (2018) and research by PLAN terra (2012) and PLAN terra (2017))*
FC-08	*Efteling*	*The SWM system must be able to operate without motorized transport movements in theme park PSP areas during theme park opening hours*
FC-09	*Efteling*	*The SWM system shall only separately collect and transport waste types that can be processed as a separate waste stream unless the definition of a waste type is narrowed down to enhance understandability in PSP areas*
FC-10	*Efteling*	*The SWM system shall process separately collected waste streams (other than residual waste) using materials recycling treatment methods that correspond to these waste streams (see table 4.13) if allowed by the respecive contamination level(s)*
FC-11	*Efteling*	*The SWM system must ensure that solid waste types that can not be compressed and that are collected decentrally with yearly total quantites higher than 150 tonnes or 1000 m^3, or waste types that require special handling, do not have to be picked up centrally by the waste management company to prevent excessive workloads for theme park staff*
FC-12	*Efteling*	*The SWM system shall only apply manual sorting to separate certain waste types from mixed waste types if these waste types can be sorted properly using manual sorting (and are included in table 4.9)*
FC-13	*Efteling*	*The SWM system must be able to handle mechanical dumpings of garden and sweeping waste from (sweeping) machines and cargo vehicles at (a) central location(s)*
FC-14	*Efteling/ Renewi*	*The SWM system shall use waste processing methods that are available at sufficient capacity in a reasonable range from the theme park*
FC-15	*Renewi*	*Containers intended for the collection and storage of specific products, such as glass, paper, tins, fabrics, synthetics, etc., shall be used exclusively for depositing these specific products*
FC-16	*Renewi*	*The size and dimensions of waste that is being disposed shall not exceed the size and dimensions of the wheelie bins, mini containers or the dustbin bags it is disposed into*
FC-17	*Renewi*	*The total weight of waste that is being disposed shall not exceed the carrying capacity of the container it is disposed into or the lifting capacity of the lifting device for this container*
FC-18	*Renewi*	*The waste materials shall be presented (to the SWM company) by the theme park in such manner as to prevent these from being lost, spilt or blown away and to prevent these from causing any nuisance, risk, damage or injury for the SWM company or third parties*
FC-19	*Renewi*	*Any hazardous Waste Materials, rubble or concrete, cadavers and/or offal and/or explosive Waste Materials shall not be deposited into regular wheelie bins, mini containers or dustbin bags (Waste Materials that are odorous, poisonous, solidifying, corrosive, aggressive and/or may be hazardous in any other way only if agreed so)*

Table 5.1: Functional Constraints

Non-Functional Constraints (NFC)		
Code	**Stakeholder(s)**	**Description**
NFC-01	*Efteling*	*The safety risks associated with the operation of the SWM system for employees as well as for guests must be as low as reasonably possible*
NFC-02	*Efteling*	*The SWM system must be able to operate in extreme Dutch weather conditions (wind and precipitation) that occur with a minimal frequency of once every 5 years*
NFC-03	*Efteling*	*The solid waste disposal facilities in PSP areas must be able to be understood by an international public, besides Dutch guests, consisting of mainly Belgian, German, English and French guests*
NFC-04	*Efteling/ Government authorities*	*The SWM system must comply with current legislation or new legislation that comes into force at the time the SWM system is introduced. This especially concerns the following documents: Environmental Protection Act (Wet MB, 2019) and National Waste Management Plan 3 (LAP3, 2019)*
NFC-05	*Efteling/ Government authorities*	*The SWM system must comply with food safety guidelines as laid down in the HACCP methodology*

Table 5.2: Non-functional constraints

5.2 Objectives

Now that the constraints have been presented, it is time to state conditions that express the satisfaction of stakeholders towards different possible SWM systems that actually meet the constraints. These conditions are called objectives and are formulated using the word 'should'. Just like the constraints, the objectives are divided into functional objectives (see table 5.3) and non-functional objectives (see table 5.4). The functional objectives state conditions towards which the functions of the system should be optimized while the non-functional objectives state conditions towards which the attributes of the system should be optimized. Note that there will be trade-offs among the different objectives in the sense that scoring well on certain ones will mean scoring worse on others. This is an inherent property of objectives (Bahill & Dean, 2009). The trade-offs among different objectives and overall scoring of SWM systems on the objectives will be discussed in the next section about KPI's (section 5.3).

Functional Objectives (FO)		
Code	**Stakeholder**	**Description**
FO-01	*Efteling*	*The amount of effort (ability and motivation) that is required from theme park guests to dispose of their waste should be as low as possible*
FO-02	*Efteling/Renewi*	*The final separation efficiency of separately collected waste streams should be as high as possible and with that, contamination levels as low as possible*
FO-03	*Efteling*	*The efficiency of the SWM with respect to dealing with strong monthly variations in waste quantities with coefficients of variation as high as 70% (see section 4.2.3) should be as high as possible*
FO-04	*Efteling*	*In addition to FC-07, separately collected waste streams should be processed using materials recycling treatment methods that correspond to these waste streams as much as possible*
FO-05	*Efteling*	*Waste that has been collected at theme park waste disposal facilities should be removed from the theme park terrain as quickly as possible to prevent the occurance of odor and pests*
FO-06	*Efteling*	*The extent to which the SWM system prevents the occurance of litter should be as high as possible*
FO-07	*Efteling*	*The extent to which theme park staff members come into (direct) contact with waste should be as low as possible*
FO-08	*Efteling*	*The extent to which working actitivites by theme park staff members outside of theme park opening hours are required by the SWM system should be as low as possible*
FO-09	*Efteling*	*The amount of manual waste sorting (see section 4.3.1) by theme park staff members that is required by the SWM system should be as low as possible*
FO-10	*Efteling*	*The SWM system should allow the gathering of non-aggregated data about collected waste quantities of all types in BTS as well as PSP areas as much as possible*

Table 5.3: Functional objectives

Non-Functional Objectives (NFO)		
Code	**Stakeholder**	**Description**
NFO-01	*Efteling*	*The total amount of CO_2 emitted by all consecutive processes (collection, sorting, tranportation and treatment) in the combined SWM system for all types of waste collected from the theme park over 1 year should be as low as possible*
NFO-02	*Efteling*	*The total operational costs for the theme park associated with the processing of theme park waste over 1 year should be as low as possible. Operational costs include labour costs, disposal costs and costs for the rental, depreciation and maintenance of waste collection facilities and equipment*
NFO-03	*Efteling*	*The total investment costs for the transition to a new SWM system for the theme park should be as low as possible.*
NFO-04	*Efteling*	*The total space (in m^2) in the theme park required for the operation of the SWM system should be as low as possible*
NFO-05	*Efteling*	*The total visual intrusion impact of the SWM system in PSP areas should be as low as possible*
NFO-06	*Efteling*	*Without compromising NFO-01, the Global Warming Potential over 100 years (GWP) that is associated with the operation of the total SWM system in 1 year should be as low as possible*

Table 5.4: Non-functional objectives

5.3 Key Performance Indicators

From the objectives listed in the previous section, several key performance indicators (KPI's) can be derived. These are measurable values that indicate how effectively a strategy is achieving one or more of the objectives (Klipfolio, 2020). Since the objectives can result in many possible KPI's and there should be only a few, the focus will be on those KPI's that adhere to the SMART criteria as much as possible. These criteria, as listed by Klipfolio (2020), are: specific, measurable, attainable, relevant and time-related.

Generally, the non-functional objectives as listed in table 5.4 are more specific, measurable and time-related than the functional objectives as listed in table 5.3. Many of the functional objectives are important at an operational level while the non-functional objectives are considered to be more relevant at this point: the strategic level. Therefore, the KPI's that will be used to assess different possible SWM strategies are derived from the non-functional objectives. The most important NFO is NFO-01 about overall CO_2 emissions, followed by economic objectives NFO-02 and NFO-03. Since environmental and economic performance is often linked to each other and may be even conflicting, a performance indicator that combines both is very useful. The concept of eco-efficiency is increasingly being applied in this context and has also been used to judge SWM strategies by Yang et al. (2015). The eco-efficiency KPI will be described in section 5.3.1. Another KPI that can be used to assess the environmental impact of SWM strategies in a wider context than just CO_2 emissions is Global Warming Potential (GWP), which is also frequently used in SWM LCA studies. GWP will be described in section 5.3.2.

5.3.1 Eco-efficiency

The concept of eco-efficiency, as described by Yang et al. (2015), refers to the linkage of economic efficiency to environmental efficiency. It can either be defined as the environmental improvement per unit of economic cost (see formula 5.1) or as the economic cost per unit of environmental improvement (see formula 5.2).

$$EE_\text{s}\ (\text{CO}_2\text{E reduction / Euro}) = \frac{\text{Environmental Improvement}_\text{ s}}{\text{Economic Costs}_\text{ s}} = \frac{EI_\text{current} - EI_\text{s}}{C_\text{s}} \qquad s = 1, 2, .., n \tag{5.1}$$

$$EE_\text{s}\ (\text{Euro / CO}_2\text{E reduction}) = \frac{\text{Economic Costs}_\text{ s}}{\text{Environmental Improvement}_\text{ s}} = \frac{C_\text{s}}{EI_\text{current} - EI_\text{s}} \qquad s = 1, 2, .., n \tag{5.2}$$

Where EE is eco-efficiency and EI is environmental impact as calculated by a LCA. The different measures or strategies are represented by s. C represents the (additional) economic costs of strategy s as calculated by an economic assessment. The final eco-efficiency values can be used to make decisions on the optimal SWM system as the values integrate environmental and economic performance (Yang et al., 2015).

As environmental improvement and economic costs can be defined in different ways, multiple subvariants of the eco-efficiency KPI may be used. Although literature about eco-efficiency agrees on the fact that environmental impacts are calculated using a LCA (Saling et al., 2002; Yang et al., 2015) to be able to capture overall environmental impact, different impact categories can be used. Examples of impact categories are: global warming potential, ozone depletion potential and acidification potential. Since the non-functional objectives have revealed that the Efteling is mainly interested in environmental impact in terms of CO_2 emissions and global warming. These will be used as environmental impact categories. Global warming impact is commonly measured using CO_2 emission equivalents. The calculation of such an equivalent is explained into more detail in the next section. Economic costs can be defined in terms of investment costs (NFO-03) or operational costs (NFO-02). The latter will be used and compared against the environmental impact of different SWM strategies because it better suits the character of many cost components (rent costs and costs for services).

5.3.2 Global Warming Potential

Global Warming Potential (GWP), which was already mentioned in NFO-06, is the most common LCA indicator to evaluate the overall impact of a system on global warming (McDougall et al., 2001). It is a so-called impact category in the sense that it groups LCI results of different substances (CO_2, N_2O, CH_4 etc.) that are associated with a particular environmental issue being global warming in this case. Since CO_2 is one of the most well known greenhouse gasses, it is used as a reference. This means that GWP is measured in CO_2 equivalents (CO_2E's). To calculate the GWP, each greenhouse gas is first converted to CO_2E's based on a particular characterisation factor (McDougall et al., 2001). The GWP characterisation factor for specific gases depends on two elements namely their ability to absorb energy (radiative efficiency) and their lifetime in the atmosphere (US EPA, 2017). The larger the GWP characterisation factor, the more that the emission of one ton of a given gas warms the earth compared to one ton of emitted CO_2.

While CO_2 stays in the atmosphere for a very long time (hundreds of years), the lifetime of CH_4 is much shorter (a decade). Still, the GWP of CH_4 is about 25 times higher than that of CO_2 because it absorbs much more energy than CO_2 in its lifetime. The GWP of N_2O is even higher because it has both a relatively long lifetime and absorbs a lot of energy. Note that the energy absorbed by a gas is measured over a certain maximum period of time. The time period that is usually used for GWP's, and that will also be used in this report, is 100 years (GWP-100) (US EPA, 2017). An alternative is GWP-20 which prioritizes gases with shorter lifetimes because it only considers their impact over 20 years. After converting each greenhouse gas emitted by a specific system to CO_2E's, the overall GWP can be obtained by summing these numbers. This procedure is applied by the LCA models described in chapter 7.

5.4 Conclusion Efteling SWM Requirements and KPI's

In this chapter, sub research question 2 has been answered. The question was: "*What requirements and KPI's for solid waste management at the Efteling can be identified?*"

By analyzing current characteristics of the SWM system at the Efteling and by speaking to many (internal) stakeholders, a framework of SWM requirements has been created. This framework is divided into constraints and objectives which are further divided into functional and non-functional constraints/objectives. The constraints, which are non-negotiable, are listed in section 5.1. Most importantly, the SWM system must prevent the accumulation of solid waste outside of disposal facilities and it must be safe and legal. The objectives, which state conditions towards which the SWM system should be optimized, are listed in section 5.2. Most importantly, the SWM system should be as efficient as possible in terms of environmental impact and resource usage. To indicate how effectively different strategies are achieving the objectives, two main key performance indicators have been derived from the objectives. These are: eco-efficiency and global warming potential. The global warming potential KPI can be integrated into the eco-efficiency KPI.

Chapter 6

Solid Waste Management Strategies for Semi-Public Spaces

In this chapter, the structure of SWM systems (for semi-public spaces) is analyzed and alternative SWM strategies are systematically assessed using general morphological analysis as described in section 3.3. The chapter follows the order of a standard general morphological analysis. First, a morphological box is constructed using the information from chapter 4. Then this morphological box is 'reduced' using the requirements from chapter 5. Secondly, the different strategies that can be composed using the morphological box are checked for their internal consistency using a step-wise cross-consistency assessment. Finally, the remaining and most relevant strategies are provided, these will be further assessed in later chapters.

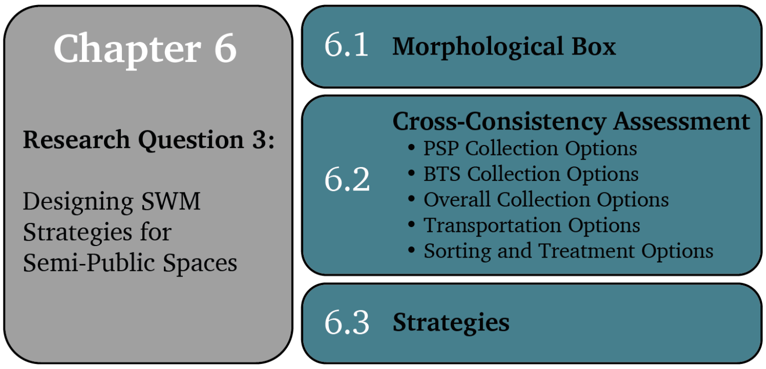

Figure 6.1: Structure of chapter 6

6.1 Morphological Box

Using all of the possible elements of a SWM system for a semi-public space that could be found in literature and practice and that are subsequently described in chapter 4, a morphological box can be created. This morphological box can be found in table 6.1. The box is divided into the same main categories as those in chapter 4. Collection is, again, divided into PSP and BTS collection since these are, to some degree, separate systems. The possible options or conditions that can be chosen for every parameter (separate collected fractions, biological treatment type etc.) are listed right beneath the parameters. A SWM strategy consists of the total combination of chosen conditions for every parameter. The waste fractions that are being distinguished in the box are the most common fractions that could be found in literature and legislation (LAP3, 2019; Rijkswaterstaat, 2016b, 2018b). Note that only operational waste types are included (see scope section 1.4). Two main characteristics of this specific morphological box are:

- As opposed to more classical morphological boxes (for example by Ritchey (2002)), this **morphological box allows the activation or selection of multiple conditions per parameter**. It is even possible to simultaneously select all conditions of a parameter. This change was made since a SWM system is dealing with many different waste types that can be managed in all possible combinations (without repetition) which would result in a morphological box with 2047 unique rows (k=11, see section 6.2.1). This format is much clearer.
- The parameter conditions within the same category (PSP collection, BTS collection, Transportation, Central sorting and Treatment) are directly linked to each other. This means that selecting a certain condition for a parameter limits the choice for conditions of other parameters belonging to the same category since

some condition combinations are mutually exclusive. An example of a mutually exclusive combination is the selection of residual waste and paper as fractions resulting from PSP collection and the separate PSP collection of more than 2 fractions. It is however possible to not separately collect any fraction and to manually sort paper (from residual waste) which also results in residual waste and paper fractions. It is also possible to select fractions (other than residual waste) resulting from PSP collection without applying separate collection or manual sorting. In this case, central sorting needs to be applied to be able to obtain the selected fractions. The consistency of parameter conditions between different categories is checked in the cross-consistency assessment (section 6.2).

The colors in the morphological box (table 6.1) indicate whether certain parameters can be directly influenced by the party managing a semi-public space or not. This is especially the case for the so-called 'front-end' parameters related to collection and partly also transportation. The 'back-end' parameters are usually under influence of the waste management company (waste processor).

Functions	**PSP Collection**			**BTS Collection**		**Transportation**			**Central Sorting**	**Treatment**		
Options	**Fractions**	**Separate collect**	**Manual Sorting**	**Fractions**	**Separate collect**	**Decentral pick up**	**Central pick up**	**Return supplier**		**Recycling**	**Biological**	**Thermal**
1	*Residual Waste*	*No*	*Paper*	*Residual Waste*	*No*	*Residual Waste*	*Residual Waste*	*Residual Waste*	*No central sorting*	*Paper and card*	*Local Composting*	*Mass-burn incineration*
2	*Paper*	*2 fractions*	*Glass*	*Paper*	*2 fractions*	*Paper*	*Paper*	*Paper*	*RDF sorting*	*Glass*	*Central Composting*	*Burning RDF*
3	*Glass*	*3 fractions*	*PET bottles*	*Glass*	*3 fractions*	*Glass*	*Glass*	*Glass*	*MRF sorting*	*Ferrous metal*	*Bio-gasification*	*Pyrolysis*
4	*PET bottles*	*4 fractions*	*Swill*	*PET bottles*	*4 fractions*	*PET bottles*	*PET bottles*	*PET bottles*		*Non-ferrous metal*	*Bio-drying / bio-stabilization*	*Gasification*
5	*Swill*	*5 fractions*	*Fat and oil*	*Swill*	*5 fractions*	*Swill*	*Swill*	*Swill*		*Plastic*		
6	*Fat and oil*	*6 fractions*	*PMD*	*Fat and oil*	*6 fractions*	*Fat and oil*	*Fat and oil*	*Fat and oil*				
7	*PMD*	*7 fractions*	*Foil*	*PMD*	*7 fractions*	*PMD*	*PMD*	*PMD*				
8	*Plastic*	*8 fractions*	*Plastic*	*Plastic*	*8 fractions*	*Plastic*	*Plastic*	*Plastic*				
9	*Foil*	*9 fractions*	*Cups*	*Foil*	*9 fractions*	*Foil*	*Foil*	*Foil*				
10	*Cups*	*10 fractions*	*Garden Waste*	*Cups*	*10 fractions*	*Cups*	*Cups*	*Cups*				
11	*Garden Waste*	*11 fractions*		*Garden Waste*	*11 fractions*	*Garden Waste*	*Garden Waste*	*Garden Waste*				

(light blue)	*Can be directly influenced by theme park*
(grey)	*Can be partly influenced by theme park*
(white)	*Can hardly be influenced by theme park*

Table 6.1: Morphological box without the application of constraints

Whereas the initial morphological box allows the construction of all SWM strategies that are theoretically possible, a lot of these strategies will not be viable in practice. To exclude morphological options that are not viable, the constraints from chapter 5 can be used. The application of these constraints to the morphological box is displayed in table 6.2. The options that are marked in red are not viable because they are in violation of certain constraints. The options marked in green are mandatory conditions because their absence would violate certain constraints. The exact constraints on the basis of which certain options are rejected or included are listed at the top of every parameter column. The codes correspond to the codes used in chapter 5. If necessary, the reasoning behind the applicability of certain constraints to certain rejections or inclusions is provided below. The numbers refer to the column numbers as provided in table 6.2.

1. Glass, fat and oil, foil and garden waste are rejected as fractions to be extracted from PSP collection as these fractions are not produced (to a detectable level) in PSP areas (FC-06) as can be concluded from the

	1	2	3	4	5	6	7	8	9	10	11	12
Functions	**PSP Collection**			**BTS Collection**		**Transportation**			**Central Sorting**	**Treatment**		
Options	**Fractions**	**Separate collect**	**Manual Sorting**	**Fractions**	**Separate collect**	**Decentral pick up**	**Central pick up**	**Return supplier**		**Recycling**	**Biological**	**Thermal**
Rejection/ inclusion require-ments	FC-06, FC-02	FC-07, FO-01, NFC-03, NFO-04, NFO-05	FC-12, FC-06, FO-07, FO-08, FO-09	NFC-04, FC-02, FC-09	NFC-04	FC-11, FC-09	FC-11, NFC-01, FC-09, FC-13 FO-07, FO-08	NFC-04	FC-14	FC-10	FC-14	FC-14
1	*Residual Waste*	*No*	*Paper*	*Residual Waste*	*No*	*Residual Waste*	*Residual Waste*	*Residual Waste*	*No central sorting*	*Paper and card*	*Local Composting*	*Mass-burn incineration*
2	*Paper*	*2 fractions*	*Glass*	*Paper*	*2 fractions*	*Paper*	*Paper*	*Paper*	*RDF sorting*	*Glass*	*Central Composting*	*Burning RDF*
3	*Glass*	*3 fractions*	*PET bottles*	*Glass*	*3 fractions*	*Glass*	*Glass*	*Glass*	*MRF sorting*	*Ferrous metal*	*Bio-gasification*	*Pyrolysis*
4	*PET bottles*	*4 fractions*	*Swill*	*PET bottles*	*4 fractions*	*PET bottles*	*PET bottles*	*PET bottles*		*Non-ferrous metal*	*Bio-drying / bio-stabilization*	*Gasification*
5	*Swill*	*5 fractions*	*Fat and oil*	*Swill*	*5 fractions*	*Swill*	*Swill*	*Swill*		*Plastic*		
6	*Fat and oil*	*6 fractions*	*PMD*	*Fat and oil*	*6 fractions*	*Fat and oil*	*Fat and oil*	*Fat and oil*				
7	*PMD*	*7 fractions*	*Foil*	*PMD*	*7 fractions*	*PMD*	*PMD*	*PMD*				
8	*Plastic*	*8 fractions*	*Plastic*	*Plastic*	*8 fractions*	*Plastic*	*Plastic*	*Plastic*				
9	*Foil*	*9 fractions*	*Cups*	*Foil*	*9 fractions*	*Foil*	*Foil*	*Foil*				
10	*Cups*	*10 fractions*	*Garden Waste*	*Cups*	*10 fractions*	*Cups*	*Cups*	*Cups*				
11	*Garden Waste*	*11 fractions*		*Garden Waste*	*11 fractions*	*Garden Waste*	*Garden Waste*	*Garden Waste*				

Rejected option based on constraint(s)
Mandatory option based on constraint(s)
Strategy specific options

Table 6.2: Morphological box with the application of constraints

sorting test. Garden waste is theoretically produced in PSP areas but only being deposited in BTS areas. Residual waste has to be included since all types of waste must be able to be processed (FC-02).

2. The constraints and objectives are self-explanatory.
3. In addition to the reasons mentioned under 1, only PET bottles are deemed to be properly sortable (manually) from the leftover fractions (FC-012) since there are practical examples of this as opposed to paper. In many cases, paper deposited in residual waste bins becomes wet and contaminated with other substances which makes recycling impossible.
4. The mandatory BTS fractions have to be separately collected because this is stated in LAP3 (2019) legislative documents (NFC-04). Although plastics (PMD) also have to be collected separately, this requirement lapses as the additional costs (relative to residual waste) of the separate collection and processing of PMD are higher than €45 per ton. Residual waste is, again, included because all types of waste must be able to be processed (FC-02). Plastic is excluded as plastics are part of PMD and PMD is the fraction that can be processed as a separate waste stream (FC-09).
5. See reasons mentioned under 4.
6. The constraints and objectives are mostly self-explanatory. Residual waste and swill have to be picked up decentrally because their total yearly quantity far exceeds 150 tonnes (FC-11). Fat and Oil has to be picked up decentrally because it requires special handling.
7. The constraints and objectives are mostly self-explanatory. Waste types that have to be picked up decentrally (FC-11) can not be picked up centrally at the same time. Decentral pick up is safer in general since this is done using specialized equipment from the waste management company (NFC-01). PMD cannot be picked up centrally since BTS and/or PSP PMD collection results in yearly PMD volumes higher than 1000 m^3 (based on a density of 60 kg/m^3 (Stichting Stimular, 2020) and section 4.2.3).

8. Many waste fractions cannot be returned to the supplier for two reasons. The first reason is that Waste transports are legally preserved to licensed waste management companies, only specific waste fractions are exempted from this and can be transported by foodstuff suppliers (NFC-04, see also section 4.3.2). Secondly, many waste fractions are not the responsibility of foodstuff suppliers since they originate from goods that are brought to the park by guests or are produced by the park itself.
9. RDF sorting is not reasonably available (FC-14) since there are only two (out of 13) combined RDF sorting and incineration plants in the Netherlands Which have a combined capacity share of only 12,5% (Rijkswaterstaat, 2020a). The plants are located in the provinces of Gelderland and Drenthe.
10. Since paper, glass, PET bottles and foil (among others) have to be collected separately in case of BTS collection, these waste streams also have to be processed using corresponding recycling treatment methods (FC-10). Therefore, paper, glass and plastic recycling are mandatory options.
11. The bio-drying and bio-stabilization option is not applied (to residual waste) in the Netherlands (FC-14).
12. The constraint is self-explanatory, see also section 4.4. Mass-burn incineration is a mandatory option since it is the only option left to process residual waste.

The options that are not viable in any strategy can be removed from the morphological box to create a more manageable one. This reduced morphological box is displayed in table 6.3. The mandatory options are still marked in green in this box.

Functions	PSP Collection			BTS Collection		Transportation			Central Sorting	Treatment		
Options	Fractions	Separate collect	Manual Sorting	Fractions	Separate collect	Decentral pick up	Central pick up	Return supplier		Recycling	Biological	Thermal
1	*Residual Waste*	*No*	*PET bottles*	*Residual Waste*	*8 fractions*	*Residual Waste*	*Paper*	*Paper*	*No central sorting*	*Paper and card*	*Local Composting*	*Mass-burn incineration*
2	*Paper*	*2 fractions*		*Paper*	*9 fractions*	*Paper*	*Glass*	*PET bottles*	*MRF sorting*	*Glass*	*Central Composting*	
3	*PET bottles*	*3 fractions*		*Glass*	*10 fractions*	*Glass*	*PET bottles*	*Foil*		*Ferrous metal*	*Bio-gasification*	
4	*Swill*			*PET bottles*		*PET bottles*	*Foil*			*Non-ferrous metal*		
5	*PMD*			*Swill*		*Swill*	*Cups*			*Plastic*		
6	*Plastic*			*Fat and oil*		*Fat and oil*	*Garden Waste*					
7	*Cups*			*PMD*		*PMD*						
8				*Foil*		*Foil*						
9				*Cups*		*Cups*						
10				*Garden Waste*								

Mandatory option based on constraint(s)
Strategy specific options

Table 6.3: Morphological box with remaining elements after application of constraints

To illustrate how the reduced morphological box can be used to form a SWM strategy, the current (or base) SWM strategy of the Efteling, as described in chapter 4, is displayed in table 6.4. PMD and cups are only separately collected at a small fraction of the BTS locations and are therefore marked in yellow.

It should be noted that although the morphological box that has been designed in this section is used to analyze and design SWM strategies for the Efteling, the box can be used to design SWM strategies for any semi-public space. To show this, the morphological box has also been applied to a totally different case, namely the TU Delft university campus. The corresponding morphological box is included in appendix C (table C.1). Most constraints that have been applied in this section to reduce the number of viable options in the morphological box are also applicable to other semi-public spaces such as the TU Delft campus.

Functions	PSP Collection			BTS Collection		Transportation			Central Sorting	Treatment		
Options	Fractions	Separate collect	Manual Sorting	Fractions	Separate collect	Decentral pick up	Central pick up	Return supplier		Recycling	Biological	Thermal
1	*Residual Waste*	*No*	*PET bottles*	*Residual Waste*	*8 fractions*	*Residual Waste*	*Paper*	*Paper*	*No central sorting*	*Paper and card*	*Local Composting*	*Mass-burn incineration*
2	*Paper*	*2 fractions*		*Paper*	*9 fractions*	*Paper*	*Glass*	*PET bottles*	*MRF sorting*	*Glass*	*Central Composting*	
3	*PET bottles*	*3 fractions*		*Glass*	*10 fractions*	*Glass*	*PET bottles*	*Foil*		*Ferrous metal*	*Bio-gasification*	
4	*Swill*			*PET bottles*		*PET bottles*	*Foil*			*Non-ferrous metal*		
5	*PMD*			*Swill*		*Swill*	*Cups*			*Plastic*		
6	*Plastic*			*Fat and oil*		*Fat and oil*	*Garden Waste*					
7	*Cups*			*PMD*		*PMD*						
8				*Foil*		*Foil*						
9				*Cups*		*Cups*						
10				*Garden Waste*								

Not applied in base strategy
Applied in base strategy
Partly applied in base strategy

Table 6.4: Morphological box of Efteling base strategy (current strategy)

6.2 Cross-consistency Assessment

Now that a morphological box with all of the viable elements of a theme park SWM strategy has been formed, it is time to look at combinations of elements. With the elements of table 6.3, thousands of unique combinations can be created. However, many of these combinations will be internally inconsistent or, in other words, mutually incompatible. This is, for example, the case for not separately collecting PMD while transporting and treating it separately. To reduce the solution space to a smaller set of internally consistent combinations, cross-consistency assessment (CCA) will be applied in this section. This is done using the 'principle of contradiction and reduction' by Zwicky (1967). CCA is applied in a step-wise manner to keep the process manageable.

First, the focus will be on combinations of PSP collection options (section 6.2.1). Secondly, possible combinations of BTS collection options are explored and assessed (section 6.2.2). The leftover PSP and BTS collection combinations are then combined and checked for overall consistency in section 6.2.3. Finally, the consistent collection combinations are extended to include transportation, sorting and treatment options that correspond to these combinations to form complete SWM strategies (section 6.3).

The CCA excludes combinations based on two types of inconsistencies. In addition to the exclusion of combinations that are logically contradictory, combinations that are empirically inconsistent are also excluded (see section 3.3 for definitions). The latter is done using a CO_2 saving quick-scan. This involves estimating the amount of CO_2 savings that a certain collection combination can accomplish using generic key figures. Combinations that accomplish (very) low CO_2 emission savings in proportion to the amount of effort that is required to facilitate this collection combination are excluded. The CO_2 saving quick-scan is performed using the variables in table 6.5. The composition of plastic and PMD waste fractions in this table is based on the sorting tests described in chapter 4.

Variable	Value	Unit	Source
Total yearly residual waste Efteling Park	[redacted]	Ton	Table ??
PSP portion of residual waste (estimate: [redacted]%)	[redacted]	Ton	Section 4.2.3
BTS portion of residual waste (estimate: [redacted]%)	[redacted]	Ton	Section 4.2.3
Paper recycling CO_2 savings relative to incineration	0,979	Ton per ton waste	CE Delft (2009)
Swill recycling CO_2 savings relative to incineration	0,063	Ton per ton waste	CE Delft (2009)
PET bottles recycling CO_2 savings relative to incineration	2,717	Ton per ton waste	CE Delft (2009)
Plastic recycling CO_2 savings relative to incineration • 27,3% plastic packaging • 72,7% PET	2,744	Ton per ton waste	Figure ?? and CE Delft (2009)
PSP PMD recycling CO_2 savings relative to incineration • 20,6% beverage cartons • 17,6% plastic packaging • 14,7% cans (50% steel + 50% aluminium) • 47,1% PET	2,961	Ton per ton waste	Figure ?? and CE Delft (2007, 2009)
BTS PMD recycling CO_2 savings relative to incineration • 26,0% beverage cartons • 52,1% plastic packaging • 5,5% cans (50% steel + 50% aluminium) • 16,4% PET	2,918	Ton per ton waste	Figure ?? and CE Delft (2007, 2009)
Cups recycling CO_2 savings relative to incineration	0,2015	Ton per ton waste	TNO and WFBR (2018)

Table 6.5: CCA and quick-scan variables

6.2.1 PSP Collection Options

All of the possible PSP collection combinations that can be made using the morphological box presented in table 6.3 are displayed in table 6.6. This concerns 44 possible options in total. The first two options consist of the collection of residual waste only and the optional manual sort of a PET bottle fraction. The options with numbers between (and including) 3 and 14 are made with combinations of residual waste and one other waste fraction to be collected separately and the optional manual sort of a PET bottle fraction. The options with numbers higher than 14 consist of the separate collection of residual waste and two other waste fractions and the optional manual sort of a PET bottle fraction. The table includes a consistency check and if a combination is consistent, a CO_2 saving quick-scan has also been included for that combination.

To verify that the number of PSP collection combinations listed in table 6.6 matches the number of combinations that can theoretically be made (without repetition) using the elements of the (reduced) morphological box, the binomial coefficient can be used. The binomial coefficient is displayed in formula 6.1 (Koshy, 2007). In this formula, n represents the number of elements to choose from and k is the number of elements chosen. This means that the number of PSP collection options can be calculated using the sum that is given in formula 6.2. This sum shows that the number of theoretical combinations is indeed 44.

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} \tag{6.1}$$

$$\text{Number of PSP collection options} = \binom{2}{1} + \binom{6}{1} * \binom{2}{1} + \binom{6}{2} * \binom{2}{1} = 44 \tag{6.2}$$

#	PSP Collection Options		Inconsis-tent	Separate collected fraction 1			Separate collected fraction 2			Manual sort	Total CO2 saving
	Separate collected fractions	*Manual sort*		*% of PSP res. waste*	*Weight (ton/yr)*	*CO_2 saving (ton/yr)*	*% of PSP res. Waste*	*Weight (ton/yr)*	*CO_2 saving (ton/yr)*	*CO2 saving (ton/yr)*	
1	*Res. waste*										*0*
2	*Res. waste*	*PET bottles*								[redacted]	*270*
3	*Res. waste + paper*			[redacted]	[redacted]	[redacted]					*42*
4	*Res. waste + paper*	*PET bottles*		[redacted]	[redacted]	[redacted]				[redacted]	*312*
5	*Res. waste + PET bottles*			[redacted]	[redacted]	[redacted]					*270*
6	*Res. waste + PET bottles*	*PET bottles*	✓								
7	*Res. Waste + swill*			[redacted]	[redacted]	[redacted]					*8*
8	*Res. Waste + swill*	*PET bottles*		[redacted]	[redacted]	[redacted]				[redacted]	*278*
9	*Res. waste + PMD*			[redacted]	[redacted]	[redacted]					*624*
10	*Res. waste + PMD*	*PET bottles*	✓								
11	*Res. waste + plastic*			[redacted]	[redacted]	[redacted]					*375*
12	*Res. waste + plastic*	*PET bottles*	✓								
13	*Res. Waste + cups*			[redacted]	[redacted]	[redacted]					*10*
14	*Res. Waste + cups*	*PET bottles*		[redacted]	[redacted]	[redacted]				[redacted]	*280*
15	*Res. waste + paper + PET bottles*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*312*
16	*Res. waste + paper + PET bottles*	*PET bottles*	✓								
17	*Res. waste + paper + swill*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*50*
18	*Res. waste + paper + swill*	*PET bottles*		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	*320*
19	*Res. waste + paper + PMD*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*666*
20	*Res. waste + paper + PMD*	*PET bottles*	✓								
21	*Res. waste + paper + plastic*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*417*
22	*Res. waste + paper + plastic*	*PET bottles*	✓								
23	*Res. waste + paper + cups*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*52*
24	*Res. waste + paper + cups*	*PET bottles*		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	*322*
25	*Res. waste + PET bottles + swill*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*278*
26	*Res. waste + PET bottles + swill*	*PET bottles*	✓								
27	*Res. waste + PET bottles + PMD*		✓								
28	*Res. waste + PET bottles + PMD*	*PET bottles*	✓								
29	*Res. waste + PET bottles + plastic*		✓								*0*
30	*Res. waste + PET bottles + plastic*	*PET bottles*	✓								
31	*Res. waste + PET bottles + cups*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*280*
32	*Res. waste + PET bottles + cups*	*PET bottles*	✓								
33	*Res. waste + swill + PMD*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*632*
34	*Res. waste + swill + PMD*	*PET bottles*	✓								
35	*Res. waste + swill + plastic*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*383*
36	*Res. waste + swill + plastic*	*PET bottles*	✓								
37	*Res. waste + swill + cups*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*18*
38	*Res. waste + swill + cups*	*PET bottles*		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	*288*
39	*Res. waste + PMD + plastic*		✓								
40	*Res. waste + PMD + plastic*	*PET bottles*	✓								
41	*Res. waste + PMD + cups*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*634*
42	*Res. waste + PMD + cups*	*PET bottles*	✓								
43	*Res. Waste + plastic + cups*			[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]		*385*
44	*Res. Waste + plastic + cups*	*PET bottles*	✓								

(red)	*Inconsistent combination*
(yellow)	*Base strategy (current)*
(green)	*High potential combination*

Table 6.6: Cross-consistency assessment and CO_2 saving potential estimation of PSP collection options (Theoretical purity of waste streams = 100%)

From the 44 combinations, 18 combinations are assessed to be inconsistent because they are logically contradictory. These are marked red. The inconsistent combinations violate the consistency 'rules' listed below:

- PSP fractions that are collected separately must be unique. They cannot overlap in terms of definition to avoid confusion. This means that PET bottles, plastic and PMD cannot be collected separately at the same time and place.
- The manual sorting of PET bottles from PSP residual waste is not consistent with the separate PSP collection of PET bottles or fractions that include PET bottles (plastic and PMD) since this should reduce the share of PET bottles in residual waste to insignificant levels (FC-12).

For the remaining 26 combinations, a CO_2 saving quick-scan has been included. This quick-scan calculates the total CO_2 emissions saving that a combination can achieve by taking the sum of the CO_2 savings of recycling one, two or three waste fractions relative to incineration. A maximum of two waste fractions can be collected separately and as a possible addition to that, PET bottles can be manually sorted from residual waste. Although the calculation of the CO_2 saving of recycling manually sorted PET bottles is not displayed as elaborately as for the separately collected fractions, the calculation is exactly the same. For all recycled waste fractions, it is assumed that they are separated from the residual waste with an efficiency of 100% to allow for fair comparisons. The weights of the different recyclable waste fractions are based on the percentages of these fractions in PSP residual waste as found by the PSP sorting test (see figure **??**). Notable things in the quick scan are, for example, the low CO_2 saving contributions of swill and cups if they are collected separately.

Using the total CO_2 savings numbers, many combinations can be excluded for further research based on empirical inconsistency (highly improbable combinations). To prevent unfair comparisons between options with a single separately collected fraction and options with two separately collected fractions (the latter can achieve more CO_2 savings but also requires more resources), the selection of options was done per category. In the end, 3 options with a single separately collected fraction and 3 options with two separately collected fractions have been marked as 'high potential combinations' since these can result in potential CO2 savings that are far higher than those for the other remaining combinations in the same category. Of course, the current PSP collection combination (strategy) has also been marked (yellow) to be researched further for comparison purposes.

One 'high potential combination' (number 5) does not have a top 3 CO_2 savings potential within the category of separately collecting one waste fraction. However, this combination has still been marked as a 'high potential combination' as opposed to combinations #4, #8 and #14 as a result of a sensitivity analysis. This sensitivity analysis is included in appendix D. The main reason for excluding #4, #8 and #14 is their heavy reliance on the manual sorting of PET bottles from residual waste for achieving their CO_2 savings. Reducing the manual sorting efficiency below 100%, which is more realistic, results in the top 3 (single separate fraction) combinations that are actually marked in table 6.6. Note that a sensitivity analysis of the combinations with two separately collected fractions did not have an impact on the final selection of high potential combinations. They remain dominant even if the efficiency of the separate PMD collection drops to 66% (versus 100% for other fractions), meaning that 34% of the PMD is still being incinerated. This shows that PMD is a very dominant fraction when it comes to realising CO_2 savings.

6.2.2 BTS Collection Options

Using the same approach as for the different PSP collection options, a CCA has been performed on the BTS collection options. Only 4 theoretical combinations can be formed using the reduced morphological box in table 6.3. These combinations and their consistency assessment are displayed in table 6.7. Note that 'Base set' refers to the fractions that have to be collected separately as a result of constraints (see also table 6.3). These mandatory fractions include: residual waste, paper, glass, PET bottles, swill, fat and oil, foil and garden waste.

All combinations in table 6.7 are consistent in the sense that they are not logically contradictory. To be able to select the most relevant combination(s) to be researched into more detail, a CO_2 saving quick-scan has, again, been included. This time, the weights of the different recyclable waste fractions are based on the percentages of these fractions in BTS residual waste as found by the BTS sorting test (see figure **??**). For comparison purposes, the base strategy, which has been marked yellow, will be selected anyway. Additionally, option number #2 has been selected as a 'high potential combination' for further research. This may seem weird as #2 is not the option with the highest CO_2 saving potential. However, the additional CO_2 benefit of option #4 is so low that it is unlikely that this 2 ton of CO_2 will outweigh the additional resources necessary for the separate collection, transportation and processing of BTS cups. Therefore, options #3 and #4 are considered to be empirically inconsistent (highly improbable).

#	BTS Collection Options	Inconsis-tent	Separate collected fraction 1			Separate collected fraction 2			Total CO2 saving
	Separate collected fractions		*% of BTS res. waste*	*Weight (ton/yr)*	*CO_2 saving (ton/yr)*	*% of BTS res. Waste*	*Weight (ton/yr)*	*CO_2 saving (ton/yr)*	
1	*Base set*								*0*
2	*Base set + PMD*		[redacted]	[redacted]	[redacted]				*180*
3	*Base set + cups*		[redacted]	[redacted]	[redacted]				*2*
4	*Base set + PMD + cups*		[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	*182*

(green)	*High potential combination*
(yellow)	*Base strategy (current)*

Table 6.7: Cross-consistency assessment and CO_2 saving potential estimation of BTS collection options (Purity of waste streams = 100%)

6.2.3 Overall Collection Options

Now that the collection options with the highest potential have been selected from all of the possible PSP and all of the possible BTS collection combinations, it is time to combine them. Table 6.8 shows all of the possible combinations of high potential PSP and BTS collection options.

#	PSP Collection Options		BTS Collection Options	Inconsis-tent
	Separate collected fractions	*Manual sort*	*Separate collected fractions*	
1	*Res. waste*	*PET bottles*	*Base set*	
2	*Res. waste*	*PET bottles*	*Base set + PMD*	
	Res. waste + PET bottles		*Base set*	✓
3	*Res. waste + PET bottles*		*Base set + PMD*	
	Res. waste + PMD		*Base set*	✓
4	*Res. waste + PMD*		*Base set + PMD*	
	Res. waste + plastic		*Base set*	✓
5	*Res. waste + plastic*		*Base set + PMD*	
	Res. waste + paper + PMD		*Base set*	✓
6	*Res. waste + paper + PMD*		*Base set + PMD*	
	Res. waste + swill + PMD		*Base set*	✓
7	*Res. waste + swill + PMD*		*Base set + PMD*	
	Res. waste + cups + PMD		*Base set*	✓
8	*Res. waste + cups + PMD*		*Base set + PMD*	

Table 6.8: Cross-consistency assessment overall (PSP + BTS) collection options

Again, a CCA is performed to reduce the solution space to a smaller set of internally consistent combinations. From the 14 combinations, 6 have been marked in red as inconsistent. This inconsistency is based on the combination of separately collecting PMD, plastic or PET bottles in PSP areas while not collecting PMD separately in BTS areas. There are two reasons why such a combination is considered to be inconsistent. The first reason is that PSP waste fractions are moved to BTS areas when their corresponding bins are full. This means that there will be collection facilities for waste fractions that are separately collected in PSP areas in BTS areas. It makes no sense not to use them for BTS collection as well. Secondly, asking guests to separate certain waste fractions while not doing this behind-the-scenes, even though staff members are easier to educate on waste separation, is something that can severely hurt the image of the company and goes against its vision. The final selection of high potential collection options have been numbered from 1 to 8. This numbering will be referred to in next sections.

6.2.4 Transportation Options

Since the consistency of a transportation strategy can only be properly assessed in relation to the collection strategy with which it is combined, transportation options are not assessed in a standalone way. As one can see in the reduced morphological box (table 6.3), some (BTS) waste fractions for which it is mandatory to be collected separately can be picked up centrally and decentrally and sometimes they can also be returned to the supplier. Since all collection strategies include these mandatory fractions, the number of possible collection plus transportation strategies would get very large. This means, at least 14 times as large as the number of high potential collection options. This is, of course, way too many to research into more detail. Therefore, it is assumed that the current transportation strategy has already been optimized over the years in terms of resource usage (energy, time and money) and will be used as a starting point. Only when the collected quantity of certain waste fractions is expected to change as a result of a different collection strategy, the transportation strategy of this waste fraction may be varied as well. This assumption can be justified in the larger context by the fact that the environmental burdens of transport are generally found to be minor in relation to the burdens/benefits of waste processing (Turner et al., 2016). The current transportation strategy is referred to as the base set. This base set is displayed in table 6.9. The strategy specific transportation options that may be added to the base set or used as a substitute for base set options are also listed in table 6.9 on the right side. The transportation options will be combined with collection and treatment options in section 6.3.

Transportation Base Set		
Decentral pick up	Central pick up	Return supplier
Residual Waste	Glass	
Paper	Foil	
Swill	PET bottles	
Fat and oil	Garden Waste	

Transportation Strategy specific options		
Decentral pick up	Central pick up	Return supplier
PMD	Cups	Paper
Cups		PET bottles
		Foil

Table 6.9: Transportation base set and strategy specific options

6.2.5 Sorting and Treatment Options

The sorting and treatment options that may be combined with the selected collection and transport options as discussed in previous sections are displayed in the reduced morphological box in table 6.3. In terms of the consistency of sorting options with treatment options there is only one 'rule': PMD and plastic waste fractions can only be recycled if they are sorted using MRF sorting. The other waste fractions do not need central sorting and can be processed using corresponding treatment methods. Combinations of treatment methods are not really limited by their mutual consistency since they are (mostly) used to process different waste fractions. The consistency of treatment options in the context of the full SWM system however is strongly dependent on the fractions which have to be processed, which in turn, depends on the collection strategy. However, since many waste types have to be collected separately (in BTS areas) and these fractions have to be processed using corresponding (recyling) methods (FC-10 and FO-04), many waste treatment methods will be included in every strategy. These methods are included in the treatment base set which is displayed in table 6.10. Furthermore, mass-burn incineration is the only viable option left for the processing of residual waste (see tables 6.2 and 6.3). This leaves only 'local composting' as a strategy specific option that can be used to supplement or substitute the current biological treatment methods: central composting and biogasification.

Treatment Base Set		
Recycling	Biological	Thermal
Paper and card	Central Composting	Mass-burn incineration
Glass	Biogasification	
Ferrous metal		
Non-ferrous metal		
Plastic		

Treatment Strategy specific options		
Recycling	Biological	Thermal
	Local Composting	

Table 6.10: Treatment base set and strategy specific options

6.3 Strategies

Using the final selection of high potential collection options from section 6.2.3 and the transportation, sorting and treatment base sets and strategy specific options from sections 6.2.4 and 6.2.5, a set of high potential full SWM strategies to be researched into more detail can be formed. These full strategies are displayed in table 6.11. The main numbers of the strategies correspond to the final selection of high potential collection options from table 6.8 while the A/B sub variants refer to variations in terms of transportation or treatment. As mentioned in section 6.2.4, sub variants are only present if a certain collection strategy gives rise to changes in waste fraction quantities and if alternative options for the transport or treatment of these waste fractions are available. This is, for example, the case if PET bottles are manually sorted or separately collected in PSP areas. In this case, a return supplier transport strategy as well as a central pick up strategy (for PET bottles) may be considered. The only case for which a local composting treatment has been added as a variant is if swill is also collected separately in PSP areas (number 7) since this combination would make sense.

Strat.		PSP Collection		BTS Collection	Transportation			Central Sorting	Treatment		
#	sub	Fractions*	Manual sort	Fractions**	Decentral pick up**	Central pick up**	Return supplier		Recycling	Biological	Thermal
1	A		PET bottles						Base set	Base set	Mass-burn
	B		PET bottles			- PET bottles	PET bottles		Base set	Base set	Mass-burn
2	A		PET bottles	+ PMD	+ PMD			MRF sorting	Base set	Base set	Mass-burn
	B		PET bottles	+ PMD	+ PMD	- PET bottles	PET bottles	MRF sorting	Base set	Base set	Mass-burn
3	A	PET bottles		+ PMD	+ PMD			MRF sorting	Base set	Base set	Mass-burn
	B	PET bottles		+ PMD	+ PMD	- PET bottles	PET bottles	MRF sorting	Base set	Base set	Mass-burn
4		PMD		+ PMD	+ PMD			MRF sorting	Base set	Base set	Mass-burn
5		Plastic		+ PMD	+ PMD			MRF sorting	Base set	Base set	Mass-burn
6	A	Paper + PMD		+ PMD	+ PMD			MRF sorting	Base set	Base set	Mass-burn
	B	Paper + PMD		+ PMD	+ PMD		Paper	MRF sorting	Base set	Base set	Mass-burn
7	A	Swill + PMD		+ PMD	+ PMD			MRF sorting	Base set	Base set	Mass-burn
	B	Swill + PMD		+ PMD	+ PMD - swill			MRF sorting	Base set	Local composting	Mass-burn
8	A	Cups + PMD		+ PMD	+ PMD	+ cups		MRF sorting	Base set	Base set	Mass-burn
	B	Cups + PMD		+ PMD	+ PMD + cups			MRF sorting	Base set	Base set	Mass-burn

* Residual waste always included
** Base set always included (+ means addition to base set, - means withdrawal from base set)

Table 6.11: Final strategies after cross-consistency assessment

6.4 Conclusion SWM Strategies for Semi-Public Spaces

In this chapter, sub research question 3 has been answered. The question was: "*What strategies can be designed to improve the sustainability of solid waste management systems in semi-public spaces?*"

To be able to compose strategies in a systematic and traceable way, a SWM morphological box for semi-public spaces has been created. This morphological box contains all of the theoretically possible options for the PSP/BTS collection, transportation, sorting and treatment of solid waste. Many of the options were found to violate certain constraints, which are specific to the problem at hand, as formulated in chapter 5. After removing these non-viable options, the reduced morphological box from figure 6.3 emerges. This morphological box allows the composition of many different SWM strategies for semi-public spaces and, more specifically, for the Efteling. However, many of these strategies (combinations of options) are internally inconsistent. A systematic step-wise cross-consistency assessment was used to rule out such inconsistent strategies. From the consistent strategies, a final selection of high potential strategies (in terms of sustainability) was made using a CO_2 saving quick-scan. The final strategies, 8 main collection variants with possible transportation/treatment subvariants, are listed in table 6.11.

Chapter 7

Modelling Solid Waste Management Systems for Semi-Public Spaces

This chapter describes how the environmental and economic impact of different SWM strategies for semi-public spaces can be estimated. The strategies that have been composed in the previous chapter will be assessed using the procedure described in this chapter. Whereas this chapter focuses on the procedure itself, the next chapter will go into the actual comparison of the impact of different strategies. The KPI's that form the basis for the comparison of different strategies have been derived in chapter 5. These are: eco-efficiency and global warming potential. Two impact components can be distinguished in these KPI's namely an environmental component and an economic component. The environmental component will be estimated using a life cycle assessment (LCA) as introduced in methodology section 3.4. The specific application of LCA to SWM in the context of this research is described in section 7.1. The application of an economic assessment to asses the economic impact of different SWM strategies is finally described in section 7.2.

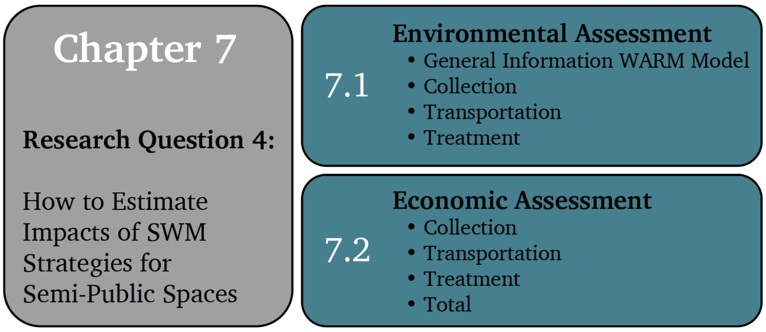

Figure 7.1: Structure of chapter 7

Although a LCA is very common in the context of assessing environmental impacts of SWM and even internationally standardized (Cherubini et al., 2009), the combination of LCA with economic assessment is less developed in SWM literature. One of the few examples of concepts that integrate environmental and economic impacts of SWM is that of eco-efficiency analysis. Eco-efficiency analysis (EEA) is a tool to link environmental performance to cost-effectiveness developed by BASF and described by Saling et al. (2002). The application of EEA for SWM purposes has been described and researched by Yang et al. (2015). In an eco-efficiency analysis, the eco-efficiency ratio of different possible SWM strategies is calculated and compared to each other in the end. Based on the principles of Yang et al. (2015) and the generic IWM system representation of Gentil et al. (2010), a specific eco-efficiency analysis framework for semi-public spaces has been developed. This framework can be found in figure 7.2. It is an extension to the schematic representation of the theme park SWM system that was presented in chapter 4. The framework includes a LCA as well as an economic assessment (see figure 7.2). As one can see in the figure, the SWM system exchanges materials and energy flows with the earth system and technosphere outside of the SWM system. These exchanges are grouped in different sources and sinks of greenhouse gasses (GHG's). Taking these into account is important as they together determine the net GHG emissions (offset) of the SWM system. At the same time, the configuration of the SWM system also influences cost components related to the SWM system. These together determine the total operational costs of the SWM system. Combining the total operational costs with the net GHG emissions results in the eco-efficiency ratio (see section 5.3.1) of the SWM system at hand.

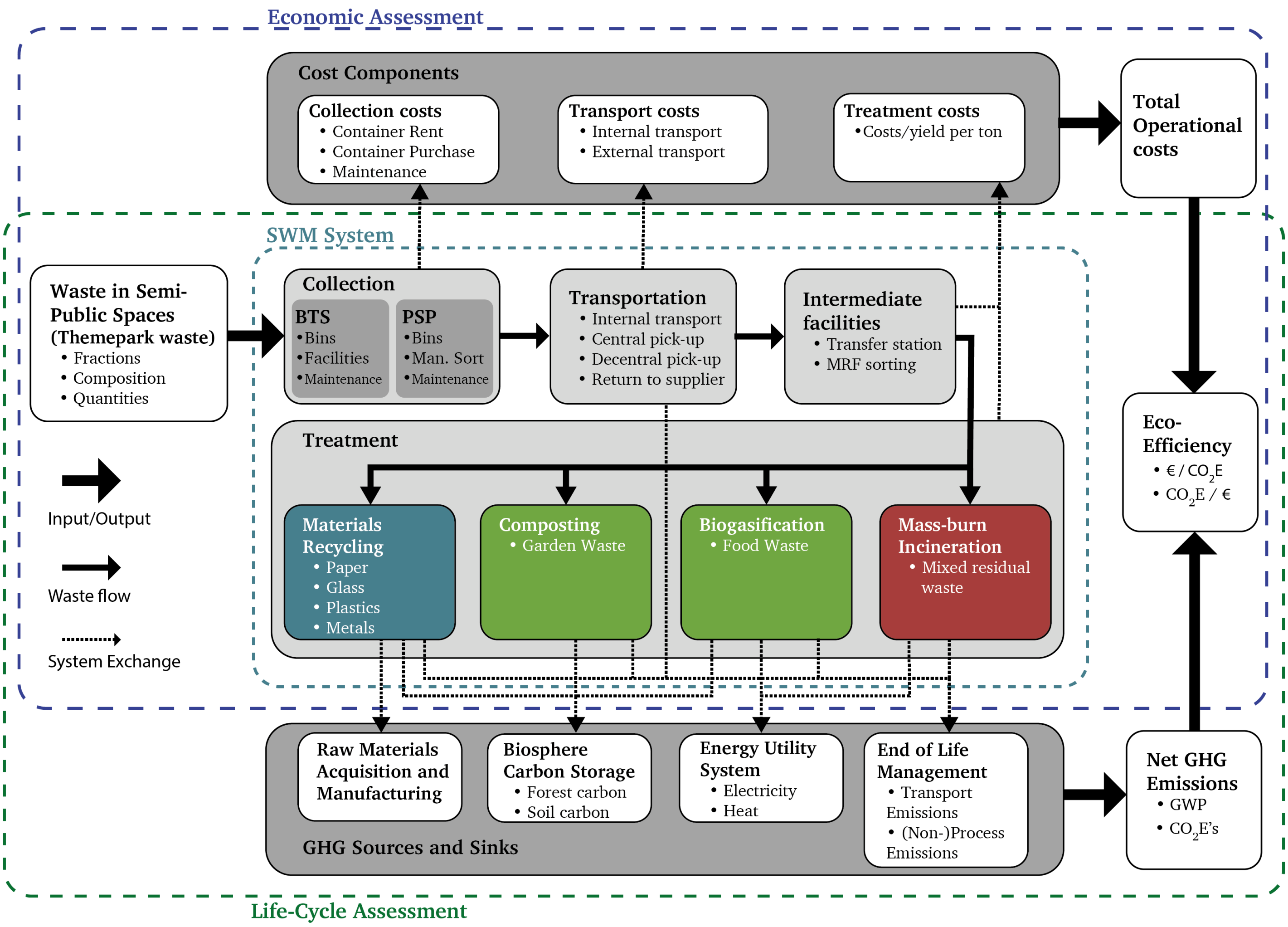

Figure 7.2: SWM eco-efficiency analysis framework for semi-public spaces using LCA and economic assessment

7.1 Environmental Assessment

The fundamentals of an LCA have been described in section 3.4. Since (good) SWM LCA models are very complex, which is related to the fact that SWM systems consist of many interrelated processes, an existing model will be adapted to calculate the impact of theme park SWM strategies. This model belongs to the very small pool of LCA models that are specifically aimed at SWM. Note that the majority of LCA models is aimed at product LCA's in which waste disposal is just a small component. In a product LCA, the infrastructure system (transportation, waste treatment etc.) is assumed to be given while the product design can be optimised. In a SWM LCA, it is the other way around, the infrastructure system is optimised to manage a given amount and composition of waste (McDougall et al., 2001). Therefore, dedicated SWM LCA models are needed. EC (2008) has mapped and classified 42 (European) LCA tools of which WRATE is the only dedicated and available SWM one. In a worldwide context, WARM is another dedicated SWM LCA (more specifically: LCI) tool that is the industry-standard in the United States. The acronyms are elaborated below:

- **WARM (US) :** Waste Reduction Model (developed by: U.S. Environmental Protection Agency)
- **WRATE (EU-UK):** Waste and Resources Assessment Tool for the Environment (developed for: UK Environment Agency)

Although both tools use the same standardized LCA/LCI procedure (ISO, 2006) to calculate environmental burdens of SWM systems, there are also differences in the way this procedure is implemented. Both tools use different background databases to characterize process emissions which may result in (slightly) different impacts. In the end, WARM was chosen to model the environmental impact of theme park SWM systems because it has a couple of major advantages over WRATE. First of all, the WARM model is more state-of-the-art compared to WRATE. Just like many other SWM LCA models, WRATE was developed in the beginning of the 21st century (Gentil et al., 2010). It was last updated in 2010. However, WRATE continues to use the GWP multipliers of the 1996 version of the IPCC guidance although these were updated in 2006 and in later years (Ballinger, 2013). Furthermore, the ecoinvent background databases used by WRATE are also quite outdated compared to WARM. The same goes for the method with which biogenic carbon is being dealt with (Ballinger, 2013). The biggest advantage of WARM over WRATE is that WARM is way more transparent in the sense that all of the assumptions regarding background data are described in supporting documents. These are lacking for WRATE. The extensive documentation that comes with WARM also allows the modeller to adapt the model to specific circumstances such as those applicable to theme parks and those in the Netherlands.

7.1.1 General Information WARM Model

The development of the WARM model started in the late nineties and the model has been improved and updated ever since. The latest version of WARM, which is also used in this research, is version 15. This version was released in may 2019. Although the model has been developed by the US Environmental Protection Agency as a National tool, it has received considerable interest by the international community (US EPA, 2019b). The methodologies of the WARM model are consistent with the IPCC guidelines (IPCC, 2006) on inventory methods.

Goal and Scope

WARM provides a so-called "streamlined LCA" by limiting itself to an inventory of GHG emissions and sinks (forests, soils) and energy impacts related to end-of-life management options. This means that the **product system** in this case is the total SWM system, including recycling, that is necessary to process waste from a semi-public space (the Efteling theme park in this case) from the moment that it is discarded until the moment that it has regained value as a new product or when it has become inert material or is converted to air emissions. The **functional unit** is all of the operational waste (as defined in section 1.4) of a semi-public space over 1 year. The limitation to GHG emissions and sinks means that only environmental impacts in terms of climate change are evaluated. The climate change impact is measured in TCO_2E's or ton CO_2 equivalents. The conversion to CO_2 equivalents is based on the global warming potentials listed in table 7.1. Other impact categories such as acidification and eutrophication are not taken into account, which is not a problem as these are less significant driving forces for sustainable decision making processes (Zaman, 2010). Furthermore, most of these other impact categories are only relevant in the case of SWM water emissions which are not really applicable in the Netherlands.

Gas Type	Global Warming Potential (100yr)
CO_2	1
CH_4	25
N_2O	298

Table 7.1: WARM model Global Warming Potentials (based on IPCC (2007))

Since WARM has been developed in the United States, the emission factors in TCO_2E's are originally measured per short ton of waste/material type. In this report, all of these factors have been converted to TCO_2E per metric ton of waste/material. This conversion is based on the equivalent numbers in the first row of the table below. Additionally, British thermal units (Btu's) were also converted to kilowatt-hours (kWh's) using the equivalent numbers in the second row.

1 short ton	907.18474 kg	0.90718474 metric ton
1 Btu	1055.05585 joule	0.00029307 kWh

Furthermore, it must be noticed that "*WARM calculates emission impacts from a waste generation reference point, rather than a raw materials extraction reference point*" (US EPA, 2019b, p.15). This means that upstream emissions and sinks (from the point that a material is discarded) are only considered for recycling and source reduction SWM practices since these are the only SWM options that affect upstream emissions. Moreover, a baseline strategy must be compared with an alternative strategy to be able to evaluate environmental benefits of SWM strategies (US EPA, 2019b).

Finally, it is important to realise that, in line with IPCC (2006), CO_2 emissions from biogenic materials that are grown on a sustainable basis are not counted. This applies to paper and wood products and to food waste. The reason for not counting these CO_2 emissions as opposed to those from burning fossil fuels is that biogenic emissions would occur anyway, be it over a longer period of time. They belong to the natural carbon cycle. Anthropogenic CO_2 emissions on the other hand, those from human activities and subject to human control, would not enter the carbon cycle were it not for human activity (US EPA, 2019b).

7.1.2 Collection

The first step in modelling the life cycle environmental impact of SWM strategies for semi-public spaces using LCA models is to transpose the known quantities of collected waste types to quantities of waste types that are included in the model database. Whereas some 10 different waste types are separated during regular operations of the Efteling, the WARM model distinguishes 60 different types of materials in its database (US EPA, 2019b). The definitions of these materials can be found in US EPA (2019b). For every material, different process emissions data is attached. Many waste materials are more narrowly defined in the model than they are in the daily separate collection practice. An example of this is the distinction between corrugated containers, magazines, newspapers, office papers and other paper types in the WARM model. The more accurate the quantities of waste materials are being transposed to the waste material categories of the LCA models, the more accurate the result will be. The transposition of the composition of Efteling waste to the WARM model is not provided in this public version of the report because the Efteling waste quantities are confidential. For some waste types, a model proxy is used. A proxy is a material that seems similar to the non-WARM material being approximated. A separate manual was used for the application of proxy's (US EPA, 2015). The division of certain waste types into multiple types of materials is based on the following (substantiated) assumptions:

- **Residual waste:** Residual waste is first divided into the 9 different types of materials that were distinguished in the sorting test (described in sections 4.2.1 and 4.2.2), since the share of these materials in the residual waste can be derived from these sorting tests. The leftover residual waste and bulky waste fractions from the sorted residual waste are labeled as mixed MSW in the model since this is the best approximation for these mixed waste types. The other sorted fractions may be divided into multiple model materials based on the assumptions below.
- **Plastic packaging:** The WARM model distinghuises the folllowing types of plastic packaging: HDPE, LDPE, PET, LLDPE, PP, PS and PVC plastics. All of these, except PVC, are used for the packaging of food and drinks. Looking at the definitions in US EPA (2019b), it is expected that the plastic packaging fraction in the Efteling mainly consists of HDPE, LDPE and PP. PET plastic is not included in plastic packaging since PET plastic was a separate category in the sorting tests. Although plastic packaging could be defined in the model as shares of PP, HDPE and LDPE, the model category of "mixed plastics" was chosen for plastic packaging for the following reasons. The shares of PP, HDPE, LDPE and other plastics are unknown and due to "LCI data availability" only HDPE and PET recycling are modelled in WARM (US EPA, 2019d). It is stated that "mixed plastics" is a good proxy for plastic with an unkown resin (US EPA, 2015).
- **Paper/card:** For the fraction of paper and card that was sorted from residual waste, a 'mixed paper' model category is assumed since this paper consists of a mix of different kinds of paper as also found in MSW. For the separately collected fraction of paper, a share of 75% corrugated containers (cardboard), 5% magazines and 20% office paper is assumed based on experience from employees of the Efteling environmental service.
- **Beverage cartons:** According to CE Delft (2007), septic beverage cartons (which is the main category of beverage cartons for the Efteling) consist of a combination of 11% PE and 89% cardboard.
- **Cups:** According to Renewi (n.d.), PE-cardboard cups (the most commonly used type of cups in the Efteling) consist of a combination of 95% cardboard and 5% (LD)PE.
- **Cans:** According to SKB (2020), cans are made of aluminium or steel. However, no information could be found about the respective share of aluminium or steel cans. Different manufacturers may use aluminium or steel or a combination of both. Therefore, general shares of 50% aluminium and 50% steel have been

assumed.

- **PMD:** The division of PMD into beverage cartons, plastic packaging, cans and PET is based on the sorting tests summarized in table 6.5. The subdivision of beverage cartons, plastic packaging and cans is based on the assumptions described above.
- **Garden waste:** Most of the garden waste is assumed to consist of leaves since these are the main product of mechanical sweeping activities, which is the most common source of garden waste. Small portions have been attributed to branches and grass based on based on experience from employees of the Efteling environmental service.

7.1.3 Transportation

The modelling of transportation emissions associated with SWM options in WARM is relatively simple. These emissions are incorporated in the treatment emission factors as described in the next section (7.1.4). However, the calculation of the specific transportation components will be described in this section. Since transport emissions are strongly dependent on the treatment method, they will be discussed per treatment method, starting with recycling.

Recycling

Transportation-related emissions from recycling that are modelled in WARM include collection and transportation to a recycling center (MRF), transportation of recycled materials to remanufacturing and the avoided emissions from the transport of raw materials and products to virgin material production (US EPA, 2019b). The emissions from retail transport, which consist of the average emissions from transporting manufactured material from the factory to the retail/distribution point, are also included (US EPA, 2019c). However, since these emissions are assumed to be the same for virgin produced as for recycled materials, they do not have an impact on the final recycling transport emission factor. This factor can be found in the rightmost column in table E.1 of appendix E. It is the difference between the transport emissions required for the virgin production of one ton of a material (including retail transport) and the transport emissions required for the recycled production of one ton of that same material (including retail transport). All of these values for all recyclable materials can be found in table E.1 of appendix E. From this table, it can be concluded that recycling saves transportation emissions for almost all materials except for plastics. The production of plastics using petroleum and/or natural gas requires less transport emissions than the production of plastics using recycled plastic resin. The values in the rightmost column are also used in table 7.3 to calculate the total benefit of recycling over virgin manufacturing. Small differences between the numbers in both tables are caused by rounding and the incorporation of loss rates for recycled materials (one ton of recovered material results in slightly less than one ton of recycled material) (US EPA, 2019d).

The emissions of the transportation of recycled materials to a MRF have a default value of 0.00 TCO_2 per ton of material. This corresponds to a distance of 20 miles (32.2 km). WARM allows users to change this distance. In this case, a factor of 0.11 kg CO2 per ton-kilometer is used to calculate the additional transport emissions for transport to a MRF (US EPA, 2019b). Since the actual transportation distances to the MRF (via possible intermediate facilities) are known for many materials in the case of the Efteling (see table 4.8 in chapter 4), the default factor for this has been adapted. The custom values are shown in table E.1 of appendix E and range between 0.00 to 0.03 TCO_2 per ton of material.

Composting

Transportation-related emissions from composting that are modelled in WARM include collection and transportation to a composting facility and the operation of composting equipment to turn the compost regularly (US EPA, 2019b). Transportation emissions from the delivery of finished compost to its final destination are not counted. Similar to recycling and incineration, the default transportation distance to the treatment facility is assumed to be 20 miles (32.3km) which results in the emission of 0.003 TCO_2E per ton of material transported (using the same emission factor as for recycling and incineration). The emissions associated with the compost turning equipment are assumed to be higher with 0.016 TCO_2 per ton of compostable waste (US EPA, 2019c).

This means that the total transportation emission factor for composting is 0.02 TCO_2E per ton compostable waste.

Anaerobic Digestion (Biogasification)

Similarly to composting, transport-related emission from anaerobic digestion that are modelled in WARM include collection and transportation to an anaerobic digestion facility. Again, a default distance of 20 miles (32.2km) is assumed for this. Additionally, emissions from the transportation and spreading of feedstock and solids during the on-site process are also taken into account but these are included in the process energy emissions and not in the transport emissions. Therefore, the transport emissions only amount to 0.003 TCO_2E per ton of transported food waste (using the same emission factor as for recycling and incineration).

Incineration

For incineration, which is mainly applicable to mixed waste types, a fixed transportation emission quantity is assumed by WARM per ton of material that is combusted. This quantity is 0.01 TCO_2E per ton combusted (US EPA, 2019d). It includes the transportation of waste to the incineration facility (0.00), the operation of on-site transportation equipment (0.00) and the transportation of residual ash to a landfill (0.01). The transportation of individual materials in mixed MSW is assumed to use the same amount of energy as transportation of mixed MSW. Although only 15% or less of residual ash is landfilled in the Netherlands, the other ash also has to be transported to be reprocessed and used as a building material (LAP3, 2019). Therefore, the ash transportation emissions are assumed to be similar to those in case of landfilling all of the ash. The default transportation distance to an incineration facility in WARM is 20 miles (32.2 km) (US EPA, 2019b). To calculate CO_2 emissions, WARM uses a factor of 0.11 kg CO_2 per ton-kilometer.

Since the locations of the incineration plants that are used to treat waste of the study case (the Efteling) are known (see section 4.3), the default transport distance in WARM has been changed (see table 7.2). The adapted transportation distance is the average of the distance to all of the plants including the internal transport distance. This results in a total incineration transport emission factor of 0.02 TCO_2E per ton combusted. Note that the the transport emissions for residual ash remain unchanged.

Transport Emission Factor (WARM)		**Default dist. to incineration facility**	**Adapted dist. to incineration facility**	**Default total incineration transport emissions**	**Adapted total incineration transport emissions**
0.00016 TCO_2/ Short Ton-Mile	0.00011 TCO_2/ Ton-Kilometer	20 miles | 32 km	57 miles | 91 km	0.01 TCO_2/ ton of material	0.02 TCO_2/ ton of material

Table 7.2: Emissions associated with transporting waste to incineration facility and ash transportation (US EPA, 2019d)

7.1.4 Treatment

The modelling of waste treatment methods in WARM is discussed per treatment method.

Recycling

Waste recycling involves transforming or remanufacturing wastes into usable secondary products or materials. Not all types of waste can be recycled. Organic waste may be composted or anaerobically digested instead. Mixed MSW cannot be recycled without separating it in recyclable materials. Two categories of recycling can be distinguished namely open-loop and closed-loop recycling. Most of the WARM materials are modelled in a closed-loop recycling process. This means that an "end-of-life product" is recycled into the same product (US EPA, 2019d). In open-loop recycling, the products of the recycling process are different than the input waste products. This is, for example, the case for mixed paper (mix of newsprint, office paper, coated paper etc.) which is recycled into boxboard due to quality constraints related to mixed paper pulp fibers (US EPA, 2019c). The recycling category for different WARM materials is displayed in the second column of table 7.3 where C stands for closed-loop recycling and O for open-loop recycling. Note that corrugated containers are modelled as a partial open-loop since 70% is generally recycled into corrugated containers (closed-loop) and 30% into boxboard (open-loop).

Recycling may result in two types of GHG reduction benefits (US EPA, 2019d, p.13):

1. "*It offsets a portion of 'upstream' GHG's emitted in raw material acquisition, manufacture and transport of virgin inputs and materials.*"
2. "*It increases the amount of carbon stored in forests (when wood and paper products are recycled).*"

Both benefits are taken into account by the WARM model when calculating the GHG benefits of recycling waste materials. With respect to the first benefit, it is assumed that recycling materials does not change the amount of materials that would otherwise have been manufactured. In other words, it is assumed that the increased recycling of a product does not change the overall demand for that product, which means that virgin-sourced materials are displaced by recycled materials (US EPA, 2019d). Using this assumption, the avoided GHG emissions resulting from recycling are calculated as "*the difference between (1) the GHG emissions from manufacturing a material with 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates associated with curbside collection losses and remanufacturing losses) with 100 percent virgin inputs*" (US EPA, 2019b, p.22). In the case of open-loop recycling, the material referred to is not the primary material itself but a secondary material for which virgin inputs or recycled inputs may be used. The final calculated difference is referred to as the 'recycled input credit' or 'recycling emission factor' when measured for 1 ton of recycled material. A negative factor means that recycling reduces GHG emissions or increases carbon storage relative to virgin manufacturing. The recycling emission factor is the sum of different components which can be found in formula 7.1. The components are described below.

$$\begin{aligned}\text{Recycling Emission Factor}(\text{TCO}_2\text{E/ton of material recovered}) = {} & \text{Process Energy Credit} + \\ & \text{Transportation Energy Credit} + \text{Process Non-Energy Credit} + \\ & \text{Forest Carbon Storage}\end{aligned} \tag{7.1}$$

- **Process Energy Emissions:** This mainly concerns CO_2 emissions from the combustion of fuels that are used in raw materials acquisition and manufacturing, except those from biomass combustion (US EPA, 2019b). This also includes emissions from extracting oil or gas or for mining coil to produce the process energy from and to transport it to the right place.
- **Transportation Energy Emissions:** This concerns CO_2 emissions from the combustion of fossil fuels to transport both raw materials and intermediate products during manufacturing. Furthermore, emissions from transporting finished products from manufacturing facilities to retail and distribution points are also included (US EPA, 2019b).
- **Process Non-Energy Emissions:** This concerns GHG emissions (including CH_4 and N_2O) that occur during the manufacturing of certain materials and that are not associated with energy consumption. An example of non-energy process emissions is the emission of CO_2 resulting from the conversion of limestone into lime for paper, steel or aluminium manufacturing. Note that these emissions may be linked to virgin production or recycling only or to both.
- **Carbon Storage:** This is mainly relevant to paper recycling and composting since these processes can change carbon sequestration and storage. *Carbon storage is the prevention of the release of carbon to the atmosphere. In the context of WARM, this storage can occur in living trees, in undecomposed biogenic organic matter (wood, paper, yard trimmings, food waste) in landfills, or in undecomposed biogenic organic matter in soils due to compost or digestate amendment* (US EPA, 2019b, p.21). Recycling and source reduction of paper increase carbon storage since they reduce the need for tree harvesting compared to a "business as usual" baseline. Corrugated containers, magazines and office paper are modelled as chemical pulp papers, which means that they require more pulpwood harvest (per ton of paper) than mechanical pulp papers (US EPA, 2019b).

All of the values regarding the components described above for all of the relevant recyclable materials are listed in table 7.3. Note that the original emission factors are measured per short ton of recycled material but have been converted to be used with metric tons instead. A more visual representation of the modelled life cycle of plastics that is used to calculate recycling emission factors is included in figure 7.3. Note that transportation and sorting are also included in this figure.

Material	Loop	Process Energy Credit	Transport Energy Credit	Process Non-Energy Credit	Forest Carbon Storage	Total Recycling Emission Factor
Aluminium Cans	C	-5.92	-0.04	-4.10	0.00	-10.06
Steel Cans	C	-1.97	-0.04	0.00	0.00	-2.02
Glass	C	-0.13	-0.02	-0.15	0.00	-0.31
HDPE	C	-0.80	0.01	-0.19	0.00	-0.98
PET	C	-1.00	0.12	-0.37	0.00	-1.26
PET (return supplier)	C	-1.00	0.11	-0.37	0.00	-1.27
Corrugated Containers	O+C	-0.02	-0.06	-0.01	-3.37	-3.46
Magazines/Third-Class Mail	C	-0.01	0.00	0.00	-3.37	-3.38
Office Paper	C	0.23	0.00	-0.02	-3.37	-3.16
Mixed Paper (general)	O	-0.42	-0.12	-0.01	-3.37	-3.92
Mixed Plastics	C	-0.93	0.08	-0.31	0.00	-1.16

Negative emission factor: net emissions saving, positive factor: net emissions generation

Table 7.3: Emission factors for recycling in TCO_2E/ton of material recovered (US EPA, 2019d), see main text for definitions

From table 7.3, it can be concluded that aluminium recycling has a very high (negative) emission factor which means that aluminium recycling has major environmental benefits over the manufacturing of aluminium from virgin inputs. These benefits are also present for all of the other recyclable materials although to a lesser degree. Paper recycling also has major benefits which are mainly caused by the increased forest carbon storage compared to paper manufacturing from virgin inputs.

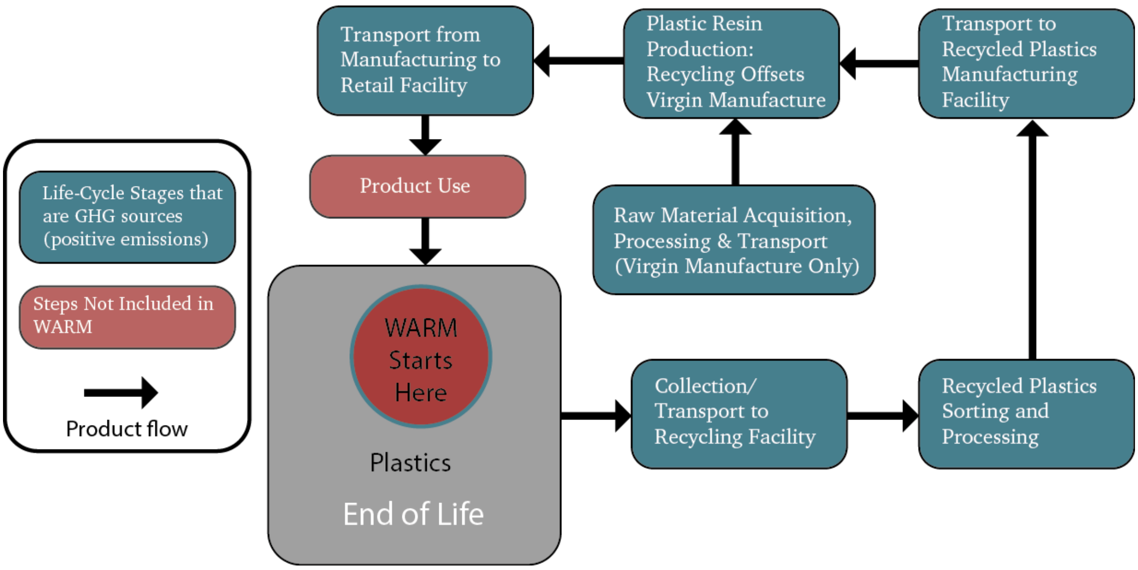

Figure 7.3: Life Cycle of Plastics that are being recycled in WARM (adaptation of US EPA (2019c))

Composting

Composting refers to the microbial decomposition of organic waste in the presence of oxygen as described in section 4.4.2. The net emissions of composting, as modelled in WARM, consist of the following components (US EPA, 2019d, p.33):

1. *Collecting and transporting the organic materials to the central composting site.*
2. *Mechanical turning of the compost pile.*

3. *Non-CO_2 GHG emissions during composting (primarily CH_4 and N_2O).* These are also referred to as fugitive emissions.
4. *Storage of carbon after compost application to soils.*

Note that the biogenic CO_2 emissions that result from composting are not modelled for the reasons mentioned in section 7.1.1. The emissions of the first two components have been quantified in the section about transport (section 7.1.3). The fugitive emissions that are generated during the composting process are dependent upon many local factors including aeration, compost density, frequency of turning, temperature etc. WARM assumes a windrow pile composting facility with a 12 week composting time for estimating fugitive emissions (US EPA, 2019d). This is a very average type of composting. Methane emissions form the largest share of fugitive emissions while nitrous oxide emission quantities are approximately half as large. The sum of both emission types for different organic materials (expressed in TCO_2E's per ton of material composted) can be found in the third column of table 7.4. Finally, the carbon storage resulting from the application of compost to soils (column 4 in table 7.4) has also been included in the net GHG emission of composting. This factor actually compensates for transport and fugitive emission. The modelling of additional soil carbon storage due to composting is very complex and US EPA (2019d) ran more than 30 scenarios in the peer-reviewed Century Soil Model with varied parameters to be able to obtain a robust estimator. Since the soil carbon storage that is added by the application of compost declines in time, WARM only assumes the added soil carbon storage that is still present 10 years after the single application of an average amount of compost of 45 tons per hectare. The final net carbon storage value results from two mechanisms namely the direct storage of carbon in depleted soils and the carbon stored in non-reactive humus compounds (US EPA, 2019d). The net GHG emissions factor for composting, which is calculated using formula 7.2, is displayed in the rightmost column of table 7.4, it is the sum of all of the components described earlier.

$$\begin{aligned}\text{Composting Emission Factor}(\text{TCO}_2\text{E/ton of material recovered}) = \text{Transport Emissions}+ \\ \text{Fugitive Emissions} + \text{Soil Carbon Storage}\end{aligned} \tag{7.2}$$

Material	**Transport Emissions**	**Fugitive Emissions**	**Soil Carbon Storage**	**Net GHG Emissions**
Food Waste (local composting)	0.00	0.05	-0.26	-0.21
Grass	0.02	0.08	-0.26	-0.16
Leaves	0.02	0.08	-0.26	-0.16
Branches	0.02	0.08	-0.26	-0.16

Negative emission factor: net emissions saving, positive factor: net emissions generation

Table 7.4: Emission factors for composting in TCO_2E/ton of material composted (US EPA, 2019d)

As one can see in the table, the local composting of food waste results in the lowest quantity of net GHG emissions. Note that the local composting of food waste is not originally included in the WARM Model but has been added by assuming zero transport emissions for the (central) composting of food waste.

Anaerobic Digestion (Biogasification)

Anaerobic digestion or biogasification refers to the microbial decomposition of organic waste in a reactor in the absence of oxygen as described in section 4.4.2. This treatment method is only applied to food waste within the context of theme park waste. Although anaerobic digestion can also be applied to garden waste, this is not very common. Food waste has a much higher biogas potential (biogas production per ton) than garden waste (Agentschap NL, 2013). The net emissions of anaerobic digestion, as modelled in WARM, consist of the following components (US EPA, 2019a):

1. *Collecting and transporting the organic materials to the biogasification facility, transporting the final digestate for land application and operating on-site transport equipment.*

2. *Process Energy: Emissions from preprocessing feedstock and curing the digestate.*
3. *Avoided utility GHG emissions from producing electricity using the combustion of biogas (methane).*
4. *Avoided fertilizer application by displacing fertilizer with digestate.*
5. *Storage of carbon after digestate application to soils.*
6. *Process Non-Energy: CH_4 and N_2O emissions during the curing process and after land application. These are also referred to as fugitive emissions.*

The emissions of the first component have been quantified in the transport section (section 7.1.3). The emissions of all of the other components are dependent on the type of anaerobic digestion that is applied. WARM is able to model dry and wet digestion with or without digestate curing. In this case, wet digestion with digestate curing is assumed as this is applicable to the Efteling case. Process energy emissions include grinding, screening, mixing and dewatering (electric) energy emissions (US EPA, 2019d). It also includes emissions needed for curing the final digestate in turned windrows to stabilize it. After this, the digestate can be applied as fertilizer which offsets the use of synthetic fertilizer. This results in Nitrogen and Phosphorous offsets which saves GHG emissions. The effect of synthethic fertilizer offsets are not modelled for composting as compost from garden waste is way less nutrient-rich and presumable incapable of replacing synthetic fertilizer as opposed to digestate from food waste (US EPA, 2019d). Just like compost, the application of digestate to land also results in additional soil carbon storage. This is modelled similarly to composting. However, the soil carbon storage resulting from garden waste compost is relatively larger than that resulting from food waste digestate as its solids content is higher (US EPA, 2019d). Additionally, the fugitive emissions (process non-energy) that occur during anaerobic digestion and after the application of digestate to land are relatively high compared to garden waste compost as food waste contains more nitrogen and emits more N_2O which has a very high GWP. On the other hand, anaerobic digestion generates methane biogas which is collected and combusted to produce electricity and heat. This is the main emissions offset component for anaerobic digestion.

The default WARM model only takes electricity generation resulting from methane biogas combustion into account when calculating avoided utility GHG emissions. However, in the Netherlands the warmth that is generated through the same combustion process is also used to offset utility GHG emissions in many cases (Agentschap NL, 2013). This warmth may be exported to third parties to replace natural gas combustion. Therefore, this form of energy recovery has been added to the adapted model that is used in this report. It is captured in the the avoided utility GHG emissions factor as reported in table 7.5. The calculation of this factor is explained in table E.2 of appendix E. It is taken into account that only 23% of the generated warmth is applied for useful purposes (Agentschap NL, 2013). Whereas the exclusion of warmth recovery in the default WARM model causes an underestimation of the benefits of anaerobic digestion, the used electric energy mix causes an overestimation of its benefits. This overestimation is caused by the average emissions factor for delivered electricity that is used in the default model. This factor is 0.221 TCO_2E per million Btu or 0.754 TCO_2E per megawatt hour (MWh). Since this factor is only representative of electricity production in the US, it has been changed to 0.30 TCO_2E/MWh which represents dutch electricity production in 2020 (PBL, 2019). Note that the factor becomes lower if a larger share of electricity is produced from renewable sources as these have a way lower emission rate per MWh. It is this lower rate that is (theoretically) being offset by energy from anaerobic digestion. All of the factors mentioned above are summarized in table 7.5. The net GHG emissions factor for anaerobic digestion is the sum of these factors (see formula 7.3).

$$\begin{aligned}\text{Anaerobic Digestion Emission Factor}(TCO_2E/\text{ton of material recovered}) = {} & \text{Transport Emissions} + \\ & \text{Process Energy Emissions} + \text{Avoided Utility GHG Emissions} + \\ & \text{Avoided Fertilizer Application} + \text{Soil Carbon Storage} + \\ & \text{Process Non-Energy Emissions}\end{aligned} \tag{7.3}$$

Material	**Transport Emissions**	**Process Energy**	**Avoided Utility GHG Emissions**	**Avoided Fertilizer Application**	**Soil Carbon Storage**	**Process Non-Energy**	**Net GHG Emissions**
Food Waste	0.00	0.01	-0.11	-0.02	-0.03	0.11	-0.04

Negative emission factor: net emissions saving, positive factor: net emissions generation

Table 7.5: Emission factors for anaerobic digestion in TCO_2E/ton of material digested (US EPA, 2019d)

Incineration

Incineration refers to mass-burn incineration with energy recovery as described in section 4.4.3. This means that no materials of the (mixed) waste stream headed for incineration are recovered prior to incineration. Incineration results in significant emissions of CO_2 and N_2O. The net emissions of waste incineration, as modelled in WARM, consist of the following components (US EPA, 2019d, p.51):

1. *Emissions from the transportation of waste to a combustion facility.*
2. *Emissions of non-biogenic CO_2.*
3. *Emissions of N_2O.*
4. *Avoided GHG emissions from the electric utility sector.*
5. *Avoided GHG emissions due to recovery and recycling of metals at the combustor.*

Component 1 has been addressed in section 7.1.3. Component 2 in the model is derived from the carbon content of the different WARM materials, which follows from their molecular formula. For plastics, it is assumed that all of this carbon is non-biogenic while paper and food waste only contain biogenic carbon. The carbon content is subsequently converted to CO_2 emissions by multiplying it with 44/12 (the molar mass of CO_2 divided by the molar mass of carbon) and assuming an oxidation factor of 98% (US EPA, 2019c). Component 3, N_2O emissions, are assumed to amount to 0,04 TCO_2E per ton of mixed MSW, as found by IPCC (2006, 2007). Since there are no N_2O values for individual components of MSW, WARM uses 0.04 as a proxy for all components of MSW except those that do no contain nitrogen. The latter applies to aluminium an steel cans, glass and plastics (US EPA, 2019d). The sum of the first three components is referred to as the 'gross GHG emissions', this number measured per ton of material combusted is listed in the second column of table 7.6.

The avoided GHG emissions from the electric utility sector (component 4) compensate for the gross GHG emissions of waste incineration by displacing some of the CO_2 emissions that were otherwise necessary to produce electric energy. Note that waste incineration plants may also export steam as a useful product but this is not modelled in WARM. Three data elements are used to estimate avoided electric utility GHG emissions in WARM namely: the energy content of each separate waste material considered, the incineration system efficiency in converting energy in waste to delivered electricity and the electric utility CO_2 emissions avoided per kilowatt-hour delivered (US EPA, 2019d). The energy contents of different waste materials are listed in US EPA (2019d), these are generally lower for organic materials (with higher moisture contents) and higher for plastics and papers. The incineration system efficiency with respect to delivering electricity has a default value of 17.8% based on several (American) sources described in US EPA (2019d). This efficiency reflects losses in converting waste energy content into steam, converting steam into electricity and delivering electricity. The default efficiency value has been increased to 20.3% which is the average electricity generation efficiency of the Dutch incineration plants that treat residual waste of the Efteling (CE Delft, 2010). Finally, WARM uses a factor of 0.221 TCO_2E per million Btu of electricity delivered for avoided utility emissions. This is equivalent to 0.754 TCO_2E per megawatt hour (MWh). Since this factor is specific to the electricity grid of the US, this factor has been changed to 0.30 TCO_2E per megawatt hour (MWh), which is the factor for the Netherlands in 2020 (PBL, 2019). This factor is based on the Dutch electricity mix in 2020 with an expected share of 25.5% of wind and solar energy [1]. The emission factor for electricity production is way lower for the Netherlands compared to the US because the US has a lower share of renewable energy production (EIA, 2019). The calculations of the avoided electric utility emissions per ton of material combusted are provided in table E.3 of appendix E. The results are listed in the third column of table 7.6 below. Note that the factors for aluminium and steel cans are negative because you actually have to add energy to heat these materials to the temperature typically found in a combustor (750°Celsius) (US EPA, 2019d).

The final component of the net emissions of waste incineration consists of the avoided GHG emissions due to metal recycling. By default, this only applies to steel cans and mixed MSW. Based on data, it is assumed that 90% of the steel that is being incinerated as part of mixed waste streams can be recovered (US EPA, 2019d). The resulting weight of steel recovered is subsequently multiplied by the total recycling emission factor of steel (cans) as listed in table 7.3. The recovery of non-ferrous metals (aluminium) is not modelled by default due to a lack of data (US EPA, 2019d) although this happens in many modern facilities. Since aluminium recovery

[1] In 2019, the realised production share of wind and solar energy in the Netherlands was 14% (CBS, 2019b). In 2020, two new wind parks at sea will be put into operation which may lead to the realisation of the projected share of wind and solar energy for 2020.

happens at all of the incineration plants that treat residual waste of the Efteling, it has been added to the adapted model. It is modelled in the same way as steel recycling, the recovery efficiency (75% based on CE Delft (2010)) is multiplied by the total recycling emission factor of aluminium cans as listed in table 7.3. The final avoided emissions numbers due to metal recovery (if applicable) can be found in the fourth column of table 7.6. For mixed MSW, the average weight of steel recovered per ton of combusted mixed MSW (0.02) times the total recycling emission factor is assumed as a factor (US EPA, 2019d).

$$\text{Incineration Emission Factor}(TCO_2E\text{/ton of material recovered}) = \text{Gross GHG Emissions}+ \\ \text{Avoided Utility GHG Emissions} + \text{Avoided emissions due to metal recovery} \tag{7.4}$$

Material	**Gross GHG Emissions**	**Avoided Utility GHG Emissions**	**Avoided CO_2 emissions due to metal recovery**	**Net GHG Emissions**
Aluminium Cans	0.02	0.01	-7.55	-7.52
Steel Cans	0.02	0.01	-1.79	-1.76
HDPE	3.10	-0.79	0.00	2.31
PET	2.27	-0.42	0.00	1.85
Corrugated Containers	0.07	-0.28	0.00	-0.21
Food Waste	0.07	-0.09	0.00	-0.03
Mixed Paper (general)	0.07	-0.28	0.00	-0.21
Mixed Plastics	2.59	-0.56	0.00	2.03
Mixed MSW	0.49	-0.20	-0.04	0.25

Negative emission factor: net emissions saving, positive factor: net emissions generation

Table 7.6: Emission factors for incineration with energy recovery in TCO_2E/ton of material combusted (US EPA, 2019d)

7.2 Economic Assessment

The economic assessment calculates the economic impact (in terms of business economic costs) of the theme park SWM system and possible alternative theme park SWM strategies. Note that all of the costs are converted to a cost amount per year. The same SWM system boundaries as those for the LCA are utilized for this, as can be seen in figure 7.2. Three cost components are distinguished in the analysis, the sum of these determines the total economic costs of a certain system. The components are: collection, transportation and treatment costs. These components are in line with the actual cost elements that were identified in chapter 4. Note that MRF sorting costs, if applicable, are mostly captured in treatment costs. The composition and calculation of the different cost components will be discussed one by one in separate sections.

Every cost component is also calculated (for the case study) in a separate spreadsheet. These spreadsheets are not included in this public version of the report because they contain confidential information.

7.2.1 Collection

The costs of collecting waste consists of costs for the exploitation of bins and collection facilities and the maintenance of these facilities as mentioned in chapter 4. The collection costs are further divided into the purchase costs of collection facilities, the rent of collection facilities and the maintenance of collection facilities. In case of the purchase of collection facilities, the purchase price is divided by 10 or 20 to come to a price per year, assuming linear depreciation. The 10 year linear depreciation period is applicable to containers and based on the standard depreciation time for containers as listed by (among others) Gemeente Heerde (2017) and Gemeente Nieuwkoop (2017). The 20 year depreciation period is applicable to cocoons as these are built using more durable materials and last longer in practice.

The quantities of containers that are necessary in the current strategy are mostly derived from the registered numbers of containers in the park at all locations. In the current strategy, only containers for 'dirty' types of waste such as residual waste and PMD are being cleaned on a regular basis. This happens on-site. Cleaning for

for paper, glass, PET bottle and cups containers is not deemed necessary as these waste types are relatively free off smelly and wet substances. Swill containers are also cleaned but this is included in the transport price as swill containers are cleaned off-site. For these reasons, it is assumed that for alternative strategies, only residual waste, PMD and plastic containers have to be cleaned on-site. Plastic containers have also been included because it is expected that they will contain a waste composition similar to that of PMD containers.

Finally, for estimating the quantities of containers that are necessary in alternative strategies, formulas 7.5, 7.6 and 7.7 are used. Formula 7.5 is used to calculate the number of containers necessary to separately collect an alternative waste fraction (other than residual waste) in BTS areas. In this case, it is applied to calculate the number of 1100 liter PMD containers necessary in strategy 2-8 which involve seperate BTS PMD collection. All three formulas use the composition of residual waste, as found by the sorting tests described in section 4.2, to determine how much containers are needed to separately collect a certain fraction within that residual waste. Furthermore, the formulas also use the density of residual waste and the density of the alternative waste fraction(s) (to be separated) since the number of necessary containers is ultimately dependent on the volume of the collected waste stream. The used densities are based on Stichting Stimular (2020) and are listed in table F.1 (appendix F). Lastly, the difference in emptying frequency (relative to that of residual waste) is also used to determine the extend to which more ore less containers are needed to store waste until the next emptying turn. Formula 7.6 is used to calculate the decreased number of residual waste containers that are still necessary in case one or more alternative waste fractions are collected separately in PSP areas. The only residual waste container quantity that is not calculated using this formula is the quantity of 1100 liter residual waste containers. These are assumed to be substituted by 1100 liter PMD containers in strategies 2-8. This means that every new 1100 liter PMD container replaces one 1100 liter residual waste container. Finally, formula 7.7 is used to calculate the number of containers necessary to separately collect an alternative waste fraction (other than residual waste) in PSP areas (relevant to strategy 3-8).

$$\text{No. containers needed for alternative BTS collection} = RWCs \times SAFinBTS \times \frac{RWdens}{AFdens} \times \frac{RWemptyfreq}{AFemptyfreq} \tag{7.5}$$

Where

$RWCs$	: Number of current residual waste containers meant for BTS collection (similar size)
$SAFinBTS$	: Share of alternative waste fraction in BTS residual waste (by weight, e.g. 0.43)
$RWdens$	: Density of residual waste (default: 150 kg/m^3 (Stichting Stimular, 2020))
$AFdens$	: Density of alternative waste fraction (kg/m^3)
$RWemptyfreq$	: Current emptying frequency of residual waste (default: 7x per week)
$AFemptyfreq$	: Intended emptying frequency of alternative waste fraction

$$\text{No. residual waste containers needed for PSP collection} = PSPcollectspots + RWRCs \times (1 - \sum_{AF=1}^{N} (SAFinPSP \times \frac{RWdens}{AFdens})) \tag{7.6}$$

Where

$PSPcollectspots$	: Number of spots (or cocoons) for waste collection in PSP areas (Efteling: 333)
$RWRCs$	: Number of current reserve residual waste containers meant for PSP collection (reserve containers are used to replace full PSP containers in between emptying turns)
AF	: Alternative waste fraction (other than residual waste) to be separated
N	: Total number of alternative waste fractions (other than residual waste) to be separated
$SAFinPSP$	: Share of alternative waste fraction (to be collected separately) in PSP residual waste (by weight, e.g. 0.43)
$RWdens$	: Density of residual waste (default: 150 kg/m^3 (Stichting Stimular, 2020))
$AFdens$	: Density of alternative waste fraction (kg/m^3)

$$\text{No. containers needed for alternative PSP collection} = currentAFCs + PSPcollectspots + (RWRCs \times SAFinPSP \times \frac{RWdens}{AFdens} \times \frac{RWemptyfreq}{AFemptyfreq}) \tag{7.7}$$

Where

$currentAFCs$	: Current number of containers for separate collection of alternative waste fraction (default: 0)
$PSPcollectspots$	: Number of spots (or cocoons) for waste collection in PSP areas (Efteling: 333)
$RWRCs$	: Number of current reserve residual waste containers meant for PSP collection (reserve containers are used to replace full PSP containers in between emptying turns)
$SAFinPSP$	: Share of alternative waste fraction in PSP residual waste (by weight, e.g. 0.43)
$RWdens$	: Density of residual waste (default: 150 kg/m^3 (Stichting Stimular, 2020))
$AFdens$	: Density of alternative waste fraction (kg/m^3)
$RWemptyfreq$	: Current emptying frequency of residual waste per week (default: 7x per week)
$AFemptyfreq$	: Intended emptying frequency of alternative waste fraction per week

From the application of the formulas, it can be concluded that nearly all alternative SWM strategies lead to additional operational costs for collection. This is related to the fact that nearly all alternative SWM strategies involve the additional seperate collection of one or more waste fractions that are currently found in residual waste. Especially the cleaning of residual waste, PMD and plastic containers lead to significant additional costs if these containers are used more in a certain strategy.

7.2.2 Transportation

Rransportation costs are divided into costs for decentralized pick up operations, centralized pick up operations (including internal transport to facilitate central pick up) and possible 'return to supplier' transport movements. These different types of (theme park) waste transport are described in section 4.3 of chapter 4. The transport 'quantities' (number of hours, transports etc.) necessary in the current strategy are mostly derived from actual case study data (Renewi, 2020a). The transport quantities necessary in alternative strategies are estimated using formula 7.8. This formula uses the numbers of containers that have been estimated in the previous section using formulas 7.5, 7.6 and/or 7.7. Furthermore, the intended emptying frequency for the alternative waste fraction that was used in the previous section should also be used in this formula. The values of the fixed variables that are used in the formula for the case study at hand, such as 'avgDTRound', are not included in this public version of the report because they are confidential.

Only two transport quantities for alternative strategies are not estimated using formula 7.8. These are the number of transports necessary for PET bottles in strategy 3A and the number of hours necessary for internal transport of PET bottles in strategy 3A. The number of transports is a linear extrapolation of the current number of transports based on the expected increase in separately collected PET bottles (see subsection 7.2.3). The number of internal transport hours is based on a custom calculation. This number is not calculated using formula 7.8 because the route for internal transport differs significantly from the route for decentral pick up operations. Furthermore, there is no preceding data regarding the (average) driving and emptying times for internal transport. These have been estimated instead.

$$\begin{aligned}\text{No. hours needed for alternative waste transport} = &(avgDtRound + (AFCs \times avgEmpttC)) \\ &\times AFemptyfreq \times 52\end{aligned} \tag{7.8}$$

Where

$avgDtRound$	: Average driving time on theme park terrain per round (without stopping)
$AFCs$	: Number of containers for the separate collection of alternative waste fraction (derived from formulas 7.5 and 7.7) or, in case of residual waste, the number of residual waste containers (derived from formula 7.6)
$avgEmpttC$	: Average emptying time per container
$AFemptyfreq$	: Intended emptying frequency of alternative waste fraction per week (should match with AFemptyfreq in formulas 7.5 and 7.7)

From the application of the formulas, it can be concluded that although the number of transport hours for residual waste is reduced in many alternative SWM strategies, these benefits are mostly offset by the additional transport hours that are necessary for the decentral pick up of the separately collected waste fraction(s). Centralized pick up operations are generally less costly than decentralized pick up operations because internal transport (necessary for central pick up) is cheaper. The most economical option is to return waste to its 'supplier'. However, this is only possible in a few strategies.

7.2.3 Treatment

For calculating alternative treatment costs, it is assumed that the total amount of waste remains constant. This means that residual waste is being substituted by separately collected waste types depending on the type of strategy. This substitution is captured by formula 7.9. The possible quantities of separately collected waste fractions in alternative strategies are derived from the sorting tests described in section 4.2.3 (chapter 4). For all 'alternative waste quantities, it is assumed that separate collection happens with a participation rate and separation efficiency of 100%. The effect of changing this percentage will be analyzed in the sensitivity analysis in section 8.5.

$$\text{Alternative residual waste quantity} = CurrentRWQ - AFQ \tag{7.9}$$

Where

$CurrentRWQ$: Current residual waste quantity
AFQ : Total quantity of separately collected fraction(s) in alternative strategy

From the application of the formulas, it can be concluded that the treatment costs in alternative strategies are strongly dependent on the type of waste that is being collected separately. Some waste types such as PET bottles and swill result in a reduction in the total treatment costs while others such as PMD increase the total treatment costs.

7.2.4 Total

The total SWM costs are the sum of the collection, transportation and treatment costs that have been discussed in previous sections. Formula 7.10 provides this summation. The results (total costs per year) for all strategies that have been defined in chapter 6 are not provided in this public version of the report. The costs of each strategy relative to the current strategy (additional costs) will however be discussed in combination with the environmental impact of the different strategies in the next chapter.

$$\text{Total SWM costs (per year)} = \text{Collection costs (p/y)} + \text{Transportation costs (p/y)} + \text{Treatment costs (p/y)} \tag{7.10}$$

7.3 Conclusion Modelling SWM Systems for Semi-Public Spaces

In this chapter, sub research question 4 has been answered. The question was: "*How can the environmental and economic impact of different solid waste management strategies for semi-public spaces be estimated?*"

The environmental impact of a SWM strategy can be estimated using a life cycle assessment (LCA), which is able to inventorize the net greenhouse gas emissions of a SWM strategy. The dedicated SWM LCA model called 'WARM' was found to be most suitable for modelling SWM systems of semi-public spaces due to its transparency and adaptability. The WARM model calculates the environmental impact of a SWM strategy by multiplying the waste quantities that are applicable to that strategy with conversion factors that correspond to the means by which that waste is being treated (including transport). The conversion factors differ per waste material and are listed per treatment type in section 7.1.4. Some factors have been adapted to reflect the actual environmental impact in the Netherlands. The adaptations include modified transportation distances and the incorporation of the Dutch electricity mix.

The economic impact of a SWM strategy can be estimated using an economic assessment that calculates the total yearly costs of the SWM strategy. The total costs consist of collection, transportation and treatment costs. These cost components are separately discussed and calculated in section 7.2. The costs for alternative strategies are calculated using formulas (7.5, 7.6, 7.7, 7.8 and 7.9) that use data about the current waste composition, transport quantities and/or numbers of bins to estimate the quantities of waste, transport and/or bins in alternative strategies. The integrated eco-efficiency analysis framework that includes both the LCA and the economic assessment can be found in figure 7.2.

Chapter 8

Assessing SWM Strategies for the Efteling

In this chapter, the alternative high potential SWM strategies for the Efteling that have been derived in chapter 6 will be assessed based on the KPI's from chapter 5. The calculation of the KPI's is based on the procedures and models described in the previous chapter. First, the WARM model will be calibrated for the Efteling case. The effect of model calibration on the environmental impact of the current strategy is also shown. Secondly, a model validation for this calibrated model is undertaken (section 8.2). After that, the environmental and economic impact of the current SWM strategy of the Efteling are assessed. These current impact numbers will be used as a reference to assess the environmental and/or economic improvement caused by possible alternative strategies. The alternative strategies are assessed in section 8.4. Since some of the parameters that are used to calculate the KPI's of the different SWM strategies are somewhat uncertain, an uncertainty analysis is included in section 8.5.

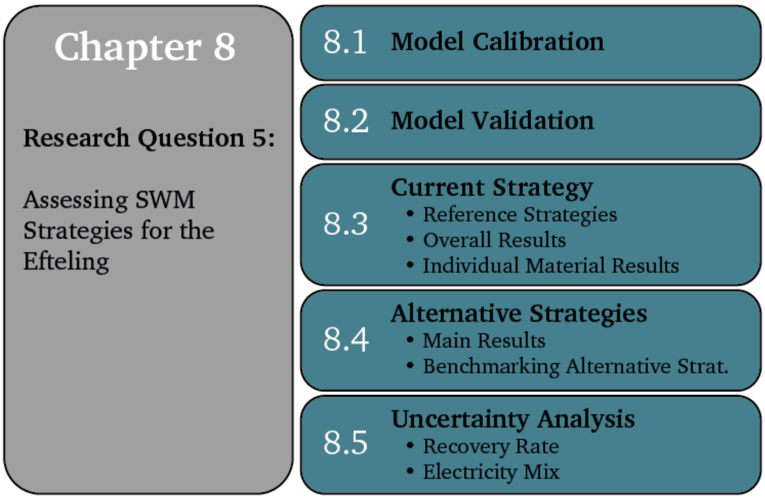

Figure 8.1: Structure of chapter 8

8.1 Model Calibration

As described in chapter 7, several default parameters of the WARM model have been adapted to better reflect the actual conditions in the Netherlands and the conditions applicable to the SWM system of the Efteling. The process of adapting these parameters is also referred to as model calibration. The following adaptations have been made:

- The default transportation distances to material recovery facilities (recycling facilities) have been adapted based on the actual distances that are applicable in the case of the Efteling. These distances are dependent on the type of waste (see table E.1 of appendix E).
- The default transportation distance to an incineration facility has been increased (see table 7.2 of chapter 7).
- Heat generated through the combustion of biogas that is produced from anaerobic digestion is now also used to offset utility greenhouse gas emissions next to electricity (see table E.2 of appendix E).
- The electric energy generation efficiency of waste incineration plants has been increased from 17.8 to 20.3

% based on the actual efficiency of the three Dutch incineration plants that are used to treat waste of the Efteling (CE Delft, 2010).

- The electric energy mix that is used to calculate the greenhouse gas offsets resulting from electricity production by waste incineration and biogas combustion has been adapted to the energy grid in the Netherlands (see tables E.3 and E.2 of appendix E). This results in less GHG offsets per megawatt hour as the energy mix in the Netherlands consists of a higher share of renewable energy production.
- Metal recovery at waste incineration plants has been extended to also include aluminium (non-ferrous metal) recovery. The applied recovery efficiency is the average of the recovery efficiency's of the Dutch incineration plants that treat Efteling waste (based on CE Delft (2010)).

Table 8.1 lists the results of the WARM model for the current strategy using the default parameters and the adapted parameters. In other words, this table shows the effects of model calibration. The amount of avoided emissions caused by the current strategy is lower in the calibrated model since (among others) the environmental benefits of mass-burn incineration have decreased as a result of a more sustainable energy mix (that is being offset by energy recovery from waste) compared to the default model (see also chapter 7). The calibrated results of the current strategy are later used to evaluate the results of alternative strategies that are also assessed using the calibrated model. These results are therefore labelled as the 'main reference strategy' or 'base strategy'.

Model Calibration		Environmental impact	
Description	Model Parameters	Emissions (TCO_2E)	Relative to base (TCO_2E)
Current strategy	Default WARM parameters	-897.44	-165.38
Current strategy	**Adapted WARM parameters**	**-732.06**	**0.00**

Main Reference Strategy (base strategy)

Table 8.1: Results with default parameters and adapted parameters

8.2 Model Validation

Using the results that have been provided in the previous section and the parameters described in chapter 7, a model validation can be undertaken. "*Validation is the task of demonstrating that the model is a reasonable representation of the actual system: that it reproduces system behaviour with enough fidelity to satisfy analysis objectives*" (Hillston, 2003, p.106). In other words, the question is to what extent the model approaches the real impact of (alternative) SWM strategies. This step is mainly considered to be relavant for the environmental LCA that was performed using the WARM model. The economic assessment is much simpler and uses data that is readily available for the processes at hand as opposed to the environmental assessment. Model validation is very difficult in this case as there are, to the best of the author's knowledge, no previous studies into the environmental impact of theme park SWM systems. The closest thing to this are the waste statistics of the Disney theme parks reported in the corporate social responsibility update of The Walt Disney Company (2019). However, these statistics only mention quantities of waste and percentages of waste diverted from landfill and incineration.

This leaves us with one feasible approach to model validation namely expert intuition. According to Hillston (2003, p.107): *the examination of the model should ideally be led by someone other than the modeller, an "expert" with respect to the system, rather than with respect to the model*. In accordance with this statement, two experts were consulted namely:

- **Dr. B.R.P. Steubing**: Assistant professor at the Institute of Environmental Sciences (CML) of Leiden University. Specialized in life cycle assessment modelling and LCI databases.
- **Dr. B. Edens**: Senior statistician and project manager natural capital accounting and valuation of ecosystem services at the United Nations (UN).

These experts were given all of the information in chapter 7 about modelling and documentation about the WARM model. Although they are not familiar with the WARM model, both experts agree on the notion that the Environmental Protection Agency (EPA) who created the model should (in general) be a good source. Furthermore, they have approved of the modifications made to specific parameters of the model to be able to calibrate it (see section 8.1). The experts were also asked about specific conversion factors that were notable with respect to the (individual material) model results (section 8.3.3). This especially concerns the factors for the recycling of paper, which are notably high in relation to other (recycling) factors. The high environmental benefits of paper recycling in the WARM model can be attributed to the increase of forest carbon storage that is assumed. The experts do not agree on this assumption. While one thinks this assumption can be justified if the consumption mix for wood is correct, the other thinks that a forest carbon storage increase is a non-marginal change and thus not appropriate in a LCA. The impact that the forest carbon storage parameter may have on the results is further analyzed in section 8.5 (uncertainty analysis). This point will also be further discussed in the discussion section.

8.3 Current Strategy

This section contains the assessment results for the current SWM strategy of the Efteling. First, a frame of reference is provided by listing the results of several 'extreme' reference strategies next to the current strategy. Secondly, the overall results in terms of the net and gross emissions (global warming potential) and costs of the current strategy are provided. Finally, the individual material results are shown. More specifically, this concerns the individual environmental impact of all of the materials that are part of the total yearly waste stream of the Efteling.

8.3.1 Reference Strategies

To provide a good frame of reference for assessing SWM strategies, several 'reference strategy' KPI's have been calculated and included in this section. All of these 'reference strategies' manage the same total amount and composition of waste, namely the yearly waste of the Efteling theme park.

The default parameters of the WARM model are used to compare the GWP of the current strategy with alternative strategies in which the same amount of waste is hypothetically treated with greatly different means of treatment. These results are listed in table 8.2. The default parameters are used because landfilling cannot be properly calibrated to the SWM system at hand since it is not used as treatment method in the Netherlands (Rijkswaterstaat, 2020a). The theoretical strategy that would result in a GWP of 0 TCO_2E's is a strategy in which collected waste is not transported nor treated or sorted. Furthermore, the waste in this theoretical reference is not allowed to decay as this would result in emissions to air, water and land. Relative to the 'zero strategy', the current strategy in which residual waste is incinerated and separately collected waste types are recycled, composted or anaerobically digested results in a GWP of -897.44 TCO_2E's under the default parameters. The negative GWP is caused by the benefits of recycling, composting and anaerobic digestion and by the recovery of energy from waste combustion as described in chapter 7.

Reference Strategies - Default parameters		Environmental impact	
Description	Model Parameters	Emissions (TCO_2E)	Relative to current (TCO_2E)
Do nothing and assume no decay (theoretical)	Default WARM parameters	0	897,44
Current strategy	Default WARM parameters	-897,44	0
All waste to landfill	Default WARM parameters	276,75	1174,19
All waste to mass-burn incineration	Default WARM parameters	-188,64	708,8

Table 8.2: Results for different reference strategies with default parameters

8.3.2 Overall results

Table 8.3 lists the overall results for the current SWM strategy of the Efteling. The economic cost value of the current strategy is not visible because it is confidential. The environmental impact is provided in terms of the net GHG emissions, gross GHG emissions and CO_2-only emissions resulting from the current strategy. The difference between these can be illustrated by figure 7.2. The net GHG emissions are the sum of all of the SWM system exchanges with all GHG sources and sinks. In other words, net emissions include emission offsets by the generation of secondary materials, biomass, compost, electricity and heat. Gross emissions do not include emission offsets, these only consist of (direct) process, non-process and transportation emissions. Therefore, SWM gross emission numbers are higher compared to net emission numbers. The net GHG emissions number is most representative of the total environmental impact of the current strategy. The gross GHG emissions and CO_2-only emissions are not considered to be life cycle environmental impacts in line with ISO (2006). The gross emissions and CO_2-only emissions are provided to give readers the opportunity to compare the gross and CO_2-only emissions of the SWM system with emission numbers of a similar kind of other systems such as the energy system and the transportation system.

Overall Results		Environmental impact		Economic Impact	Eco-efficiency
Description	*Model Parameters*	*Emissions (TCO_2E)*	*Relative to base (TCO_2E)*	*Yearly Operational costs*	*kg CO_2E saving/€*
Current strategy	**Adapted WARM parameters**	**-732.06**	**0.00**	[redacted]	**0.00**
Current strategy (only CO_2)	*Adapted WARM parameters*	*-718.14*	*13.92*		
Current strategy (gross emissions)	*Only gross emissions*	*1117.24*	*1849.30*		

Main Reference Strategy (base strategy)

Table 8.3: Overall results for current strategy (net, gross and CO_2-only)

8.3.3 Individual Material Results

The detailed (individual material) impact results of the current SWM strategy are not provided in this version of the report because they are confidential. However, some general remarks can be given. Residual waste (which is incinerated) results in quite some positive CO_2E emissions coming from different materials within that residual waste while materials that are being recycled do offset a lot of these emissions. Materials in the latter category mostly show negative emission numbers. Fractions within residual waste that cause a high share of emissions are plastic packaging, PET bottles and non-sortable residual waste. The impact of cans and paper is limited because of metal recovery from incinerator bottom ash and because of the biogenic character of paper. Waste types that are being recycled or biologically treated and that contribute a lot to reducing the overall emissions of the SWM system are paper and garden waste. This is mostly due to the large quantities in which these waste types are being recycled/composted.

8.4 Alternative Strategies

This section contains the assessment results for the alternative SWM strategies for the Efteling. First, the main results are presented and analyzed. After that, the results are benchmarked against sustainability measures in other sectors.

8.4.1 Main Results

This section lists and analyzes the assessment results, in terms of environmental and economic impact, of the alternative strategies that have been designed for the Efteling in chapter 6. The results can be found in tables 8.4 and 8.5 and are also visualised in figure 8.2. The main results are listed in table 8.4 whereas the results for strategies that rely on a 'return to supplier' transport scheme are listed in table 8.5. The latter strategy results have been separated because 'return to supplier' strategies cannot be implemented unilaterally by the theme park (as described in chapter 6). These strategies may actually be cheaper than the current strategy but their implementation is dependent on external (political) factors. The possible lower-than-current costs of the 'return to supplier' strategies may also cause confusion when presented along with the other strategies because they result in negative eco-efficiency KPI values. Furthermore, it should also be noted that all of the results in this section assume a recovery rate of 100%. This means that the waste types that are being separated and recycled in certain strategies are recovered from residual waste with an efficiency of 100%. The impact of assuming lower recovery rates is analyzed in section 8.5.1.

Strategy 1A is the current strategy and therefore has the same results as those presented in the previous section. All of the other (alternative) strategies result in less GHG emissions, and thus in a more positive environmental impact, compared to the current strategy, just as they were designed to. The environmental impact in tables 8.4 and 8.5 is presented relative to the current strategy. The economic impact of every strategy, which is measured in yearly operational costs, is also presented relative to the current strategy. The two eco-efficiency KPI's that have been described in section 5.3.1 (chapter 5) are reported in the columns on the right side. The rightmost column contains a ranking of the alternative strategies based on their eco-efficiency. The absolute environmental impact of the strategies, as reported by the WARM model (relative to the theoretical 'do nothing' reference point), is not provided in this public version of the report. The same goes for the absolute economic impact of every strategy in terms of yearly operational costs.

Strategy		PSP Collection		BTS Collection	Transport & Treatment	Environmental Impact	Economic Impact		Eco-efficiency			
#	sub	*Fractions **	*Manual sort*	*Fractions ***	*Alteration relative to current strategy*	*Relative to base (TCO $_2$E/year)*	*Relative to base (€/year)*		*kg CO $_2$E saving / €*	*€ / TCO $_2$E saving*		Rank
1	A		*PET bottles*			*0.00*	€	-	**0.00**	€	-	-
2	A		*PET bottles*	*PMD*		*-189.21*	€	*9,730*	**19.45**	€	**51.43**	*2*
3	A	*PET bottles*		*PMD*		*-496.17*	€	*19,311*	**25.69**	€	**38.92**	*1*
4		*PMD*		*PMD*		*-797.45*	€	*110,445*	**7.22**	€	**138.50**	*5*
5		*plastic*		*PMD*		*-613.40*	€	*61,590*	**9.96**	€	**100.41**	*4*
6	A	*paper + PMD*		*PMD*		*-957.81*	€	*133,793*	**7.16**	€	**139.69**	*6*
7	A	*swill + PMD*		*PMD*		*-800.18*	€	*279,509*	**2.86**	€	**349.31**	*9*
	B	*swill + PMD*		*PMD*	*Local composting*	*-861.68*	€	*69,878*	**12.33**	€	**81.09**	*3*
8	A	*cups + PMD*		*PMD*	*Cups central pick-up*	*-958.18*	€	*134,021*	**7.15**	€	**139.87**	*7*
	B	*cups + PMD*		*PMD*	*Cups decentral pick-up*	*-958.18*	€	*148,236*	**6.46**	€	**154.71**	*8*

**Residual waste always included*

***Base set always included*

Table 8.4: Results for alternative high potential strategies (recovery rate: 100%)

From table 8.4, it can be concluded that the environmental as well as the economic impact of the alternative strategies differ strongly per strategy. Generally, an increased share of separate collected recyclable materials in BTS as well as PSP areas results in an increasingly low quantity of emissions. At the same time, this generally results in higher yearly operational costs.

Starting with the alternative strategies that have the least economic impact, it can be seen that strategy 2 (BTS PMD collection) already has quite a significant environmental impact. Almost 190 tonnes of CO_2E's can potentially be saved with this on a yearly basis. This corresponds to an increase in yearly avoided SWM system emissions of about 25% for the Efteling case (from a life-cycle perspective). Since it is a relatively 'cheap' strategy, the resulting eco-efficiency of implementing strategy 2 is also quite high. The same goes for strategy 3 (PSP PET collection + BTS PMD collection) which is ranked as the most eco-efficient strategy. Strategy 3 is a bit more expensive than strategy 2 (lower treatment costs as a result of less residual waste but higher collection costs, see table **??**) but it also results in more than double the amount of CO_2E's savings. The B variants of strategies 1,2 and 3 that implement a 'return to supplier' transport scheme for PET bottles do not result in much emission savings but do have a considerable economic impact (see table 8.5). Especially strategy 3B is way cheaper than strategy 3A.

Among the more 'expensive' strategies, the emission savings are between approximately 500 and 1000 tonnes of CO_2E's per year. To indicate the significance of this in a wider context, 1000 tonnes of CO_2 corresponds to the CO_2 sequestered by approximately 40,000 trees over a year of time (WUR et al., 2020). Of the strategies that separately collect a single fraction in PSP areas, PMD collection (strategy 4) is by far the most effective in terms of reducing emissions, followed by plastic and PET bottles. The increases in yearly avoided SWM system emissions are 109%, 84% and 68% respectively. The separate collection of PMD in PSP areas is, in fact, so effective that it results in an environmental impact that is close to the impact of separately collecting two different fractions in PSP areas. However, the separate collection of PMD in PSP areas is also relatively expensive compared to the separate collection of plastic and PET bottles. Additionally, the recovery rate (purity) of PMD may be worse than the purity of PET bottles or plastic. The effect of recovery rate on environmental impact will be analyzed in section 8.5.1.

Among the strategies that implement a collection scheme in which two fractions are separated in PSP areas on top of BTS PMD collection, strategy 8 is able to achieve the highest emission savings. The difference in terms of environmental impact with strategies 6 and 7 is however fairly small. The increase in yearly avoided SWM system emissions ranges between 131% for strategies 6 and 8, and 109% for strategy 7A. Swill (food waste) is shown to only have a minor additional impact on emission savings (Strategy 7A is similar to strategy 4). However, swill does have a considerable economic impact. Especially the difference between strategy 7A and 7B is striking. In the case of implementing strategy 7 (separating PSP swill), local composting is way cheaper than central composting in combination with decentral pick up transport. This also results in a way higher eco-efficiency for strategy 7B relative to strategy 7A. The eco-efficiencies of the other 'two-fraction-strategies' are fairly close to one another. It must be noted that although strategies 2 and 3 have the highest eco-efficiency, these strategies can achieve a maximum amount of CO_2E savings of approximately 200 and 500 tonnes respectively. Other strategies can potentially save more than double this amount but do this against a higher cost per saved kilo of CO_2 equivalent.

Strategy		PSP Collection		BTS Collection	Transport & Treatment	Environmental Impact	Economic Impact	Eco-efficiency	
#	*sub*	*Fractions **	*Manual sort*	*Fractions ***	*Alteration relative to current strategy*	*Relative to base (TCO_2E/year)*	*Relative to base (€/year)*	*kg CO_2E saving / €*	*€ / TCO_2E saving*
1	**B**		*PET bottles*		*PET return supplier*	*-0.16*	*-€ 1,779*	**-0.09**	**€ -11,121**
2	**B**		*PET bottles*	*PMD*	*PET return supplier*	*-189.49*	*€ 7,951*	**23.83**	**€ 41.96**
3	**B**	*PET bottles*		*PMD*	*PET return supplier*	*-497.55*	*€ 5,473*	**90.90**	**€ 11.00**
6	**B**	*paper + PMD*		*PMD*	*Paper return supplier*	*-957.81*	*€ 131,677*	**7.27**	**€ 137.48**

**Residual waste always included*

***Base set always included*

Table 8.5: Results for alternative high potential 'return to supplier' strategies (recovery rate: 100%)

Figure 8.2 visualises the findings above by plotting every strategy on a graph with a horizontal axis that represents emission savings and a vertical axis that represents (additional) costs. This way, every dot can be interpreted as an eco-efficiency indicator. The ideal strategy would be located as low as possible on the far right side. Every strategy is indicated on this graph by a visualisation of waste fractions that are being separated in that strategy as well as by the respective strategy number. Note that only A variants are displayed except for strategy 7B and 8B which are both unilateral and therefore also visualised. Strategy 8A is located on the same spot as strategy 6A. Strategy 7B is indicated by a PMD container and a composting machine. The extra wide PMD container next to strategy 2A refers to the collection of PMD in BTS areas only (where 1100 liter containers are common).

Besides the SWM strategies, two eco-efficiency lines have also been plotted in figure 8.2. Every dot on such a line has the same eco-efficiency. The green line represents the highest eco-efficiency of the (unilateral) SWM strategies that were modelled, namely the eco-efficiency of strategy 3A. Therefore, all of the other strategies are above this line. The red line represents an important eco-efficiency benchmark that will be discussed in the next section. In short, it shows that all SWM strategies, except 7A, are more eco-efficient than electric energy production using Solar PV panels on office buildings.

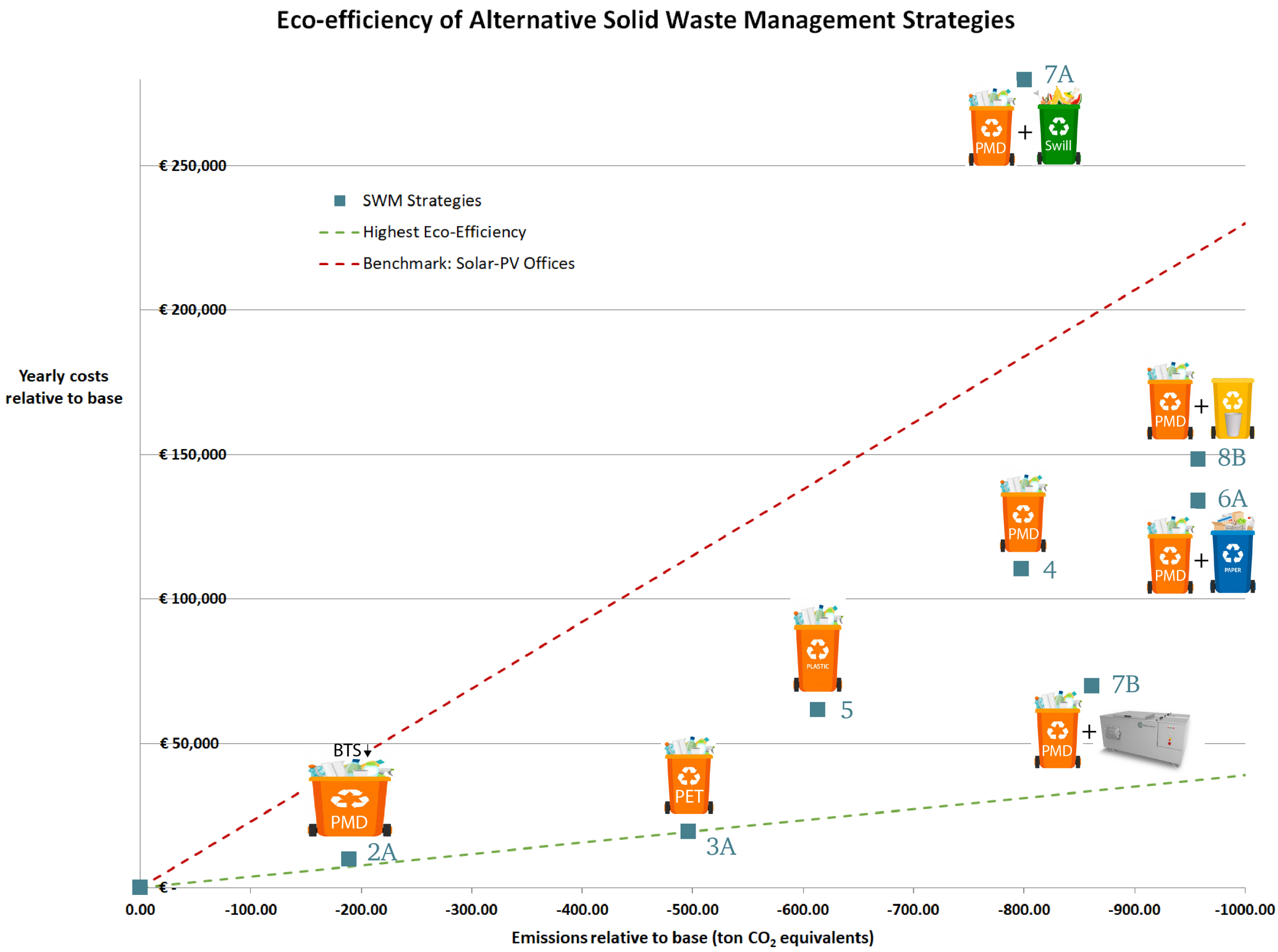

Figure 8.2: Visualisation of environmental and economic impact (eco-efficiency) results of alternative strategies

8.4.2 Benchmarking Alternative Strategies

The eco-efficiency scores that were calculated for every (alternative) strategy in the previous section can be used to benchmark the effectiveness of these strategies. This means that they can be used to compare the effectiveness of these SWM strategies with the effectiveness of other standards in the context of sustainable development. Such standards can be found in other sectors such as the electricity (utility) sector and the built environment sector. Additionally, the price of a European Allowance Credit in the EU Emissions Trading System (ETS) may also be used as a benchmark (reference value). Owning an allowance credit grants a company in the EU the right to emit GHG emissions equivalent to the global warming potential of 1 tonne of CO_2 equivalent (TCO_2E) (European Commission, 2015). The price of allowances is partly determined by politics (cap) and partly by supply and demand in the market (trade) (European Commission, 2015). It is, however, the closest thing to a 'market price' of GHG emissions.

Table 8.6 shows the benchmarking results for the alternative SWM strategies for the Efteling. Every column on the right side of the table represents a different benchmark. Strategies that are more eco-efficient or, in other words, achieve a CO_2E reduction of 1 tonne against lower costs, than the benchmark have a check mark in the corresponding box. As one can see in the table, strategies 2A and 3A perform better than any of the benchmarks except the current price of an EU allowance. This means that these strategies reduce GHG emissions against lower costs than any (listed) means of sustainable electricity production and any (listed) means of sustainable building management. This latter statement is also true for strategy 7b. Strategies 2A and 3A are even more cost-effective (within their emission reduction range) than buying EU allowances for emissions in 2030, assuming the high scenario for allowance prices (CE Delft, 2018). This is remarkable since there are actually many concerns regarding the low price of EU allowances due to the oversupply of allowances

(CE Delft, 2018).

Although many of the other SWM strategies (4, 5, 6, 7 etc.) are more expensive than EU allowances (per ton CO_2E) they are generally more eco-efficient than sustainable electricity production from wind at sea and solar PV panels at office buildings. The latter benchmark is also plotted as a line[1] in figure 8.2. Since small-scale (household) sustainable energy production is even more expensive (PBL, 2017), the SWM strategies are also more eco-efficient than these forms of electricity production. A few strategies are even more eco-efficient than nuclear energy and/or solar PV panels at large (industrial) power plants. Measures to reduce GHG emissions in the built environment are generally way less eco-efficient than implementing alternative SWM strategies, as can be seen in table 8.6. The only strategies that perform worse than a majority of the benchmarks are strategies 7A and 8B.

Strat.		PSP Collection		BTS Collection	Transport & Treatment	Eco-efficiency	EU Allowance credit (ETS)		Electric Energy Production				Built Environment	
#	sub	Fractions *	Manual sort	Fractions **	Alteration relative to current strategy	€ / TCO_2E saving	Current price: €29 [1]	High scenario 2030: €55 [2]	Nuclear Energy: €95 [3]	Solar-PV Industrial Scale: €130 [3]	Wind at sea: €140 [3]	Solar-PV Offices: €230 [3]	ATES[4] for offices: €360 [3]	Insulation of offices: €2060 [3]
2	A		PET bottles	PMD		€ 51.43		✔	✔	✔	✔	✔	✔	✔
3	A	PET bottles		PMD		€ 38.92		✔	✔	✔	✔	✔	✔	✔
4		PMD		PMD		€ 138.50					✔	✔	✔	✔
5		plastic		PMD		€ 100.41				✔	✔	✔	✔	✔
6	A	paper + PMD		PMD		€ 139.69					✔	✔	✔	✔
7	A	swill + PMD		PMD		€ 349.31							✔	✔
	B	swill + PMD		PMD	Local composting	€ 81.09			✔	✔	✔	✔	✔	✔
8	A	cups + PMD		PMD	Cups central pick-up	€ 139.87					✔	✔	✔	✔
	B	cups + PMD		PMD	Cups decentral pick-up	€ 154.71						✔	✔	✔

**Residual waste always included*

***Base set always included*

✔ SWM strategy is more eco-efficient than benchmark

[1] EUA price on 15-07-2020 (Ember, 2020)

[2] (CE Delft, 2018)

[3] National costs per ton CO_2 reduction in 2030 (PBL, 2017)

[4] Aquifer thermal energy storage

Table 8.6: Benchmarking results for alternative high potential strategies (recovery rate: 100%)

The results of the benchmarking process indicate that optimizing waste management is generally more cost-effective, in terms of reducing emissions, for theme parks (and semi-public spaces) than investing in sustainable electricity or sustainable buildings.

8.5 Uncertainty Analysis

This section includes an analysis of the most important sources of uncertainty in the modelling process. These uncertainties may influence the results that have been provided in previous sections. Uncertainty in this case mainly concerns parameter uncertainty and uncertainty due to choices (see section 3.5). Table 8.7 includes the (choice) parameters that are described as being uncertain in the WARM documentation or by the model validation experts. Only parameters that are relevant to the materials and processes being modelled in the case study are included.

Table 8.7 lists the used values for each parameter as well as their theoretical minimum and maximum values (based on literature). The impact that the uncertainty range of each parameter can have on the result for strategy 4 has also been calculated. Strategy 4 was chosen as a benchmark because it is considered to be the 'average' strategy among the other strategies that were assessed. Average in this case means that it achieves

[1]Note that this line is an approximation, it may not be completely straight in practice due to economies of scale

average CO_2E emission reductions. Note that the impact on the results of strategy 4 are expressed in terms of the changes in the TCO_2E benefits of strategy 4. These benefits are the difference between the environmental burdens of strategy 4 and the environmental burdens of the current strategy. This approach is consistent with the purpose of WARM to evaluate alternative management practices relative to baseline activities (US EPA, 2019b). In practice, it means that in order to calculate the impact of a minimum or maximum parameter value, this value has to be implemented in the current strategy model as well as in the alternative strategy model.

Using the range between which the TCO_2E benefits of strategy 4 differ as a result of varying a parameter value within its uncertainty range, the relative uncertainty of this parameter can be calculated. This is done using the following formula:

$$\text{Relative Uncertainty} = \frac{(max.\Delta TCO_2E.benefits - min.\Delta TCO_2E.benefits)}{default.TCO_2E.benefits} \times 100 \quad (8.1)$$

Where

- $max.\Delta TCO_2E.benefits$: The maximum increase in TCO_2E benefits that can be achieved using the minimum or maximum parameter value. The increase is measured relative to the 'default' benefits of strategy 4 in this case (797.45 TCO_2E's).
- $min.\Delta TCO_2E.benefits$: The maximum decrease in TCO_2E benefits that can be achieved using the minimum or maximum parameter value. The decrease is measured relative to the 'default' benefits of strategy 4 in this case (797.45 TCO_2E's).
- $default.TCO_2E.benefits$: The TCO_2E benefits of strategy 4 (relative to current strategy) that result from the 'used' parameter value (797.45 TCO_2E's).

Parameter	Unit	Parameter Value				Impact on strategy 4 (TCO2E benefits)		Relative Uncertainty	Ref.
		Min.	*Used*	*Max.*		*Min.*	*Max.*		
Material Recovery Rate	*%*	*40*	*100*	*100*		*-478.52*	*+0.00*	*60.0%*	*(1)*
Electricity mix (electricity generation emission factor)	*TCO_2/MWh*	*0.09*	*0.30*	*0.53*		*-80.29*	*+73.12*	*19.2%*	*(2)*
Emission factor for forest carbon storage resulting from paper recycling	*TCO_2E/short ton recovered*	*-3.06*	*-3.06*	*0.00*		*-178.27*	*+0.00*	*22.4%*	*(3)*
N_2O emission factor for waste incineration (only for materials that contain nitrogen)	*TCO_2E/short ton combusted*	*0.01*	*0.04*	*0.05*		*-1.75*	*+0.58*	*0.3%*	*(4)*

References:

(1) Conservative estimation of the min. recovery rate based on sorting tests of source separated paper and plastic in public space (Bureau Milieu & Werk, 2013)

(2) Based on PBL (2019): default value is 2020 projection, max. value is actual realisation 2015 and min. value is 2030 projection

(3) For the maximum value, increased forest carbon storage is assumed to be a non-marginal change and thus not accounted for as proposed by one of the model validation experts (see section 8.3)

(4) Based on Park et al. (2011): min. value is derived from sample from the Netherlands, max. value is derived from sample from Canada

Table 8.7: Uncertainty analysis of uncertain parameters

The relative uncertainties of the analyzed parameters can be used as an indication for the importance of these parameters in relation to the results. It can be concluded that the material recovery rate is a very important parameter that is also very uncertain. Therefore, this parameter will be further analyzed in section 8.5.1. The electricity mix parameter will also be further analyzed in section 8.5.2 because it is related to time and can be reviewed in this way. The uncertainties are analyzed using a scenario analysis in which different values are assumed for the uncertain parameters. The concept of scenario analysis has been described in section 3.5 of chapter 3.

8.5.1 Recovery Rate

The material recovery rate resulting from (separate) waste collection is a major source of uncertainty. This uncertainty is caused by the influence of psychological factors on waste collection and by a lack of research on separate waste collection in (semi-)public spaces. The concept of material recovery rate, which is related to both the participation rate and the separation efficiency, has been introduced in section 4.2 of chapter 4. The relation between material recovery rate, participation rate and separation efficiency is displayed in formula 8.2 (McDougall et al., 2001).

$$\text{Material Recovery Rate} = \text{Participation Rate} \times \text{Separation Efficiency} \tag{8.2}$$

Where

Participation Rate : Percentage of guests and staff members or locations that participate in separate waste collection

Separation Efficiency : Percentage of material that is correctly sorted and separated (1 - contamination level)

Note that until now, a material recovery rate of 100% has been assumed to calculate the environmental and economic impact of the current and alternative SWM strategies. The material recovery rate applies to both PSP and BTS collected waste. In table 8.8, the environmental effect of assuming a lower recovery rate of 80, 60 or even 40% is shown. In this scenario analysis, the recovery rate parameter is applied to all separately collected waste types. The economic impact of lower recovery rates is not shown as it is unclear what the rejection and inspection costs of separately collected waste streams are. However, it can be said that a waste type that has a lower treatment cost factor than residual waste will cause higher treatment costs when its recovery rate decreases. This is because separately collected waste that is being rejected due to (too much) contamination will be treated as residual waste. The treatment costs for waste types that have a higher treatment cost factor than residual waste will decrease instead.

Strategy		**PSP Collection**		**BTS Collection**	**Transportation & Treatment**	**Emissions relative to base (TCO2E)**			
#	*sub*	*Fractions **	*Manual sort*	*Fractions ***	*Alteration relative to current strategy*	*100% Recovery*	*80% Recovery*	*60% Recovery*	*40% Recovery*
1	A		*PET bottles*			*0.00*	*0.00*	*0.00*	*0.00*
	B		*PET bottles*		*PET return supplier*	*-0.16*	*-0.16*	*-0.16*	*-0.16*
2	A		*PET bottles*	*PMD*		*-189.21*	*-151.34*	*-113.47*	*-75.63*
	B		*PET bottles*	*PMD*	*PET return supplier*	*-189.49*	*-151.57*	*-113.71*	*-75.85*
3	A	*PET bottles*		*PMD*		*-496.17*	*-396.89*	*-297.65*	*-198.41*
	B	*PET bottles*		*PMD*	*PET return supplier*	*-497.55*	*-398.02*	*-298.55*	*-199.07*
4		*PMD*		*PMD*		*-797.45*	*-637.92*	*-478.43*	*-318.93*
5		*plastic*		*PMD*		*-613.40*	*-490.68*	*-368.00*	*-245.31*
6	A	*paper + PMD*		*PMD*		*-957.81*	*-766.21*	*-574.64*	*-383.08*
	B	*paper + PMD*		*PMD*	*Paper return supplier*	*-957.81*	*-766.21*	*-574.64*	*-383.08*
7	A	*swill + PMD*		*PMD*		*-800.18*	*-640.11*	*-480.07*	*-320.03*
	B	*swill + PMD*		*PMD*	*Local composting*	*-861.68*	*-697.89*	*-534.13*	*-370.38*
8	A	*cups + PMD*		*PMD*	*Cups central pick-up*	*-958.18*	*-766.50*	*-574.86*	*-383.22*
	B	*cups + PMD*		*PMD*	*Cups decentral pick-up*	*-958.18*	*-766.50*	*-574.86*	*-383.22*

**Residual waste always included*
***Base set always included*

Table 8.8: Environmental impact results for different material recovery rates

The table reveals that a lower material recovery rate results in less emission reductions and thus in less environmental benefits. However, even with a recovery rate of 40% the emission reductions are still quite significant for many alternative strategies. The absolute impact of recovery rate on emission reductions is highest for strategies that have the highest total emission reduction potential (strategy 4, 6, 7 and 8). A graphical representation of the effect of recovery rate on environmental impact is provided in figure 8.3. In this figure, every bar represents an alternative strategy. The full bar length indicates the full emission reduction potential of a strategy while the color segments indicate the emission reductions for different material recovery rate intervals. The figure can be used to compare the effect of different strategies when you have information about the expected recovery rate of different waste materials.

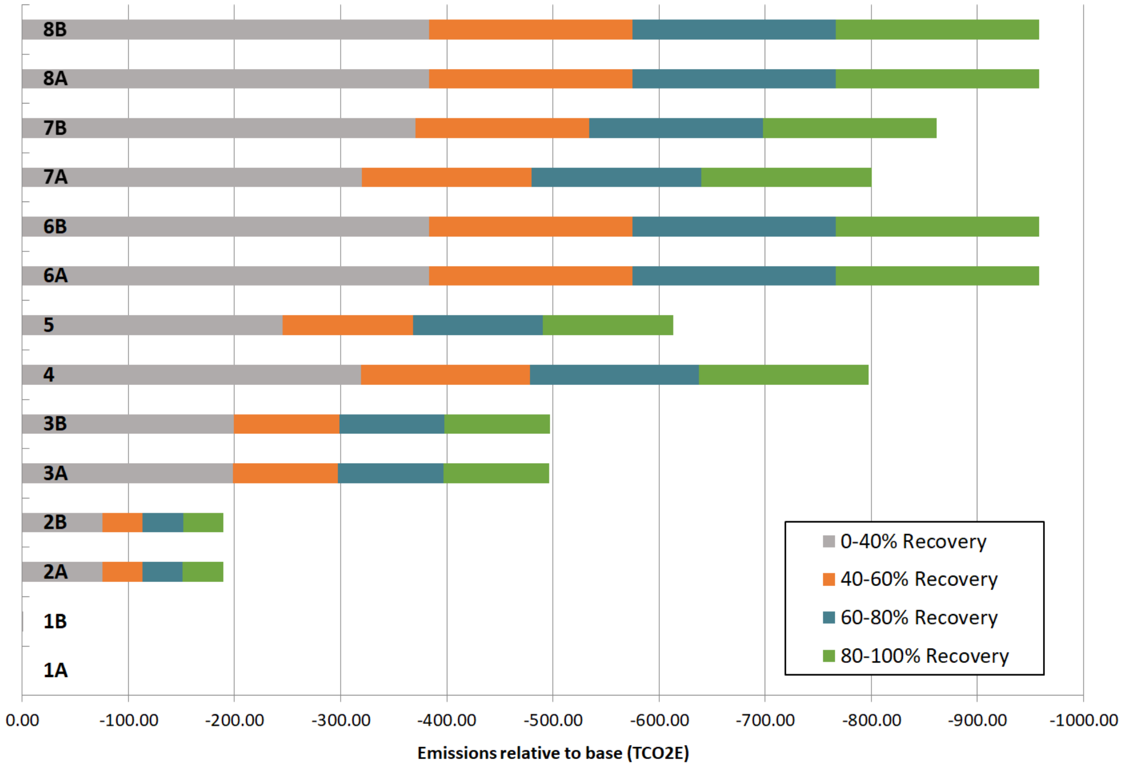

Figure 8.3: Visualisation of environmental impact results for different material recovery rates

From the figure, it can for example be concluded that achieving a material recovery rate of 40% for strategies 3-8 results in more emission reductions than operating strategy 2 with a recovery rate of 100%. Furthermore, it seems that strategies in which two fractions are being separated are equally effective under a recovery rate of 40% than strategies in which one fraction is being separated under a recovery rate of 50 to 60%.

8.5.2 Electricity Mix

Another source of uncertainty that will have effect on the SWM environmental impact results in the future is the electricity consumption mix. The electricity consumption mix entails the set of means by which consumed electricity is being generated. This can for example be a combination of gas-fired power plants, nuclear power plants and wind and solar energy plants. Together, this mix determines the average amount of CO_2 emissions that is necessary to produce electricity. This factor, which can be expressed in TCO_2E/MWh, also determines the environmental compensation benefits of waste incineration plants that recover electric energy from waste. A 'greener' electricity mix that consists of a higher share of renewable sources of electric energy will lower the CO_2E emissions per MWh. This also directly lowers the amount of avoided CO_2E emissions in the electric utility sector that are the result of waste energy recovery. Since an unknown increase in the share of renewable energy sources is expected in the Netherlands over time (PBL, 2019), the electricity mix is a source of uncertainty that is related to time.

As mentioned in section 7.1.4 (under incineration), a factor of 0.30 TCO_2E/MWh has been assumed for calculating the environmental impacts of the SWM strategies. This factor is based on PBL (2019) and is a projection for the current year (2020). This projection has also been extended towards the year 2030 which involves a greater deal of uncertainty. The expected emission factor for 2030 is 0.09 TCO_2E/MWh with a share of 65.5% of wind and solar energy (PBL, 2019). In table 8.9, the environmental impacts of the SWM strategies have been calculated again using this 2030 factor. The results are compared against the 2020 results. According to the table, the emission savings that can be achieved by implementing alternative SWM strategies are expected to increase in the future. The increased benefits differ per strategy. Generally, it can be said that alternative strategies in which more of the total produced waste is being recycled will benefit more from a greener electricity mix. The results are also visualised in figure 8.4.

Strategy		PSP Collection		BTS Collection	Transportation & Treatment	Emissions (TCO2E)		Emissions relative to base (TCO2E)	
#	sub	*Fractions* *	*Manual sort*	*Fractions* **	*Alteration relative to current strategy*	*2020*	*2030*	*2020*	*2030*
1	A		*PET bottles*			-732.06	-542.32	0.00	0.00
	B		*PET bottles*		*PET return supplier*	-732.22	-542.48	-0.16	-0.16
2	A		*PET bottles*	*PMD*		-921.27	-750.88	-189.21	-208.56
	B		*PET bottles*	*PMD*	*PET return supplier*	-921.55	-751.16	-189.49	-208.84
3	A	*PET bottles*		*PMD*		-1228.23	-1087.34	-496.17	-545.02
	B	*PET bottles*		*PMD*	*PET return supplier*	-1229.61	-1088.72	-497.55	-546.40
4		*PMD*		*PMD*		-1529.51	-1412.89	-797.45	-870.57
5		*plastic*		*PMD*		-1345.46	-1219.32	-613.40	-677.00
6	A	*paper + PMD*		*PMD*		-1689.87	-1581.38	-957.81	-1039.06
	B	*paper + PMD*		*PMD*	*Paper return supplier*	-1689.87	-1581.38	-957.81	-1039.06
7	A	*swill + PMD*		*PMD*		-1532.24	-1415.62	-800.18	-873.30
	B	*swill + PMD*		*PMD*	*Local composting*	-1593.74	-1499.73	-861.68	-957.41
8	A	*cups + PMD*		*PMD*	*Cups central pick-up*	-1690.24	-1583.81	-958.18	-1041.49
	B	*cups + PMD*		*PMD*	*Cups decentral pick-up*	-1690.24	-1583.81	-958.18	-1041.49

**Residual waste always included*

***Base set always included*

Table 8.9: Environmental impact results for current and future expected electricity mix

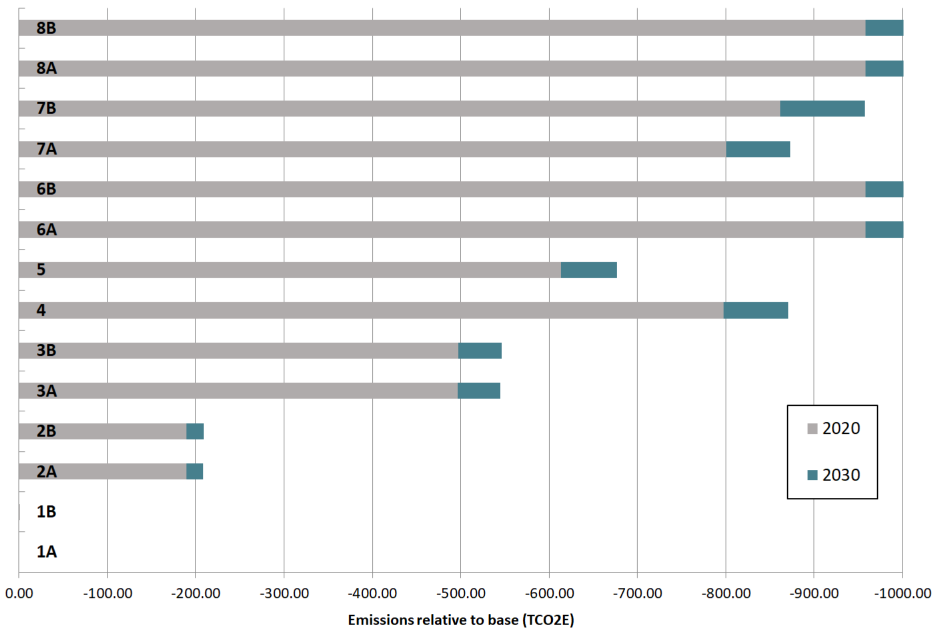

Figure 8.4: Visualisation of environmental impact results for current and future expected electricity mix

It can be argued that a 'greener' electricity mix also influences the recycling emission factors because electricity consumption emissions that occur as a result of the manufacturing processes are incorporated in these factors. However, this effect cannot be quantified because US EPA (2019d) does not contain information about the role that electricity consumption plays in process and non-process emissions. Furthermore, it is expected that the net effect of a changing electricity mix is quite small as recycling emission factors are the result of the difference between virgin and recycled manufacturing which are both similarly affected by a changing electricity mix.

8.6 Conclusion Assessing Efteling SWM Strategies

In this chapter, sub research question 5 has been answered. The question was: "*What is the environmental and economic impact of different strategies to improve the sustainability of solid waste management at the Efteling?*"

To be able to evaluate the environmental and economic impact that the alternative SWM strategies for the Efteling may have, the impact of the current strategy had to be calculated first. The results of this are provided in section 8.3. Table 8.1 shows the effect of calibrating the model that was described in chapter 7 on the impact results of the current strategy. Tables 8.2 and **??** provide a frame of reference for assessing environmental impact numbers. These tables contain impact results for managing the same amount and composition of waste as in the current strategy but with greatly different means of treatment. The overall and individual material results for the current strategy are provided in tables 8.3, **??** and **??**. Next, the environmental and economic impacts of the alternative SWM strategies (defined in chapter 6) were calculated. These are provided in tables 8.4 and 8.5 and visualised in figure 8.2. The impact assessment of the current strategy enables the provision of relative impact numbers for the alternative strategies. The environmental and economic impact of every alternative strategy is also expressed in combined eco-efficiency KPI's.

From the results, it can be concluded that strategies 2 and 3 have the highest eco-efficiency values, closely followed by strategy 7B. These strategies are also relatively cheap to implement. However, similar or higher emission reductions can be achieved with strategies 4 up to and including 8. These strategies greatly differ in terms of yearly operational costs. Of the strategies that separate one fraction from residual waste in PSP areas, strategy 4 (PMD) is by far the most effective in terms of reducing emissions. Strategy 6 and 8 achieve the highest environmental benefits but require the separation of two fractions (PMD + paper or PMD + cups). The eco-efficiency results of the alternative SWM strategies were also benchmarked against the eco-efficiency of sustainability measures in other fields. The results of the benchmarking process indicate that optimizing waste management is generally more cost-effective, in terms of reducing emissions, for theme parks (and semi-public spaces) than investing in sustainable electricity or sustainable buildings.

The results are subject to some degree of parameter uncertainty and uncertainty due to choices. The uncertainty analysis showed that the material recovery rate parameter causes the highest degree of relative uncertainty in the results. Therefore, the material recovery rate as well as the electricity mix (which changes in time) were analyzed using a scenario analysis. The results of this are provided in tables 8.8 and 8.9.

Chapter 9

Conclusions and Recommendations

9.1 Conclusions

This research revolved around answering the following **main research question:**

How can the sustainability of solid waste management in semi-public spaces be improved?

The answer to this question consists of different components that are captured by the different sub research questions. First of all, the characteristics of solid waste management (sub RQ1) were analyzed to be able to establish an approach to improve its sustainability. Secondly, a methodology for composing and modelling (improved) alternative solid waste management strategies for semi-public spaces was worked out (sub RQ2,3 and 4). Finally, high potential alternative solid waste management strategies were assessed, using a case study, for their environmental and economic impact (sub RQ5).

Approach and Methodology

Based on an integrated waste management approach, it was found that many alternative solid waste management (SWM) strategies can be designed to improve the sustainability of SWM in semi-public spaces. The approach takes into account that the collection, transportation, sorting and treatment of different waste types are interrelated. A morphological analysis of the current SWM system allowed the systematic composition of alternative SWM strategies. However, only few of these strategies proved to be viable and internally consistent and also significant in terms of emission reduction potential. The strategies that do meet these criteria differ widely in terms of their (relative) environmental and economic impact. The environmental impact of alternative SWM strategies was assessed using a life cycle assessment, which is able to estimate the integrated environmental burdens of the collection, transportation, sorting and treatment processes of a SWM system. The economic impact was estimated using an integrated economic assessment that takes all of the SWM cost components (collection, transport and treatment) into account. Both assessments were used to assess the impact of the alternative SWM strategies for the Efteling case. The Efteling is major theme park in Europe, located in the Netherlands.

The application of an integrated approach in which the impact of all operational theme park waste types over their entire 'life time' are taken into account is something that was never done before. The same goes for the combined assessment of environmental performance and economic performance in this context. The full approach is summarized in figure 9.1. The approach allows decision makers to make a holistic decision on which improved SWM strategy is most sustainable, both environmentally and economically, for their specific case. This allows for better decision-making compared to conventional decision-making based on the hierarchy of waste management.

Case Study Results

The case study at hand demonstrated that there is great potential for improving the sustainability of SWM practice in theme parks and (semi-)public spaces in general. The LCA showed that emissions reductions of almost 190 ton CO_2 equivalents (TCO_2E's) per year, relative to the current strategy, can already be achieved by separating (and recycling) more recyclable fractions from behind-the-scenes waste. This corresponds to an increase in yearly avoided SWM system emissions of about 25% for the Efteling case (from a life-cycle perspective). When public/semi-public waste is also separated and recycled, emission reductions of up to 800 TCO_2E's per year can be achieved for single-fraction separation (e.g. PMD, plastic or PET) and up to 960 TCO_2E's per year for two-fraction separation (e.g. PMD + paper or PMD + cups). This corresponds to increases in avoided SWM system emissions of 110% and 131% respectively. It must however be noted that there is a general trade-off between the environmental benefits of a SWM strategy and the costs of a strategy.

Two-fraction separation was commonly found to be more expensive compared to single-fraction separation but the cost differences within these strategy types are quite large and depending on the fraction(s) being separated. It was also found that relatively small interventions in the transportation and/or treatment SWM system components are able to make a big difference in the environmental and/or economic impact of a SWM strategy. Return to supplier transport schemes and local composting treatment means can save a lot of costs. The cost difference between local composting (by theme park) and external treatment of food waste was found to be more than €200,000 per year. Local composting may also save a lot of emissions. Return to supplier transport can save between €1800 and €15,000 per year but it requires cooperation in the SWM chain. Return to supplier transport does not have significant environmental benefits.

Finally, the environmental and economic performances of improved SWM strategies have also been converted into integrated 'eco-efficiency' indicator scores. These help to make decisions on SWM strategies by taking the tradeoff between emission reductions and costs into account. The eco-efficiency scores show that some improved strategies are able to realise very high emission reductions per extra unit of operational costs. The highest score of almost 26 kg's of CO_2E reductions per extra Euro or its equivalent of €38.92 per TCO_2E reduction is related to the full separation and recycling of PET bottles in combination with the separation and recycling of PMD in behind-the-scenes waste. It should however be noted that the eco-efficiency indicator does not say anything about the range over which a certain strategy can reduce emissions. Strategies with a higher emission reduction potential generally have a lower eco-efficiency score of about 7 kg's of CO_2 reduction per extra Euro. This corresponds to about €140 per TCO_2E reduction. In line with the IWM approach, choosing a certain SWM strategy, which includes trading off eco-efficiency and emission reduction potential, should be done according to 'local' conditions such as the relative importance of the formulated objectives (budget but also space, staffing etc.).

Validation and Uncertainty

Since (semi-)public spaces including theme parks have proven to be quite challenging when it comes to managing waste in a sustainable way, the results have been analyzed with respect to uncertainties. The theoretical emission reductions that have been mentioned may not always be realisable in practice due to separation inefficiencies. The uncertainty analysis showed that the material recovery rate parameter, which expresses these separation inefficiencies, causes the highest degree of relative uncertainty in the results. Many strategies are within each other's range of uncertainty when it comes to recovery rate. This means that different recovery rates for different strategies can change the ranking of strategies with respect to environmental benefits. Low recovery rates of only 40%, which indicate that only 40% of recyclable fractions are properly separated and subsequently recycled, do however still results in considerable amounts of emission savings for the case study at hand. Separating 40% of the PET bottles in (semi-)public waste results in 200 TCO_E's of extra avoided emissions per year (27% increase). This increases to 300 up to 385 TCO_E's (41-53% increase) for two-fraction separation or PMD separation with a recovery rate of 40%. Furthermore, the emission savings attributed to improved SWM strategies are expected to increase in the future as a result of the electricity mix becoming 'greener' (more renewable electricity generation).

General Implications

The high eco-efficiency that was attributed to several alternative SWM strategies for the case study should also be applicable to similar strategies in other contexts. This means that the results are not only relevant for other theme parks but also for other companies and parties that manage (semi-)public spaces. Furthermore, it was found that many of the alternative SWM strategies for the case study perform better, meaning more cost-effective, at reducing GHG emissions than a range of benchmarks. These benchmarks include sustainable electricity production from wind at sea and solar PV plants as well as sustainability measures in the built environment such as building insulation. The results of the benchmarking process indicate that optimizing waste management is generally more cost-effective, in terms of reducing emissions, for semi-public spaces than investing in sustainable electricity or sustainable buildings and should therefore also be prioritized. The results also justify an increase in the amount of (scientific) research into sustainable waste management. Given that worldwide waste quantities are rising and that many theme parks and semi-public spaces are struggling with their commitments to reduce their environmental footprint, the case study results show that researching and implementing more sustainable solid waste management strategies can definitely make a difference.

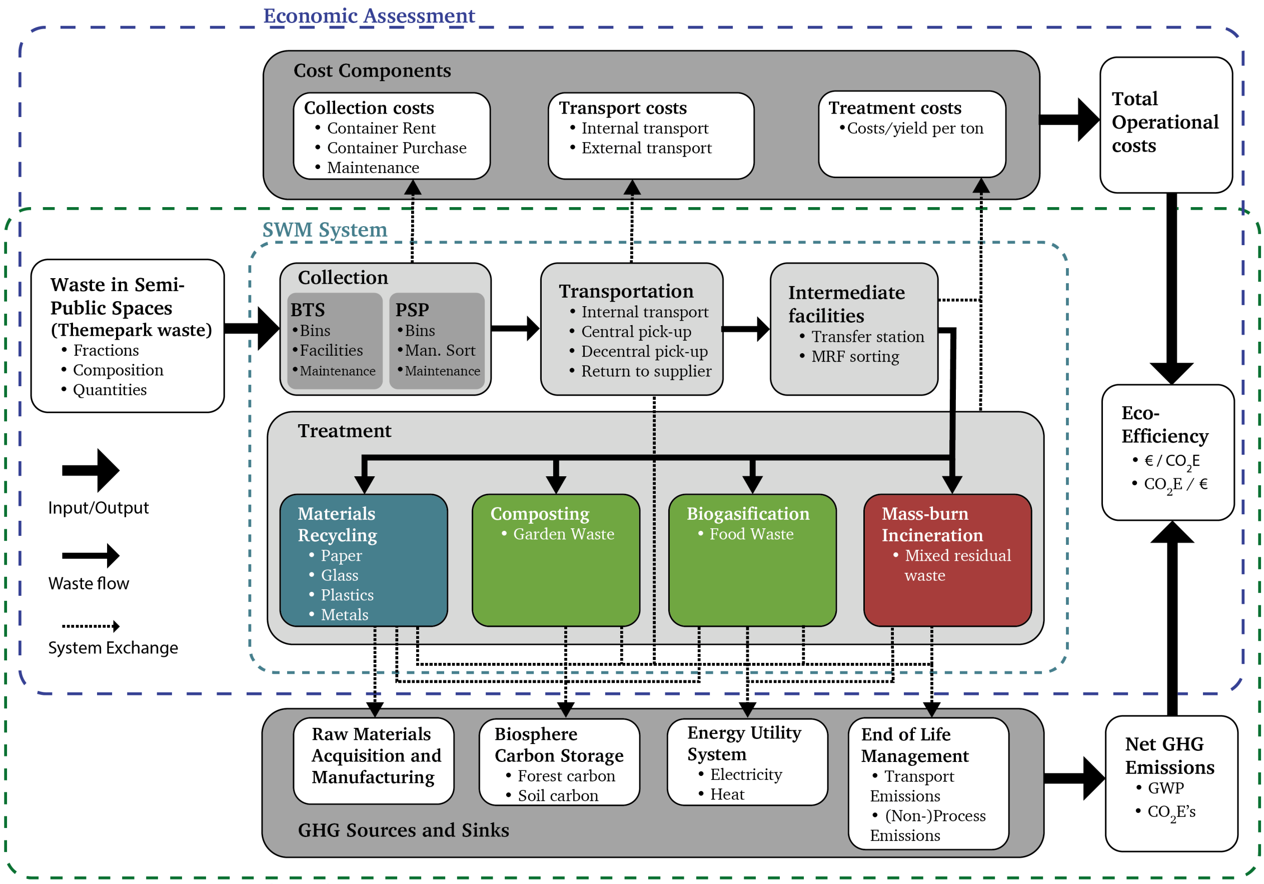

Figure 9.1: SWM eco-efficiency analysis framework for semi-public spaces using LCA and economic assessment

9.2 Recommendations

The recommendations that arise from this research can be divided into recommendations for science and recommendations for the Efteling. The recommendations for science are mostly about future research subjects whereas the recommendation for the Efteling are mostly about implementation.

9.2.1 Recommendations for Science

The recommendations for science that follow from this research can be divided into three themes:

Waste separation efficiency/recovery rate: As mentioned in the uncertainty analysis and the conclusion, the recovery rate is a major source of uncertainty for modelling the environmental benefits of SWM strategies in which waste fractions are separately collected in PSP areas. There is hardly any (scientific) literature about the relation between waste types and the efficiency at which people/visitors/guests manage to properly dispose these waste types into the right bin. There is also hardly any literature about the relation between waste purity and the number of separately collected fractions. Finally, research and data about the deployment of post-separation central sorting techniques is also scarce. These points are considered to be the most important scientific gaps to be researched.

Application of integrated waste management in the context of (semi-)public spaces: This study is, to the best of the author's knowledge, the first one that applies an integrated waste management approach to semi-public spaces. Therefore, it would be valuable to compare the (life-cyle) environmental and economic impact of Efteling SWM strategies to the impact of SWM strategies in other companies and organizations as a means of validation and benchmarking. Furthermore, the improved SWM strategies that were found using the approach and methods in this research have proven to be very eco-efficient (potentially) in relation to other sustainability measures. This calls for a further prioritization of IWM (optimization) research.

Biosphere carbon storage resulting from paper recycling and organic waste composting/digestion: The estimates for the forest carbon storage resulting from increased paper recycling are based on US EPA (2019b), which takes the forest sector of the United States as a starting point. Research about the effect of paper recycling on timber harvests and the subsequent effect of changes in timber harvests on forest carbon stocks in Europe have not been found. Such research would help to improve the accuracy of the WARM model in European contexts. The same goes for research about the amount of soil carbon storage resulting from compost or digestate application to land.

9.2.2 Recommendations for Efteling

Since it was found that there is great potential for greenhouse gas reductions in alternative (improved) SWM strategies for the Efteling, it is recommended to implement such a strategy. The eco-efficiency of implementing an improved SWM strategy is higher than the eco-efficiency of investing in solar or wind energy or than sustainability investments in the built environment (see section 8.4.2). In the process of choosing a specific SWM strategy, it is of major importance to consider the following aspects: emission reduction potential, costs, number of separated fractions and the expected recovery rate of waste fractions that are to be separated.

A great indicator for the costs and benefits of a certain SWM strategy is the eco-efficiency of that strategy. **The strategies with the highest eco-efficiencies are strategy 2,3 and 7B. These strategies are therefore highly recommended.** Strategy 2 concerns the additional separation of PMD from BTS waste relative to the current strategy whereas strategy 3 concerns the separation of pet bottles from PSP waste and the additional separation of PMD from BTS waste. The absolute highest eco-efficiency (strategy 3B) can be achieved if a 'return to supplier' transport scheme can be arranged for the PET bottles in strategy 3. The highest eco-efficiency does however not mean that strategy 3 achieves the highest emission reductions. It means that it achieves the most emission reductions per unit of (extra) economic costs. Strategy 7B, on the other hand, involves the separation and local composting of swill from PSP waste and the separation of PMD from both BTS and PSP waste. A critical factor for choosing strategy 7B is the state of development of local composting machines. Currently, these machines look promising but time should prove their practicality.

The highest emission reduction can be achieved with strategy 4, for one-fraction separation, and strategy 8, for two-fraction separation. These strategies are relatively more expensive but still more eco-efficient than sustainability investments in other 'sectors' (energy and built environment). **Therefore, if budget is less of a limiting factor, strategies 4 or 8 are recommended.** There is one important remark with respect to this recommendation. If there are any signs that the recovery rate of plastic is significantly higher than that of PMD because the definition of plastic is easier to understand than the definition of PMD, than strategy 5 should be preferred over strategy 4. Such signs were not found in this research. Finally, the ultimate choice between one-fraction or two-fraction separation (for PSP waste) should ideally be based on pilot projects that test the recovery rate of waste materials in one- and two-fraction separation setups. The current pilot project in the Efteling that involves the small-scale separate collection of PET bottles in PSP areas can serve as an example for this. The use of pilot projects to test recovery rates also advocates implementation of improved SWM strategies in a step-wise way. This allows further improvements along the way.

9.3 Limitations

The conclusions and recommendations that have been presented are subject to some study limitations. The primary limitation with respect to generalization is, of course, that the results in this research are based on a case study. Although the case involves a major theme park and semi-public space that is used by millions of people per year from a very diverse group (all ages and social classes), other theme parks and (semi-)public spaces may have a different residual waste composition. Furthermore, other companies and organizations that manage (semi-)public spaces may also operate different SWM systems (other collection, transport, sorting and treatment options). This means that the environmental en economic impact of alternative SWM strategies (corrected for differences in waste quantities) may be different for these companies and organizations. The method that has been developed and used to calculate the impacts of SWM strategies in this research is however universally applicable.

The case study results themselves are also subject to some (secondary) limitations. These are mainly applicable to the estimated environmental impacts. The economic impacts are based on data with a lower degree of uncertainty (generally). The case study limitations are discussed one-by-one.

- The input to the WARM model is, among others, based on the residual waste sorting tests and the estimated BTS/PSP ratio described in section 4.2. The sorting tests have taken location bias into account by using samples from all over the park. Time bias has however not been taken into account. All of the samples were taken on the same day. The average residual waste composition may be (slightly) different on different days and in different seasons. This effect is counteracted by the stable character of the food and beverage assortments. The BTS/PSP ratio, which is based on bin volumes, may also differ over time.
- The material recovery rate of waste fractions that are to be separated in a SWM strategy can have a large impact on the environmental benefits of that strategy. This effect has been analyzed in section 8.5.1.
- The GHG emission factors that WARM uses for the manufacturing of materials are based on estimated industry averages for energy usage (US EPA, 2019b). The factors may be different for the actual supply chains in the considered case.
- The incineration system efficiency with respect to delivering electricity may be improving. A higher efficiency means less CO_2 emissions per ton of waste combusted (US EPA, 2019d). This effect is, however, counteracted by the electricity consumption mix becoming greener (see section 8.5.2).
- The modelling approach assumes closed-loop recycling (and stable overall demand) for most materials as a result of resource limitations. Thereby, "it does not fully reflect the prevalence and diversity of open-loop recycling" (US EPA, 2019d, p.2-6). As a result, recycling benefits may be higher or lower.
- The carbon storage benefits of adding compost to soils are based on Century model simulations. These are limited by a lack of data on yard trimmings and food discards composting and a lack of data on carbon in compost that is passive (US EPA, 2019d). Still, it appears to be the best available option.
- The costs for collecting, transporting and/or treating different waste types may change in the future. Price increases are however limited by contractual agreements.

Given these limitations, it is clear that IWM modelling, and especially the LCA modelling part, is very complex and requires lots of data about many different processes and substances. Every research that may contribute to SWM LCA models becoming more accurate is very welcome. According to US EPA (2015), they will continue to add new materials and emission factors to WARM if sufficient data is available. Therefore, it is expected that the WARM model will become more accurate in the future. Using the most recent version of WARM is recommended. Furthermore, having an up-to-date SWM LCA model (like WARM) that is specifically developed for a European context would be a great leap forwards. More specific recommendations for science that emerged from this research are provided in section 9.2.1.

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Appendices

Chapter A

Scientific Paper

Optimizing Solid Waste Management in Semi-Public Spaces: A Case Study of the Efteling Theme Park

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Abstract

This research focuses on identifying and evaluating ways to improve the sustainability of solid waste management (SWM) in semi-public spaces using the Efteling theme park as a case study. To the best of the author's knowledge, this study is the first to apply an integrated waste management approach to optimize SWM in this context. The approach consists of assessing the integrated environmental and economic burdens of the collection, transportation, sorting and treatment processes of a SWM strategy. Approximately 10 alternative high potential SWM strategies were composed and selected out of a very large pool of possible SWM strategies. The environmental and economic impact of these high potential SWM strategies for the Efteling case was subsequently assessed using the WARM LCA model and a custom economic assessment model. The results reveal that emission reductions of up to 190 ton CO_2 equivalents (TCO_2E's) per year, relative to the current strategy, can already be achieved by separating and recycling more fractions from behind-the-scenes (BTS) waste. This corresponds to an increase in yearly avoided SWM system emissions of about 25% for the Efteling case (from a life-cycle perspective). When public/semi-public (PSP) waste is also included, emission reductions of up to 800 TCO_2E's per year can be achieved for single-fraction separation (e.g. PMD or PET) and up to 960 TCO_2E's per year for two-fraction separation (e.g. PMD + paper or PMD + cups). This corresponds to major increases in avoided SWM system emissions of 110% and 131% respectively. It was also found that small interventions in the transport and/or treatment waste management components can make a big difference in the environmental and/or economic impact of a SWM strategy. A majority of the alternative SWM strategies has an eco-efficiency (emission reduction cost-effectiveness) ranging from €39 to about €140 per TCO_2E saving. This eco-efficiency is (much) higher than that of a range of benchmarks such as the eco-efficiency of solar-pv panels at a non-industrial scale, wind turbines at sea and the eco-efficiency of office building insulation. This indicates that optimizing waste management should be given more priority in (scientific) research as well as in practice.

Keywords: Solid Waste Management (SWM), Integrated Waste Management (IWM), Life Cycle Assessment (LCA), Recycling, Waste Logistics

1. Introduction

The worldwide production of solid waste is rapidly increasing along with its environmental footprint [1]. A considerable climate benefit can potentially be achieved by managing this solid waste in more sustainable ways [2]. Improving solid waste management (SWM) systems is, in many cases, complicated because these systems consist of many distinct processes that are interrelated.

While much research has focused on the sustainable SWM of residential waste, the SWM of commercial waste[1] and especially waste from (semi-)public spaces has received less attention. This category does however prove to be relatively problematic when it comes to shares of waste that are processed for useful applications[2]. In the Netherlands, the share of waste from private households that is processed for useful applications is higher than that of (commercial) waste from offices, stores and services (see table 1). The same goes for Germany [4, 5]. This is remarkable as household waste is one of the hardest sources of waste to manage because it consists of a wide range of materials mixed together [6]. Commercial and industrial waste is often more homogeneous which makes it easier to manage effectively. Waste produced in semi-public spaces takes a unique position in this sense as its composition is more homogeneous than household waste but also less homogeneous than strictly commercial waste [7].

The culture, sport and recreation sector and the financial services sector seem to be doing especially poorly when it comes to reducing shares of mixed (unrecyclable) waste (see table 1). Using (among others) waste data of 580 companies, waste quick scans and interviews, the mixed waste percentages of more specific offices, stores and services subsectors in the Netherlands could also be estimated (see figure 2) [9]. Accord-

[1] Waste from premises used wholly or mainly for the purposes of a trade or business or the purposes of sport, recreation or entertainment excluding household waste or industrial waste [3].

[2] Re-use + recycling + composting + fermentation

Origin	Total Waste x1000 ton	Mixed waste x1000 ton	%	Recyclable waste x1000 ton	%	Organic waste x1000 ton	%	Useful Applications %
Private households	8107	3960	49	1819	22	1874	23	46
Retail, transport and hospitality	1902	724	38	562	30	204	11	40
Financial services	117	86	74	25	21	4	3	25
Business	1154	575	50	263	23	262	23	45
Government, education and healthcare	2094	1006	48	274	13	641	31	44
Culture, sport, recreation and others	**160**	**98**	**61**	**48**	**30**	**10**	**6**	**36**

Table 1: Dutch waste quantities per origin in 2016 [8] (chemical waste, mineral waste and discarded equipment are excluded as subcategories)

Sector	Subsector	Mixed Waste %
Culture, sport and recreation		**68**
	Theatres and pop stages	62
	Event halls	53
	Festivals	79
	Museums	63
	Zoos	62
	Theme/amusement parks	**86**
	Sport clubs	85
	Swimming pools	55
Hospitality industry		**61**
	Restaurants, cafes and cafetarias	62
	Hotels	57
	Bungalow parks	85
	Camping sites	79
Retail		**18**
Education		**74**
Government		**42**
	Offices	46
	Public space	42
Transport		**85**
	Public transport: Train and bus	51
	Transport over water	High*
	Aviation	65
Business		**68**
	Offices	67
	Film, TV and sound recordings	High*

* Qualitatively assessed to be high %, insufficient data for quantitative assessment

Table 2: Mixed waste per (sub)sector [11–17]

ing to these estimations, a majority of waste is still processed as mixed waste in nearly all (sub)sectors. The only sectors that manage to re-use and recycle more than 50% of waste are the retail and government sector. Note that 50% is the actual target value that the EU has set for 2020 for waste re-use and recycling [10]. The worst subsectors about which sufficient waste data is available are: festivals (79% mixed waste), theme and amusement parks (86%), sport clubs (85%), bungalow parks (85%) and camping sites (79%). All of these subsectors have in common that they 'collect' (mixed) waste that is mainly being produced by third parties, being customers, guests or visitors in semi-public spaces. Therefore, this research has focused on identifying and evaluating ways to improve the sustainability of solid waste management in semi-public spaces.

The subsector with the highest percentage of mixed (unrecyclable) waste is the theme and amusement park sector. Therefore, the Efteling is considered to be an effective case study subject. The Efteling is a major theme park in Europe, located in the Netherlands. It is, by far, the most visited (tourist) attraction in the Netherlands with more than 5 million visitors per year [18]. The park covers 65 hectares of semi-public space and operates 365 days per year [19]. Only the SWM belonging to the regular operation (operational waste) will be analyzed and optimized extensively. This concerns everything except the SWM of waste types that are released during maintenance and construction activities since these are hard to generalize to other parks and semi-public spaces.

2. Literature Overview

In this section, the existing literature regarding SWM (optimization) will be analyzed. This includes describing the most influential approaches to sustainable SWM. First, the hierarchy of waste management approach and the integrated waste management (IWM) approach, which is a counterpart to the hierarchy, are introduced. After that, current literature on optimizing the sustainability of solid waste management will be listed and sorted based on these approaches.

2.1. Hierarchy of Waste Management

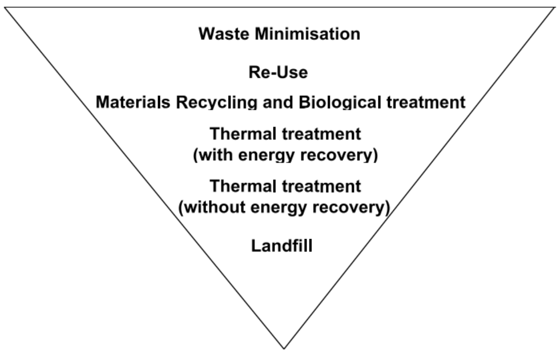

Figure 1: Hierarchy of Waste Management [6]

A concept that is widely used in international as well as national policy and legislation about SWM is the Hierarchy of Waste Management. It provides a priority list for waste management options where options at the top of the hierarchy such as waste minimisation and re-use are to be prioritized over thermal treatment and landfill (see figure 1). The clarity and ease of use of the hierarchy explains part of its popularity. However, despite its wide application, the hierarchy has quite some limitations. Most importantly, it has no scientific basis and does not incorporate costs [6]. Furthermore, the hierarchy cannot asses a system that combines several waste treatment options while many waste streams require sequential treatments. Because of the limitations of the Hierarchy of Waste Management, this research utilizes the Integrated Waste Management (IWM) approach instead.

2.2. Integrated Waste Management (IWM)

IWM is a holistic approach to SWM striving for environmental effectiveness, economic affordability and social acceptability. The principles of IWM are extensively documented in the book 'Integrated solid waste management: A Life Cycle Inventory' by McDougall et al. [6]. Since the three objectives of IWM are difficult to maximize simultaneously, there will be a trade-off. *"The balance that needs to be achieved is to reduce the overall environmental burdens of the waste management system as far as possible, within an acceptable level of cost"* [6, p.44]. As the term IWM already implies, this approach revolves around two key principles: all types of solid waste materials and all sources of this solid waste are considered. The reason for this is that focusing on specific materials or sources is likely to be less effective (both environmentally and economically). Instead of making minor changes to the old system, the whole (interconnected) system is being looked at. Two more ways in which IWM is an integrated approach are that all collection and all treatment methods are considered. As opposed to the 'hierarchy of waste management', which is often referred to by policy and legislation, IWM does recognize that all waste management options can play a role in optimizing the whole system, depending on the local situation. In other words, IWM recognizes that there is no uniform SWM ideal, conditions determine the outcome. This is also illustrated by figure 2.

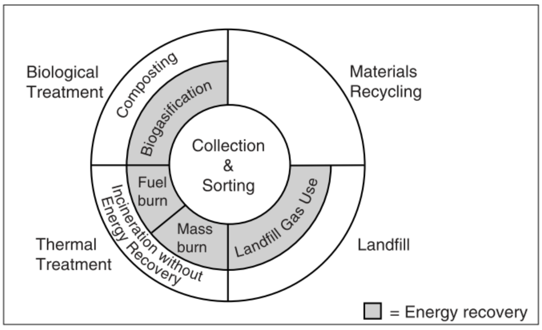

Figure 2: Integrated Waste Management (IWM) [6]

IWM is all about balancing the elements of figure 2 in a way that is optimized for a given context. This can be done using a Life Cycle Assessment (LCA), which will be described later, as an assessment method. The step that precedes effective IWM, in reality, is waste minimization or waste prevention. This is, therefore, not part of the IWM framework but a precursor to it [6].

2.3. Solid Waste Management Optimization

There are many previous studies into solid waste management optimization with respect to sustainability. These studies can be divided based on the approaches that have been described in the previous sections. This division is visualized in table 3. On the one hand, there are studies that take the hierarchy of waste management as a starting point. These studies generally analyze SWM systems based on the components of the waste hierarchy and aim at optimization towards (higher) hierarchy standards. These studies do usually not include a LCA to quantify environmental burdens. On the other hand, there are studies that implicitly or explicitly apply the concept of IWM. These studies generally compare the (life cycle) environmental burdens of different SWM strategies based on a LCA without prior assumptions on the hierarchy of management options.

		Approach		Application		
		Hierarchy of Waste Management*	Integrated Waste Management**	Individual Product Supply Chains	Municipalities / Residential Waste	(Semi-)Public Spaces / Recreational Waste
Kopicki et al. (1993)	[20]	●		●		
Radwan (2009)	[21]	●				●
Annepu (2012)	[22]	●			●	
Pirani & Arafat (2014)	[23]	●				●
Martinho et al. (2018)	[24]	●				●
Rafiee et al. (2018)	[25]	●				●
CE Delft (2007)	[26]		●	●		
Parkes et al. (2015)	[27]		●		●	
Turner et al. (2016)	[28]		●		●	
TNO & WFBR (2018)	[29]		●	●		
This Article			○			○

* Optimization towards hierarchy standards
** LCA approach, no assumptions on best SWM strategy

Table 3: Literature overview [20–29]

Table 3 also organizes SWM optimization studies based on their application area. Most existing studies focus on (household) waste collected by municipalities. Furthermore, there are also quite some studies that focus on the environmental burdens of individual (packaging) product supply chains. A more niche research area relevant to this research is SWM in (semi-)public spaces or SWM of recreational waste. There are only few studies with this application area and all of them are currently done according to the hierarchy of waste management approach [23]. Furthermore, these studies have not focused on other (sub)sectors than hotels, restaurants and festivals yet. The research gap that this study is trying to fill consists of applying the IWM approach to semi-public spaces and theme parks in particular. Additionally, the IWM approach will be applied in its most holistic form, the way it was intended [6]. This means that the aim is to optimize environmental effectiveness as well as economic affordibility in an integrated way, which is unique in this area of application. Finally, it must be noted that applying the IWM approach to semi-public spaces does not mean that a blueprint procedure is being implemented, the very nature of the IWM approach requires an extensive analysis of a specific SWM system to be able to optimize it. This analysis is included in the next section.

3. Solid Waste Management System Characteristics

The current characteristics of SWM systems in semi-public spaces will be analyzed using the Efteling as a case study. This is done for all of the elements that are commonly distinguished within a SWM system in scientific literature [6, 30]. These elements are waste collection, waste transportation, waste sorting and waste treatment. The structure of this section is also based on these elements.

3.1. Collection

Waste collection forms the contact point between waste generators (guests, staff members, operations) and the SWM process chain. This means that collection also has a major impact on subsequent steps in the SWM process chain. As McDougall et al. [6] describes, the collection determines which waste management options can be used and whether these are economically and environmentally sustainable. Furthermore, the collection method also influences the quality of possible recovered materials, compost and/or energy and thereby also their market potential. From a pure recycling point of view, the ideal collection process would result in purely separated homogeneous waste streams. Looking at it in a more integral way, this is unlikely to be optimal as both the collection processes and the subsequent handling processes of purely separated waste streams require a lot of effort and energy. The reason for this is that benefits from economies of scale and synergies between different waste treatment options are (partly) lost [6].

The quality of waste separation in the collection phase is dependent on the characteristics of the waste generators. Different models and theories exist for explaining this waste separation behavior. The model that is used in this study to predict the amount of correctly sorted waste in the collection phase follows the logic of the theory of planned behavior by Ajzen [31]. This is one of the most widely used theories in this context. The formula for the total amount of recovered waste material (e.g. paper or plastic) is given below [6]:

$$\text{Amount of material recovered} = \text{Amount of material in waste stream} \times \text{Participation rate} \times \text{Separation efficiency} \tag{1}$$

The participation rate is the percentage of, in this case, guests and staff members (or locations) that participate in separate waste collection. The separation efficiency refers to the percentage of material that is correctly sorted and separated. The concept of material recovery rate integrates the participation rate and the separation efficiency (participation rate × separation efficiency).

Two types of waste collection operations can be distinguished in the Efteling and in many other semi-public spaces:

- *Behind-The-Scenes (BTS) collection:* Refers to the collection of waste in spaces that are only accessible to staff members. This includes waste collected in kitchens, sculleries, warehouses and workshops.
- *Public/Semi-Public (PSP) collection:* Refers to the collection of waste in areas that are accessible to guests and visitors.

Since BTS collection is handled by staff members, the extent to which this process can be controlled is higher compared to PSP collection. By means of staff education, motivation and management, the participation rate and separation efficiency can be increased relative to PSP collection. This (partly) explains why the number of separately collected waste types in BTS areas is usually higher compared to PSP collection. Another reason is that in legislation about waste collection [32, 33], a distinction between BTS and PSP collection is being made in the sense that mandatory separate BTS waste collection is deemed to be more reasonable than separate PSP waste collection.

Currently, PSP waste collection in the Efteling only consists of the collection of mixed (residual) waste and, at a very limited scale, the separate collection of PET bottles (as a pilot). BTS waste collection, on the other hand, consists of the separate collection of paper, glass, PET bottles, swill (food waste), fat and oil, plastic foil, garden waste and residual waste.

3.2. Transportation and Sorting

Transportation and sorting processes are key in the total SWM chain. They connect the collection of waste to the different treatment processes for waste. Since sorting and transportation processes may be present at different places in the SWM chain, depending on the type(s) of waste collected and the availability of treatment facilities, they are jointly addressed.

3.2.1. Manual Sorting

Manual sorting refers to hand picking by humans. This may take place before, after or during mechanical sorting processes. In the case of the Efteling, manual sorting is currently applied to separate PET bottles from residual waste. The residual waste remains in its own bin during this process so only PET bottles that are easily accessible are separated. This is mostly done at the different cluster sites throughout the park after park closure. Manual sorting rates vary widely depending on the type of material(s) being sorted. The sorting rates are also affected by the setting in which the sorting takes place, the position of the sorter, the tiredness of the sorter and lighting conditions. PET bottle sorting rates found in literature range from 160 to 31,25 kilograms per person per hour [6, 34, 35]. The sorting rate of

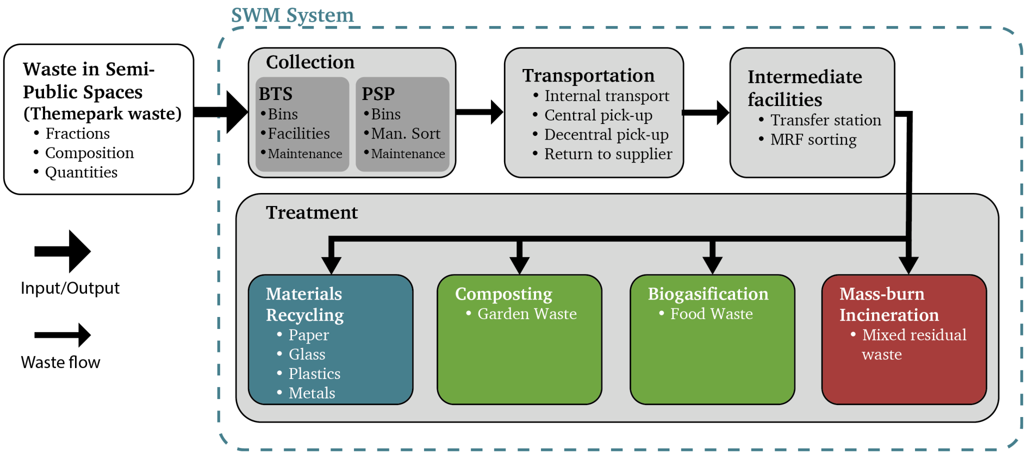

Figure 3: Schematic representation of the SWM system of semi-public spaces

PET bottles in the Efteling is expected to be in the lower range or even lower than 31,25 kilograms per person per hour.

3.2.2. Transportation

Transportation refers to the transport of waste types from collection sites to treatment facilities via possible intermediate facilities such as sorting facilities and transfer stations. The amount of waste transport depends on the amounts and types of waste collected, the storage capacity, the vehicle capacity, the distance between facilities and (company) waste policy. For the Efteling, many waste transports are planned in a predefined schedule based on expected numbers of visitors. Three main transport types can be distinguished for the Efteling, namely:

- *Decentralized Pick Up:* The external waste management company picks up specific waste from all of the cluster sites in the Efteling park where this waste is being collected.
- *Centralized Pick Up:* The external waste management company picks up specific waste at a central location that has previously been brought to this location from relevant cluster sites by internal Efteling transport operations.
- *Return to Supplier:* (Waste) materials are taken back by the suppliers of these materials after they have been used and disposed. A major advantage of this transport type is that it prevents unnecessary transport kilometers since the good delivery return trips, that used to be empty, are now used for waste transport. A disadvantage is that you are dependent upon good suppliers for the transport of waste, this may not be sufficient.

3.2.3. MRF Sorting

Materials Recovery Facility (MRF) sorting refers to the separation of materials that have enough value to make their recovery worthwhile in a MRF [6]. Although some separately collected waste types such as glass and paper may also receive some limited kind of manual or mechanical sorting to remove contamination, this is not referred to as MRF sorting. In this case, MRF sorting mainly applies to PMD which is a mix of different kinds of recyclable materials that have to be separated to be eligible for materials recycling treatment. There is no standard procedure for MRF sorting, different sorting methods (e.g. air knife, flotation, magnetic separation) may be combined and adapted based on the process inputs and desired final outputs.

3.3. Treatment

Waste treatment processes are the final step in the integrated SWM chain. After (consecutive) treatment, waste materials have either become inert material, emissions to air and water or they have regained value as compost, secondary material or fuel [6]. Waste treatment processes are responsible for large parts of the total environmental burdens of the total SWM system. At the same time, the types of treatment processes that are applied are very much dependent on earlier steps in the SWM chain such as collection, sorting and transportation processes. Four main types of waste treatment can be distinguished. These are listed below. Within each treatment type, different methods are employed to treat (different types of) waste. The methods that are relevant to the SWM system of the Efteling and similar systems are also given.

- *Thermal treatment:* The valorisation of solid waste by recovering energy from it using (intense) heat.
  - Mass-burn Incineration: The treatment of waste using ’mass-burn’ technologies without much preprocessing.
  - Burning Refuse-Derived Fuel (RDF): The combustion of the mechanically separated and shredded combustible fraction of solid waste (requires RDF sorting).
- *Biological Treatment:* The valorisation of the biodegradable components of waste using naturally occurring microorganisms. Possible products are: compost, biogas and/or energy.

- Composting (Aerobic): Decomposition of organic waste in the presence of oxygen.
- Biogasification (Anaerobic): Decomposition of organic waste in the absence of oxygen.

• *Recycling: "The reprocessing of recovered materials at the end of product life, returning them into the supply chain"* [36, p.10]. This can take many different forms depending on the material type(s).

• *Landfill:* The dumping of waste in a containment system designed to minimize environmental pollution [37].

A schematic representation of the total SWM system of the Efteling that has been described in this section can be found in figure 3.

4. Designing SWM Strategies

Since SWM systems are fairly complex and consist of a chain of interrelated processes, composing relevant (improved) strategies has to be done in a systematic way. General Morphological Analysis (GMA) is a widely used method in this context and will also be applied in this research for composing strategies. It is, however, preceded by requirements engineering which is aimed at identifying requirements applicable to any SWM strategy for semi-public spaces.

4.1. Requirements Engineering

Before starting to design and model (alternative) SWM strategies, it is important to define what the stakeholders need from these strategies and what the underlying systems must do in order to satisfy these needs. This can be done using requirements engineering as described by Hull et al. [38] and Bahill and Dean [39]. Different types of requirements can be distinguished. Some requirements are non-negotiable, these are also called mandatory requirements or constraints. Others requirements that are negotiable are called trade-off requirements or objectives. The most important constraints and objectives that were identified for the Efteling case using an extensive system analysis and stakeholder inputs are listed in table 4.

Note that there will be trade-offs among the different objectives in the sense that scoring well on certain ones will mean scoring worse on others. This is an inherent property of objectives [39]. The trade-offs among different objectives and overall scoring of SWM systems on the objectives can be captured in key performance indicators (KPI's). These are measurable values that indicate how effectively a strategy is achieving one or more of the objectives [43]. Since environmental and economic performance (the two most important objectives) are often linked to each other and may be even conflicting, a performance indicator that combines both is very useful. The concept of eco-efficiency is increasingly being applied in this context and will also be applied in this research. Yang et al. [44] adapted the concept of eco-efficiency to optimize municipal SWM. The eco-efficiency KPI's adapted for this research are provided in formula's 2 and 3.

Constraints	
Code*	**Description**
FC-01	Prevent accumulation of solid waste outside of disposal facilities
FC-02	Process all waste types that are being generated
FC-06	Only separately collect waste types in BTS and PSP areas if these waste types are produced in these respective areas and thus originate there
FC-07	Limit number of separately collected waste types to 3 to prevent confusion (in line with JMA [38] and PLAN Terra [39, 40]
FC-09	Only separately collect waste types that can be processed as a separate waste stream unless the definition of a waste type is narrowed down to enhance understandability in PSP areas
FC-10	Process separately collected waste streams (other than residual waste) using materials recycling treatment methods that correspond to these waste streams if allowed by the respecive contamination level(s)
FC-11	Decentral pick up if: yearly waste quantity >150 tonnes or >1000 m3 or if special handling is required
FC-12	Only apply manual sorting to separate certain waste types from mixed waste types if these waste types can be sorted properly using manual sorting
FC-14	Use waste treatment methods that are available at sufficient capacity in a reasonable range from the theme park
NFC-04	Comply with legislation, especially environmental Protection Act [30] and National Waste Management Plan 3 [31]
Objectives	
Code**	**Description**
NFO-01	Minimize the total amount of CO_2 emitted by all consecutive processes (collection, sorting, tranportation and treatment) in the combined SWM system for all types of waste collected
NFO-02	Minimize the total operational costs for the theme park associated with the processing of all theme park solid waste.

* FC: functional constraint, NFC: non-functional constraint
** NFO: non-functional objective

Table 4: Most important SWM system requirements for the Efteling

$$EE_s\ (CO_2E\ \text{reduction} / €) = \frac{\text{Environmental Improvement}_s}{\text{Economic Costs}_s} = \frac{EI_{\text{current}} - EI_s}{C_s} \quad (2)$$

$$s = 1, 2, .., n$$

$$EE_s\ (€/\ CO_2E\ \text{reduction}) = \frac{\text{Economic Costs}_s}{\text{Environmental Improvement}_s} = \frac{C_s}{EI_{\text{current}} - EI_s} \quad (3)$$

$$s = 1, 2, .., n$$

Where EE is eco-efficiency and EI is environmental impact as calculated by LCA. The different measures or strategies are represented by s. C represents the (additional) economic costs of strategy s as calculated by economic assessment. The final eco-efficiency values can be used to make decisions on the optimal SWM system as the values reveal the best environmental improvement measure per unit of economic costs [44].

4.2. Morphological Analysis

To design alternative (improved) SWM strategies, the order of a general morphological analysis (GMA), as described by Zwicky [45], is followed. First, a morphological box is being created using the analysis in section 3. Secondly, this morphological box is reduced to only include viable options for

	1	2	3	4	5	6	7	8	9	10	11	12
Functions	**PSP Collection**			**BTS Collection**		**Transportation**			**Central Sorting**	**Treatment**		
Options	**Fractions**	**Separate collect**	**Manual Sorting**	**Fractions**	**Separate collect**	**Decentral pick up**	**Central pick up**	**Return supplier**		**Recycling**	**Biological**	**Thermal**
Rejection/ inclusion require-ments	FC-06, FC-02	FC-07, FO-01, NFC-03, NFO-04, NFO-05	FC-12, FC-06, FO-07, FO-08, FO-09	NFC-04, FC-02, FC-09	NFC-04	FC-11, FC-09	FC-11, NFC-01, FC-09, FC-13 FO-07, FO-08	NFC-04	FC-14	FC-10	FC-14	FC-14
1	*Residual Waste*	*No*	*Paper*	*Residual Waste*	*No*	*Residual Waste*	*Residual Waste*	*Residual Waste*	*No central sorting*	*Paper and card*	*Local Composting*	*Mass-burn incineration*
2	*Paper*	*2 fractions*	*Glass*	*Paper*	*2 fractions*	*Paper*	*Paper*	*Paper*	*RDF sorting*	*Glass*	*Central Composting*	*Burning RDF*
3	*Glass*	*3 fractions*	*PET bottles*	*Glass*	*3 fractions*	*Glass*	*Glass*	*Glass*	*MRF sorting*	*Ferrous metal*	*Bio-gasification*	*Pyrolysis*
4	*PET bottles*	*4 fractions*	*Swill*	*PET bottles*	*4 fractions*	*PET bottles*	*PET bottles*	*PET bottles*		*Non-ferrous metal*	*Bio-drying / bio-stabilization*	*Gasification*
5	*Swill*	*5 fractions*	*Fat and oil*	*Swill*	*5 fractions*	*Swill*	*Swill*	*Swill*		*Plastic*		
6	*Fat and oil*	*6 fractions*	*PMD*	*Fat and oil*	*6 fractions*	*Fat and oil*	*Fat and oil*	*Fat and oil*				
7	*PMD*	*7 fractions*	*Foil*	*PMD*	*7 fractions*	*PMD*	*PMD*	*PMD*				
8	*Plastic*	*8 fractions*	*Plastic*	*Plastic*	*8 fractions*	*Plastic*	*Plastic*	*Plastic*				
9	*Foil*	*9 fractions*	*Cups*	*Foil*	*9 fractions*	*Foil*	*Foil*	*Foil*				
10	*Cups*	*10 fractions*	*Garden Waste*	*Cups*	*10 fractions*	*Cups*	*Cups*	*Cups*				
11	*Garden Waste*	*11 fractions*		*Garden Waste*	*11 fractions*	*Garden Waste*	*Garden Waste*	*Garden Waste*				

Rejected option based on constraint(s)
Mandatory option based on constraint(s)
Strategy specific options

Figure 4: Morphological box with the application of constraints

Functions	**PSP Collection**			**BTS Collection**		**Transportation**			**Central Sorting**	**Treatment**		
Options	**Fractions**	**Separate collect**	**Manual Sorting**	**Fractions**	**Separate collect**	**Decentral pick up**	**Central pick up**	**Return supplier**		**Recycling**	**Biological**	**Thermal**
1	*Residual Waste*	*No*	*PET bottles*	*Residual Waste*	*8 fractions*	*Residual Waste*	*Paper*	*Paper*	*No central sorting*	*Paper and card*	*Local Composting*	*Mass-burn incineration*
2	*Paper*	*2 fractions*		*Paper*	*9 fractions*	*Paper*	*Glass*	*PET bottles*	*MRF sorting*	*Glass*	*Central Composting*	
3	*PET bottles*	*3 fractions*		*Glass*	*10 fractions*	*Glass*	*PET bottles*	*Foil*		*Ferrous metal*	*Bio-gasification*	
4	*Swill*			*PET bottles*		*PET bottles*	*Foil*			*Non-ferrous metal*		
5	*PMD*			*Swill*		*Swill*	*Cups*			*Plastic*		
6	*Plastic*			*Fat and oil*		*Fat and oil*	*Garden Waste*					
7	*Cups*			*PMD*		*PMD*						
8				*Foil*		*Foil*						
9				*Cups*		*Cups*						
10				*Garden Waste*								

Mandatory option based on constraint(s)
Strategy specific options

Figure 5: Morphological box with remaining elements after application of constraints (used to design alternative SWM strategies)

alternative SWM systems using the requirements from the previous section. Combinations of options are subsequently assessed using a systematic (step-wise) cross-consistency assessment. From the consistent strategies, a final selection of high potential strategies (in terms of sustainability) is made using a CO2 saving quick-scan.

4.2.1. Morphological Box

The morphological box of a SWM system for semi-public spaces can be found in figure 4. The box is divided into the same main categories as those in section 3. Collection is, again, divided into PSP and BTS collection since these are, to some degree, separate systems. The possible options or conditions that can be chosen for every parameter (separate collected fractions, biological treatment type etc.) are listed right beneath the parameters. A SWM strategy consists of the total combination of chosen conditions for every parameter. The waste fractions that are being distinguished in the box are the most common fractions that could be found in literature and legislation [33, 46, 47]. Note that, in line with the scope of this research, only operational waste types are included. The colors in figure 4 indicate, based on the constraints from table 4, whether certain options are rejected in every strategy (red), mandatory for every strategy (green) or optional for a strategy (white). Two main characteristics of this specific morphological box are:

- As opposed to more classical morphological boxes (for example by Ritchey [48]), this morphological box allows the activation or selection of multiple conditions per parameter. This change was made since a SWM system is dealing with many different waste types that can be managed in all possible combinations (without repetition) which would result in a morphological box with 2047 unique rows (k=11). This format is much clearer.

- The parameter conditions within the same category (PSP collection, BTS collection, Transportation, Central sorting and Treatment) are directly linked to each other. This means that selecting a certain condition for a parameter limits the choice for conditions of other parameters belonging to the same category since some condition combinations are mutually exclusive.

4.2.2. Cross-Consistency Assessment

The options that are not viable in any strategy can be removed from the morphological box to create a more manageable one. This reduced morphological box is displayed in figure 5. The mandatory options are still marked in green in this box. Note that these mandatory options are, of course, also part of the current strategy or base strategy. Using the elements of figure 5, thousands of unique combinations can be created. Every combination is a potential (alternative) SWM strategy. However, many of these combinations will be internally inconsistent or, in other words, mutually incompatible. To reduce the solution space to a smaller set of internally consistent combinations, cross-consistency assessment (CCA) has been applied. The CCA excludes combinations based on two types of inconsistencies. In addition to the exclusion of combinations that are logically contradictory[3], combinations that are empirically inconsistent[4] are also excluded. The latter is done using a CO2 saving quick-scan. This involves estimating the amount of CO2 savings that a certain collection combination can accomplish using generic key figures (ton CO_2 savings per ton waste material) from CE Delft [26, 49], TNO and WFBR [29]. Combinations that accomplish (very) low CO2 emission savings in proportion to the amount of effort that is required to facilitate this collection combination are excluded. This concerns (among others) the separate collection of swill or cups in PSP areas. In total 44 PSP collection combinations, 4 BTS collection combinations and 14 combined (PSP+BTS) collection combinations have been evaluated sequentially. The final selection of high potential collection options have been numbered from 1 to 8 and are provided in table 7.

[3]Contradictory based on the nature of the concepts [48]

[4]Combinations that are highly improbable on empirical grounds [48]

Transportation Base Set		
Decentral pick up	**Central pick up**	**Return supplier**
Residual Waste	*Glass*	
Paper	*Foil*	
Swill	*PET bottles*	
PMD	*Garden Waste*	
Fat and oil		

Transportation Strategy specific options		
Decentral pick up	**Central pick up**	**Return supplier**
Cups	*Cups*	*Paper*
		PET bottles
		Foil

Table 5: Transportation base set and strategy specific options

Treatment Base Set		
Recycling	**Biological**	**Thermal**
Paper and card	*Central Composting*	*Mass-burn incineration*
Glass	*Biogasification*	
Ferrous metal		
Non-ferrous metal		
Plastic		

Treatment Strategy specific options		
Recycling	**Biological**	**Thermal**
	Local Composting	

Table 6: Treatment base set and strategy specific options

After selecting high potential collection combinations, the transportation, sorting and treatment components can be included. Since the consistency of a transportation, sorting or treatment (sub)strategy can only be properly assessed in relation to the collection strategy with which it is combined, these components are not assessed in a standalone way. For transport, it is assumed that the current transportation strategy has already been optimized over the years in terms of resource usage (energy, time and money) and will be used as a starting point. Only when the collected quantity of certain waste fractions is expected to change as a result of a different collection strategy, the transportation strategy of this waste fraction may be varied as well. This assumption can be justified in the larger context by the fact that the environmental burdens of transport are generally found to be minor in relation to the burdens/benefits of waste processing [28]. The current transportation strategy is referred to as the base set. This base set is displayed in table 5. The strategy specific transportation options that may be added to the base set or used as a substitute for base set options are also listed in table 5 on the right side.

In terms of the consistency of sorting options with treatment options there is only one 'rule': PMD and plastic waste fractions can only be recycled if they are sorted using MRF sorting. The other waste fractions do not need central sorting and can be processed using corresponding treatment methods. Combinations of treatment methods are not really limited by their mutual consistency since they are (mostly) used to process different waste fractions. The consistency of treatment options in the context of the full SWM system however is strongly dependent on the fractions which have to be processed, which in turn, depends on the collection strategy. However, since many waste types have to be collected separately (in BTS areas) and these fractions have to be processed using corresponding (recyling) methods , many waste treatment methods will be included in every strategy. These methods are included in the treatment base set which is provided in table 6. Furthermore, mass-burn incineration is the only viable option left for the processing of residual waste (see figures 4 and 5). This leaves only 'local composting' as a strategy specific option that can be used to supplement or substitute the current biological treatment methods: central composting and biogasification.

Using the final selection of high potential collection options and the transportation, sorting and treatment base sets and strategy specific options, a set of high potential full SWM strategies to be researched into more detail can be formed. These full strategies are displayed in tables 7 and 8. The main numbers of the strategies correspond to the final selection of high potential collection options while the A/B sub variants refer to variations in terms of transportation or treatment. As mentioned earlier, sub variants are only present if a certain collection strategy gives rise to changes in waste fraction quantities and if alternative options for the transport or treatment of these waste fractions are available.

5. Modelling SWM Strategies

To be able to assess (improved) potential SWM strategies, they have to be modelled. This allows (among others) the calculation of their KPI's (derived in section 4.1). Two impact components can be distinguished in the KPI's namely an environmental component and an economic component. The environmental component will be estimated using a life cycle assessment and the economic component using an economic assessment. Although a LCA is very common in the context of assessing environmental impacts of SWM and even internationally standardized [50], the combination of LCA with economic assessment is less developed in SWM literature. One of the few examples of concepts that integrate environmental and economic impacts of SWM is that of eco-efficiency analysis (EEA). The application of EEA for SWM purposes has been described and researched by Yang et al. [44]. In an eco-efficiency analysis, the eco-efficiency ratio of different possible SWM strategies is calculated and compared to each other in the end. Based on the principles of Yang et al. and the generic IWM system representation of Gentil et al. [30], a theme park eco-efficiency analysis framework has been developed. This framework can be found in figure 6. It is an extension to the schematic representation of the theme park SWM system that was presented in figure 3.

As one can see in the figure, the SWM system exchanges materials and energy flows with the earth system and technosphere outside of the SWM system. These exchanges are grouped in different sources and sinks of greenhouse gasses (GHG's). Taking these into account is important as they together determine the net GHG emissions (offset) of the SWM system. At the same time, the configuration of the SWM system also influences cost components related to the SWM system. These together determine the total operational costs of the SWM system. Combining the total operational costs with the net GHG emissions results in the eco-efficiency ratio of the SWM system at hand.

5.1. Environmental Assessment

Since (good) SWM LCA models are very complex, an existing model will be adapted to calculate the impact of SWM strategies for semi-public spaces. This model belongs to the very small pool of LCA models that are specifically aimed at SWM. Note that the majority of LCA models is aimed at product LCA's in which waste disposal is just a small component. In a product LCA, the infrastructure system (transportation, waste treatment etc.) is assumed to be given while the product design can be optimised. In a SWM LCA, it is the other way around, the infrastructure system is optimised to manage a given amount and composition of waste [6]. Therefore, dedicated SWM LCA models are needed.

The European Comission (EC) [51] has mapped and classified 42 (European) LCA tools of which WRATE is the only dedicated and available SWM one. In a worldwide context, WARM is another dedicated SWM LCA (more specifically: LCI) tool that is the industry-standard in the United States. WARM stands for Waste Reduction Model and was developed by the U.S. Environmental Protection Agency (US EPA). In the end, WARM was chosen to model the environmental impact of theme park SWM systems because it has a couple of major advantages over WRATE. First of all, the WARM model is more state-of-the-art compared to WRATE. The latter was last updated in 2010 and continues to use the GWP multipliers of the 1996 version of the IPCC guidance although these were updated in 2006 and in later years [52]. Secondly, the Ecoinvent background databases used by WRATE are also quite outdated compared to WARM. The same goes for the method with which biogenic carbon is being dealt with [52]. The biggest advantage of WARM over WRATE is however that WARM is way more transparent in the sense that all of the assumptions regarding background data are described in supporting documents. These are lacking for WRATE. The extensive documentation that comes with WARM also allows the modeller to adapt the model to specific circumstances such as those applicable to semi-public spaces and those in the Netherlands.

5.1.1. General Information WARM model

The most important information about the WARM model and its application in this research is provided below:

- *Used version:* 15 (released in may 2019)
- *Product system:* Total SWM system (including recycling) necessary to process waste from the moment it is discarded until the moment it has regained value as a new product or when it has become inert material or is converted to air emissions.
- *Functional unit:* All of the operational waste (as defined in section 1) of a theme park over 1 year.
- *Reference point:* Waste generation (not raw materials extraction). Upstream emissions and sinks (from the point that a material is discarded) are only considered for recycling and source reduction SWM practices since these are the only SWM options that affect upstream emissions.
- *Impact category:* Global Warming Potential over 100 years (GWP100), based on IPCC [53] conversion factors. Measured in ton CO_2 equivalents (TCO_2E's).

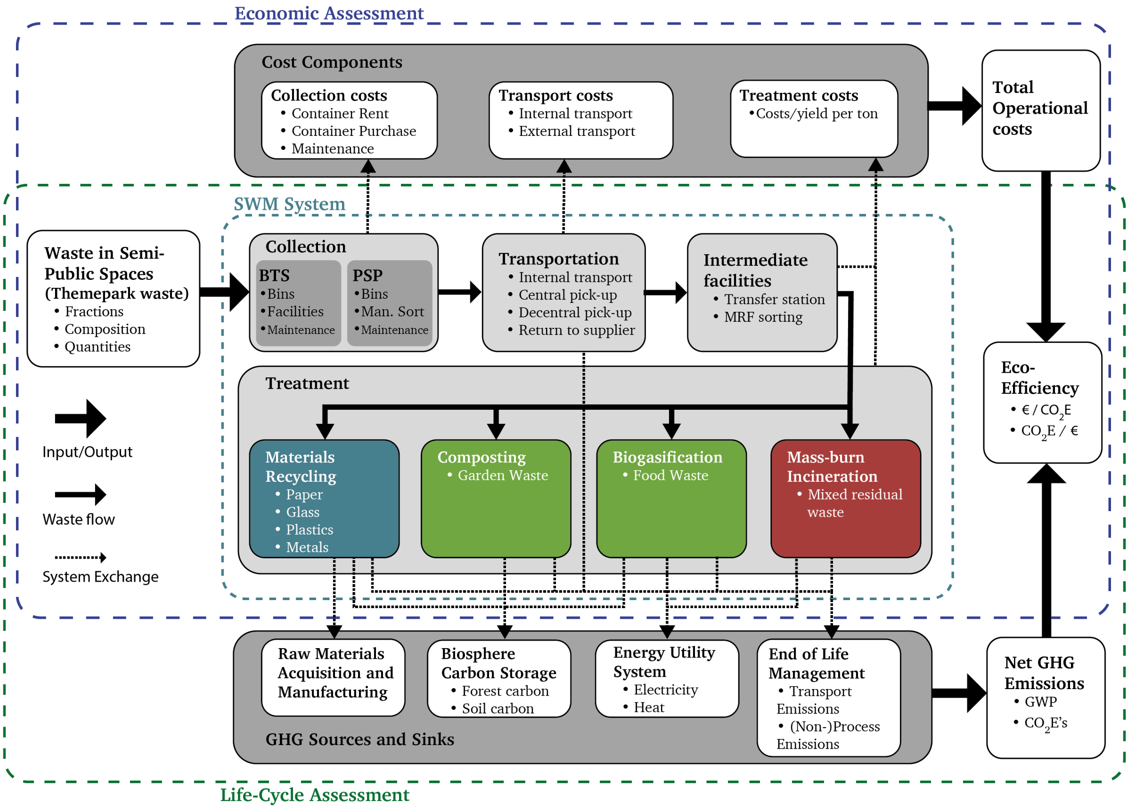

Figure 6: SWM eco-efficiency assessment framework

- *Handling of CO_2 emissions from biogenic sources:* In line with IPCC [54], CO_2 emissions from biogenic materials that are grown on a sustainable basis are not counted. This applies to paper, wood and food waste emissions. These emissions are considered to close the natural carbon cycle as opposed to anthropogenic CO_2 emissions (burning fossil fuels) [55].

The WARM model calculates the environmental impact of a SWM strategy by multiplying the waste quantities that are applicable to that strategy with emission (conversion) factors that correspond to the means by which that waste is being treated (including transport). Therefore, the emission factors differ per waste material and per treatment type. The formulas for calculating the emission factors are described in the next subsections. Some factors have been adapted to reflect the actual environmental impact in the Netherlands. These calibration modifications are listed in Appendix A.

To be able to estimate the quantities of (recyclable) materials that may be recovered from residual waste in certain strategies using separate collection or manual/mechanical sorting, the results of a sample-based sorting test are being used. In this sorting test, residual waste samples from many different locations spread over the Efteling park were sorted into 9 different types of materials by means of hand picking. This way, the share of these materials (by weight) in residual waste could be determined. This was done separately for BTS residual waste and for PSP residual waste since these have a very different composition.

5.1.2. Recycling

Most of the WARM materials are modelled in a closed-loop recycling process. This means that an "end-of-life product" is recycled into the same product [56]. Furthermore, it is assumed that the increased recycling of a product does not change the overall demand for that product, which means that virgin-sourced materials are displaced by recycled materials [56]. Using this assumption, the avoided GHG emissions resulting from recycling are calculated as "the difference between (1) the GHG emissions from manufacturing a material with 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates associated with curbside collection losses and remanufacturing losses) with 100 percent virgin inputs" [55, p.22]. The final calculated difference is referred to as the 'recycling emission factor' when measured for 1 ton of recycled material. The recycling emission factor is the sum of different components which can be found in formula 4. The components are called 'credits' because recycling (usually) reduces GHG emissions or increases carbon storage relative to virgin manufacturing, which results in negative emission factors. The components are described below.

$$\begin{aligned}&\text{Emission Factor}(TCO_2E/\text{ton material}) = \text{Process Energy Credit}+\\&\text{Transport Energy Credit} + \text{Process Non-Energy Credit}+\\&\text{Forest Carbon Storage}\end{aligned} \tag{4}$$

Where

Process Energy Credit :	Concerns CO_2 emissions from the combustion of fuels that are used in raw materials acquisition and manufacturing, except those from biomass combustion [55].
Transport Energy Credit :	Concerns CO2 emissions from the combustion of fossil fuels to transport both raw materials and intermediate products during manufacturing.
Process Non-Energy Credit :	Concerns GHG emissions (including CH_4 and N_2O) that occur during the manufacturing of certain materials and that are not associated with energy consumption.
Forest Carbon Storage :	The prevention of the release of carbon to the atmosphere. Recycling of paper increases carbon storage since it reduces the need for tree harvesting compared to a "business as usual" baseline [55].

5.1.3. Composting

The emission factors for waste types that are being composted are calculated in a similar way using the formula below.

$$\text{Emission Factor}(\text{TCO}_2\text{E/ton material}) = \text{Transport Emissions} + \text{Fugitive Emissions} + \text{Soil Carbon Storage} \quad (5)$$

Where

Fugitive Emissions :	Concerns non-CO_2 GHG emissions during composting (primarily CH_4 and N_2O).
Soil Carbon Storage :	Storage of carbon after compost application to soils. WARM only assumes the added soil carbon storage that is still present 10 years after the single application of an average amount of compost.

5.1.4. Biogasification

The emissions of biogasification are dependent on the type of biogasification that is applied. WARM is able to model dry and wet digestion with or without digestate curing. In this case, wet digestion with digestate curing is assumed as this is applicable to the Efteling case. The corresponding emission factors are calculated using the formula below.

$$\text{Emission Factor}(\text{TCO}_2\text{E/ton material}) = \text{Transport Emissions} + \text{Process Energy emissions} + \text{Avoided Utility GHG Emissions} + \text{Avoided Fertilizer Application} + \text{Soil Carbon Storage} + \text{Process Non-Energy Emissions} \quad (6)$$

Where

Avoided Utility GHG Emissions :	Avoided GHG emissions due to the production of electricity (and heat) from the combustion of biogas (methane).
Avoided Fertilizer Application :	Avoided emissions from displacing fertilizer with digestate.

(See section 5.1.2 and 5.1.3 for other definitions.)

Note that the default WARM model only takes electricity generation resulting from methane biogas combustion into account when calculating avoided utility GHG emissions. Since the heat that is generated through the same combustion process is also used to offset utility GHG emissions in the Netherlands [57], this form of energy recovery has been added to the adapted model that is used in this report.

5.1.5. Mass-burn Incineration

Incineration results in significant emissions of CO_2 and N_2O. The net emissions of waste incineration, as modelled in WARM, consist of the following components:

$$\text{Emission Factor}(\text{TCO}_2\text{E/ton material}) = \text{Gross GHG Emissions} + \text{Avoided Utility GHG Emissions} + \text{Avoided Emiss. due to metal recovery} \quad (7)$$

Where

Gross GHG Emissions :	Concerns transport emissions to an incineration facility as well as non-biogenic CO_2 emissions and N_2O emissions released to the atmhosphere through waste incineration.
Avoided Utility GHG Emissions :	Consists of the avoided GHG emissions due to the production of electricity from waste
Avoided Emiss. Metal Recovery :	Consists of the avoided GHG emissions due to the recycling of the metals recovered from incinerator bottom ash (IBA).

5.2. Economic Assessment

The economic assessment calculates the economic impact (in terms of business economic costs) of possible (alternative) theme park SWM strategies. Note that all of the costs are converted to a cost amount per year. The same SWM system boundaries as those for the LCA are utilized for this, as can be seen in figure 6. Three cost components are distinguished in the analysis, the sum of these determines the total economic costs of a certain system. The components are: collection, transportation and treatment costs. Note that MRF sorting costs, if applicable, are mostly captured in treatment costs. The composition and calculation of the different cost components will be discussed one by one in separate sections.

5.2.1. Collection

The costs of collecting waste consists of costs for the exploitation of bins and collection facilities and the maintenance of these facilities. Bins can either be purchased or rented. The latter is common practice for the Efteling. The costs of rented bins can simply be calculated by multiplying the number of bins of a certain type with the rent costs of this bin type (per year). In case of the purchase of collection facilities, the purchase price has to be divided by the depreciation period to come to a price per year, assuming linear depreciation (10 years is a standard depreciation period for containers [58, 59]). For estimating the quantities of containers that are necessary in alternative strategies, formulas 8, 9 and 10 are used. These formulas use, among others, the composition of residual waste, as found by the sorting tests mentioned earlier, and the densities of different waste types (derived from [60]) to determine how much containers are needed to separately collect a certain fraction within that residual waste. Formula 8 is used to calculate the number of containers necessary to separately collect an alternative waste fraction (other than residual waste) in BTS areas. Note that it is assumed that these containers (PMD containers in this case) substitute residual waste containers in BTS areas.

$$\#\text{Containers alternative BTS collection} = RWCs \times SAFinBTS \times \frac{RWdens}{AFdens} \times \frac{RWemptyfreq}{AFemptyfreq} \quad (8)$$

Where

$RWCs$	: Number of current residual waste containers meant for BTS collection (similar size)
$SAFinBTS$	: Share of alternative waste fraction in BTS residual waste (by weight, e.g. 0.43)
$RWdens$	: Density of residual waste (default: 150 kg/m^3 [60])
$AFdens$	: Density of alternative waste fraction (kg/m^3)
$RWemptyfreq$	: Current emptying frequency of residual waste (default: 7x per week)
$AFemptyfreq$	: Intended emptying frequency of alternative waste fraction

Formula 9 is used to calculate the number of containers necessary to separately collect an alternative waste fraction (other than residual waste) in PSP areas (relevant to strategy 3-8).

$$\#\text{Containers alternative PSP collection} = PSPcollectspots + (RWRCs \times SAFinPSP \times \frac{RWdens}{AFdens} \times \frac{RWemptyfreq}{AFemptyfreq}) \quad (9)$$

Where

$PSPcollectspots$	: Number of spots (or cocoons) for waste collection in PSP areas (Efteling: 333)
$RWRCs$	: Number of current reserve residual waste containers meant for PSP collection (reserve containers are used to replace full PSP containers in between emptying turns)
$SAFinPSP$	: Share of alternative waste fraction in PSP residual waste (by weight, e.g. 0.43)

(See formula 8 for other definitions.)

Finally, formula 10 is used to calculate the decreased number of PSP residual waste containers that are still necessary in case one or more alternative waste fractions are collected separately in PSP areas.

$$\#\text{Residual waste containers for PSP collection} = PSPcollectspots + RWRCs \times (1 - \sum_{AF=1}^{N} (SAFinPSP \times \frac{RWdens}{AFdens})) \quad (10)$$

Where

AF	: Alternative waste fraction (other than residual waste) to be separated
N	: Total number of alternative waste fractions (other than residual waste) to be separated

(See formulas 8 and 9 for other definitions.)

5.2.2. Transportation

The transportation costs are divided into costs for decentralized pick up operations, centralized pick up operations (including internal transport to facilitate central pick up) and possible 'return to supplier' transport movements. Decentral pick up operations, the most common form of waste transport in this case, are charged per hour (on theme park terrain) whereas central pick up operations are charged per transport. The transport 'quantities' (number of hours, transports etc.) necessary in the current strategy are mostly derived from actual case study data. The number of transport hours necessary in alternative strategies (in case of decentral pick up) are estimated using formula 11. This formula uses the numbers of containers that have been estimated in the previous section using formulas 8, 9 and/or 10. The number of transports necessary in alternative strategies (in case of central pick up) are based on a linear extrapolation of the current number of transports based on the expected increase in separately collected waste types.

$$\#\text{Hours alternative waste transport} = (avgDtRound + (AFCs \times avgEmpttC)) \times AFemptyfreq \times 52 \quad (11)$$

Where

$avgDtRound$	: Average driving time on theme park terrain per round (without stopping)
$AFCs$	: Number of containers for the separate collection of alternative waste fraction (derived from formulas 8 and 9) or, in case of residual waste, the number of residual waste containers (derived from formula 10)
$avgEmpttC$	: Average emptying time per container
$AFemptyfreq$	: Intended emptying frequency of alternative waste fraction per week (should match with AFemptyfreq in formulas 8 and 9)

5.2.3. Treatment

Waste treatment costs are charged per ton of waste but differ strongly per waste type. There are also waste types, like glass, PET bottles or oil, that have negative treatment costs which means that offering these waste types for treatment actually generates revenue. For calculating alternative treatment costs, it is assumed that the total amount of waste remains constant. This means that residual waste is being substituted by separately collected waste types depending on the type of strategy. This substitution is captured by formula 12.

$$\text{Alternative residual waste quantity} = CurrentRWQ - AFQ \quad (12)$$

Where

$CurrentRWQ$	: Current residual waste quantity
AFQ	: Total quantity of separately collected fraction(s) in alternative strategy

6. Case Study Results

In this section, the alternative high potential SWM strategies for the Efteling that have been derived in section 4.2 will be assessed based on the KPI's from section 4.1. The calculation of the KPI's is based on the procedures and models described in the previous section.

6.1. Main Results

The case study results can be found in tables 7 and 8 and are also visualised in figure 7. Table 7 contains the main results whereas the results for strategies that rely on a 'return to supplier' transport scheme are listed in table 8. The latter strategy results have been separated because 'return to supplier' strategies cannot be implemented unilaterally by the theme park. These strategies may actually be cheaper than the current strategy but their implementation is dependent on external (political) factors. Furthermore, it should be noted that all of the results in this section assume a recovery rate of 100%. This

Strategy		PSP Collection		BTS Collection	Transport & Treatment	Environmental Impact	Economic Impact	Eco-efficiency		
#	sub	*Fractions **	*Manual sort*	*Fractions ***	*Alteration relative to current strategy*	*Relative to base (TCO_2E/year)*	*Relative to base (€/year)*	*kg CO_2E saving / €*	*€ / TCO_2E saving*	Rank
1	A		*PET bottles*			*0.00*	*€ -*	0.00	€ -	*-*
2	A		*PET bottles*	*PMD*		*-189.21*	*€ 9,730*	19.45	€ 51.43	*2*
3	A	*PET bottles*		*PMD*		*-496.17*	*€ 19,311*	25.69	€ 38.92	*1*
4		*PMD*		*PMD*		*-797.45*	*€ 110,445*	7.22	€ 138.50	*5*
5		*plastic*		*PMD*		*-613.40*	*€ 61,590*	9.96	€ 100.41	*4*
6	A	*paper + PMD*		*PMD*		*-957.81*	*€ 133,793*	7.16	€ 139.69	*6*
7	A	*swill + PMD*		*PMD*		*-800.18*	*€ 279,509*	2.86	€ 349.31	*9*
	B	*swill + PMD*		*PMD*	*Local composting*	*-861.68*	*€ 69,878*	12.33	€ 81.09	*3*
8	A	*cups + PMD*		*PMD*	*Cups central pick-up*	*-958.18*	*€ 134,021*	7.15	€ 139.87	*7*
	B	*cups + PMD*		*PMD*	*Cups decentral pick-up*	*-958.18*	*€ 148,236*	6.46	€ 154.71	*8*

**Residual waste always included*
***Base set always included*

Table 7: Results for alternative high potential SWM strategies (recovery rate:100%)

means that the waste types that are being separated and recycled in certain strategies are recovered from residual waste with an efficiency of 100%.

Strategy 1A is the current strategy (base strategy) and therefore has an environmental and economic impact of 0 relative to base. All of the other (alternative) strategies result in less GHG emissions, and thus in a more positive environmental impact, compared to the current strategy, just as they were designed to. The two eco-efficiency KPI's that have been described in section 4.1 are reported in the columns on the right side. The rightmost column contains a ranking of the alternative strategies based on their eco-efficiency.

From table 7, it can be concluded that the environmental as well as the economic impact of the alternative strategies differ strongly per strategy. Generally, an increased share of separate collected recyclable materials in BTS as well as PSP areas results in an increasingly low quantity of emissions. At the same time, this generally results in higher yearly operational costs.

Starting with the alternative strategies that have the least economic impact, it can be seen that strategy 2 (BTS PMD collection) already has quite a significant environmental impact. Almost 190 tonnes of CO_2E's can potentially be saved with this on a yearly basis. This corresponds to an increase in yearly avoided SWM system emissions of about 25% for the Efteling case (from a life-cycle perspective). Since it is a relatively 'cheap' strategy, the resulting eco-efficiency of implementing strategy 2 is also quite high. The same goes for strategy 3 (PSP PET collection + BTS PMD collection) which is ranked as the most eco-efficient strategy. Strategy 3 is a bit more expensive than strategy 2 (lower treatment costs as a result of less residual waste but higher collection costs) but it also results in more than double the amount of CO_2E's savings. The B variants of strategies 1,2 and 3 that implement a 'return to supplier' transport scheme for PET bottles do not result in much emission savings but do have a considerable economic impact (see table 8). Especially strategy 3B is way cheaper than strategy 3A.

Among the more 'expensive' strategies, the emission savings are between approximately 500 and 1000 tonnes of CO_2E's per year. To indicate the significance of this in a wider context, 1000 tonnes of CO_2 corresponds to the CO_2 sequestered by approximately 40,000 trees over a year of time [61]. Of the strategies that separately collect a single fraction in PSP areas, PMD collection (strategy 4) is by far the most effective in terms of reducing emissions, followed by plastic and PET bottles. The increases in yearly avoided SWM system emissions are 109%, 84% and 68% respectively. The separate collection of PMD in

Strategy		PSP Collection		BTS Collection	Transport & Treatment	Environmental Impact	Economic Impact	Eco-efficiency	
#	sub	*Fractions **	*Manual sort*	*Fractions ***	*Alteration relative to current strategy*	*Relative to base (TCO_2E/year)*	*Relative to base (€/year)*	*kg CO_2E saving / €*	*€ / TCO_2E saving*
1	B		*PET bottles*		*PET return supplier*	*-0.16*	*-€ 1,779*	-0.09	€ -11,121
2	B		*PET bottles*	*PMD*	*PET return supplier*	*-189.49*	*€ 7,951*	23.83	€ 41.96
3	B	*PET bottles*		*PMD*	*PET return supplier*	*-497.55*	*€ 5,473*	90.90	€ 11.00
6	B	*paper + PMD*		*PMD*	*Paper return supplier*	*-957.81*	*€ 131,677*	7.27	€ 137.48

**Residual waste always included*
***Base set always included*

Table 8: Results for alternative high potential 'return to supplier' SWM strategies (recovery rate:100%)

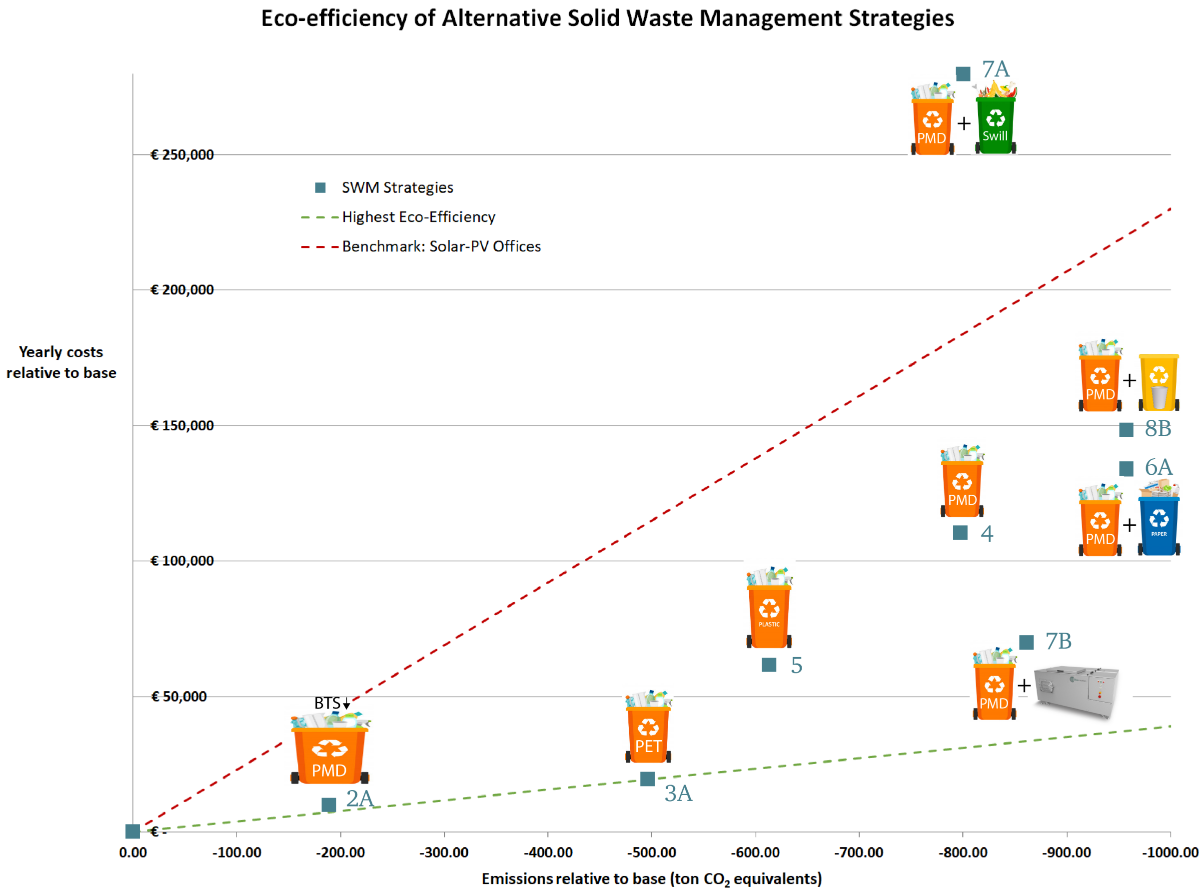

Figure 7: Visualisation of environmental and economic impact (eco-efficiency) results of alternative strategies

PSP areas is, in fact, so effective that it results in an environmental impact that is close to the impact of separately collecting two different fractions in PSP areas. However, the separate collection of PMD in PSP areas is also relatively expensive compared to the separate collection of plastic and PET bottles. Additionally, the recovery rate (purity) of PMD may be worse than the purity of PET bottles or plastic.

Among the strategies that implement a collection scheme in which two fractions are separated in PSP areas on top of BTS PMD collection, strategy 8 is able to achieve the highest emission savings. The difference in terms of environmental impact with strategies 6 and 7 is however fairly small. The increase in yearly avoided SWM system emissions ranges between 131% for strategies 6 and 8, and 109% for strategy 7A. Swill (food waste) is shown to only have a minor additional impact on emission savings (Strategy 7A is similar to strategy 4). However, swill does have a considerable economic impact. Especially the difference between strategy 7A and 7B is striking. In the case of implementing strategy 7 (separating PSP swill), local composting is way cheaper than central composting in combination with decentral pick up transport. This also results in a way higher eco-efficiency for strategy 7B relative to strategy 7A. The eco-efficiencies of the other 'two-fraction-strategies' are fairly close to one another. It must be noted that although strategies 2 and 3 have the highest eco-efficiency, these strategies can achieve a maximum amount of CO_2E savings of approximately 200 and 500 tonnes respectively. Other strategies can potentially save more than double this amount but do this against a higher cost per saved kilo of CO_2 equivalent.

6.2. Benchmarking Alternative SWM Strategies

The eco-efficiency scores that were calculated for every (alternative) strategy in the previous section can be used to benchmark the effectiveness of these strategies. This means that they can be used to compare the effectiveness of these SWM strategies with the effectiveness of other standards in the context of sustainable development. Such standards can be found in other sectors such as the electricity (utility) sector and the built environment sector. Additionally, the price of a European Allowance Credit in the EU Emissions Trading System (ETS) may also be used as a benchmark (reference value). Owning an allowance credit grants a company in the EU the right to emit GHG emissions equivalent to the global warming potential of 1 tonne of CO_2 equivalent (TCO_2E) [65].

Table 9 shows the benchmarking results for the alternative SWM strategies for the Efteling. Every column on the right side of the table represents a different benchmark. Strategies that are more eco-efficient or, in other words, achieve a CO_2E reduction of 1 tonne against lower costs, than the benchmark have a check mark in the corresponding box. As one can see in the table,

Strat. #	sub	PSP Collection: Fractions *	PSP Collection: Manual sort	BTS Collection: Fractions **	Transport & Treatment: Alteration relative to current strategy	Eco-efficiency: € / TCO_2E saving	EU Allowance credit (ETS): Current price: €29 [1]	EU Allowance credit (ETS): High scenario 2030: €55 [2]	Electric Energy Production: Nuclear Energy: €95 [3]	Electric Energy Production: Solar-PV Industrial Scale: €130 [3]	Electric Energy Production: Wind at sea: €140 [3]	Electric Energy Production: Solar-PV Offices: €230 [3]	Built Environment: ATES[4] for offices: €360 [3]	Built Environment: Insulation of offices: €2060 [3]
2	A		PET bottles	PMD		€ 51.43		✔	✔	✔	✔	✔	✔	✔
3	A	PET bottles		PMD		€ 38.92		✔	✔	✔	✔	✔	✔	✔
4		PMD		PMD		€ 138.50					✔	✔	✔	✔
5		plastic		PMD		€ 100.41				✔	✔	✔	✔	✔
6	A	paper + PMD		PMD		€ 139.69					✔	✔	✔	✔
7	A	swill + PMD		PMD		€ 349.31							✔	✔
	B	swill + PMD		PMD	Local composting	€ 81.09			✔	✔	✔	✔	✔	✔
8	A	cups + PMD		PMD	Cups central pick-up	€ 139.87					✔	✔	✔	✔
	B	cups + PMD		PMD	Cups decentral pick-up	€ 154.71						✔	✔	✔

**Residual waste always included*

***Base set always included*

✔ SWM strategy is more eco-efficient than benchmark

[1] EUA price on 15-07-2020 [62]
[2] High CO_2 credit price used in sensitivity analysis [63]
[3] National costs per ton CO_2 reduction in 2030 [64]
[4] Aquifer thermal energy storage

Table 9: Benchmarking results for alternative high potential strategies (recovery rate:100%)

strategies 2A and 3A perform better than any of the benchmarks except the current price of an EU allowance. This means that these strategies reduce GHG emissions against lower costs than any (listed) means of sustainable electricity production and any (listed) means of sustainable building management. This latter statement is also true for strategy 7b. Strategies 2A and 3A are even more cost-effective (within their emission reduction range) than buying EU allowances for emissions in 2030, assuming the high scenario for allowance prices [63]. This is remarkable since there are actually many concerns regarding the low price of EU allowances due to the oversupply of allowances [63].

Although many of the other SWM strategies (4, 5, 6, 7 etc.) are more expensive than EU allowances (per ton CO_2E) they are generally more eco-efficient than sustainable electricity production from wind at sea and solar PV panels at office buildings. The latter benchmark is also plotted as a red line in figure 7. Since small-scale (household) sustainable energy production is even more expensive [64], the SWM strategies are also more eco-efficient than these forms of electricity production. A few strategies are even more eco-efficient than nuclear energy and/or solar PV panels at large (industrial) power plants. Measures to reduce GHG emissions in the built environment are generally way less eco-efficient than implementing alternative SWM strategies, as can be seen in table 9. The only strategies that perform worse than a majority of the benchmarks are strategies 7A and 8B.

The results of the benchmarking process indicate that optimizing waste management is generally more cost-effective, in terms of reducing emissions, for theme parks than investing in sustainable electricity or sustainable buildings.

6.3. Uncertainty Analysis

The modelling results have also been analyzed with respect to uncertainties. The relative uncertainties of the (choice) parameters that are described as being uncertain in the WARM documentation or that were found to be uncertain by the modeller were calculated. A relative uncertainty indicates the range over which the TCO_2E benefits of a strategy may differ (relative to the default benefits as presented in tables 7 and 8) as a result of varying a parameter value within its uncertainty range. It was found that the material recovery rate (as described in section 3.1) causes, by far, the highest relative uncertainty in the results. In other words, it is a very important parameter that is also very uncertain. Therefore, this parameter has been analyzed into more detail using a scenario analysis. Until now, a material recovery rate of 100% has been assumed to calculate the environmental and economic impact of the current and alternative SWM strategies. In the scenario analysis, a lower recovery rate of 80, 60 or even 40% is assumed. The analysis reveals that a lower material recovery rate results in less emission reductions and thus in less environmental benefits. However, even with a recovery rate of only 40%, which is a conservative estimation of the minimum recovery rate in public spaces [66], the emission reductions are still quite significant for many alternative strategies. Strategies 2, 3, 4 and 7B achieve emission savings of 76, 198, 319 and 370 TCO_2E's per year respectively (increases of 10 up to 51%) with only 40% of the fractions to be separated being recovered from residual waste.

7. Conclusions and Recommendations

Based on an integrated waste management (IWM) approach, it was found that many alternative solid waste management (SWM) strategies can be designed to improve the sustainability of SWM in theme parks and (semi-)public spaces in general. The approach takes into account that the collection, transportation, sorting and treatment of different waste types are interrelated. A morphological analysis of the current SWM system allowed the systematic composition of alternative SWM strategies. However, only few of these strategies proved to be viable and internally consistent and also significant in terms of emission reduction potential. The strategies that do meet these criteria differ widely in terms of their (relative) environmental and economic impact.

The LCA that was conducted for the SWM strategies for the case study at hand showed that emissions reductions of almost 190 ton CO_2 equivalents (TCO_2E's) per year, relative to the current strategy, can already be achieved by separating (and recycling) more recyclable fractions from behind-the-scenes waste. This corresponds to an increase in yearly avoided SWM system emissions of about 25% for the Efteling case (from a life-cycle perspective). When public/semi-public waste is also separated and recycled, emission reductions of up to 800 TCO_2E's per year can be achieved for single-fraction separation (e.g. PMD, plastic or PET) and up to 960 TCO_2E's per year for two-fraction separation (e.g. PMD + paper or PMD + cups). This corresponds to increases in avoided SWM system emissions of 110% and 131% respectively. It must however be noted that there is a general trade-off between the environmental benefits of a SWM strategy and the costs of a strategy. Two-fraction separation was commonly found to be more expensive compared to single-fraction separation but the cost differences within these strategy types are quite large and depending on the fraction(s) being separated. It was also found that relatively small interventions in the transportation and/or treatment SWM system components are able to make a big difference in the environmental and/or economic impact of a SWM strategy. Return to supplier transport schemes and local composting treatment means can save a lot of costs. The cost difference between local composting (by theme park) and external treatment of food waste was found to be more than €200,000 per year. Local composting may also save a lot of emissions. Return to supplier transport can save between €1800 and €15,000 per year but it requires cooperation in the SWM chain. Return to supplier transport does not have significant environmental benefits.

Finally, the environmental and economic performances of improved SWM strategies have also been converted into integrated 'eco-efficiency' indicator scores. These help to make decisions on SWM strategies by taking the tradeoff between emission reductions and costs into account. The eco-efficiency scores show that some improved strategies are able to realise very high emission reductions per extra unit of operational costs. The highest score of almost 26 kg's of CO_2E reductions per extra Euro or its equivalent of €38.92 per TCO_2E reduction is related to the full separation and recycling of PET bottles in combination with the separation and recycling of PMD in behind-the-scenes waste. It should however be noted that the eco-efficiency indicator does not say anything about the range over which a certain strategy can reduce emissions. Strategies with a higher emission reduction potential generally have a lower eco-efficiency score of about 7 kg's of CO_2 reduction per extra Euro. This corresponds to about €140 per TCO_2E reduction. In line with the IWM approach, choosing a certain SWM strategy, which includes trading off eco-efficiency and emission reduction potential, should be done according to 'local' conditions such as the relative importance of the formulated objectives (budget but also space, staffing etc.).

The high eco-efficiency that was attributed to several alternative SWM strategies for the case study should also be applicable to similar strategies in other contexts. This means the results are not only relevant for other theme parks but also for other companies and parties that manage (semi-)public spaces. Furthermore, it was found that many of the alternative SWM strategies for the case study perform better, meaning more cost-effective, at reducing GHG emissions than a range of benchmarks. These benchmarks include sustainable electricity production from wind at sea and solar PV plants as well as sustainability measures in the built environment such as building insulation. The results of the benchmarking process indicate that optimizing waste management is generally more cost-effective, in terms of reducing emissions, for semi-public spaces than investing in sustainable electricity or sustainable buildings and should therefore also be prioritized. The results also justify an increase in the amount of (scientific) research into sustainable waste management. Given that worldwide waste quantities are rising and that many theme parks and semi-public spaces are struggling with their commitments to reduce their environmental footprint, the case study results show that researching and implementing more sustainable solid waste management strategies can definitely make a difference.

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Appendix A. WARM Model Calibration

As mentioned in section 5.1.1, several default parameters of the WARM model have been adapted to better reflect the actual conditions in the Netherlands and the conditions applicable to the SWM system of the Efteling. The process of adapting these parameters is also referred to as model calibration. The following adaptations have been made:

- The default transportation distances to material recovery facilities (recycling facilities) have been adapted based on the actual distances that are applicable in the case of the Efteling. These distances are dependent on the type of waste.

- The transportation distance to an incineration facility has been increased from 32 kilometers (default) to 91 kilometers. The adapted transportation distance is the average of the distance to all of the incineration plants that treat waste of the case study (Efteling) including the internal transport distance

- Heat generated through the combustion of biogas that is produced from anaerobic digestion is now also used to offset utility greenhouse gas emissions next to electricity.

- The electric energy generation efficiency of waste incineration plants has been increased from 17.8 to 20.3 % based on the actual efficiency of the three Dutch incineration plants that are used to treat waste of the Efteling [67].

- The electric energy mix that is used to calculate the greenhouse gas offsets resulting from electricity production by waste incineration and biogas combustion has been adapted to the energy grid in the Netherlands. This results in less GHG offsets per megawatt hour as the energy mix in the Netherlands consists of a higher share of renewable energy production.

- Metal recovery at waste incineration plants has been extended to also include aluminium (non-ferrous metal) recovery. The applied recovery efficiency is the average of the recovery efficiency's of the Dutch incineration plants that treat Efteling waste [67].

The emissions caused by the current SWM strategy are higher in the calibrated model than in the default model since the environmental benefits of mass-burn incineration have decreased as a result of a more sustainable energy mix (that is being offset by energy recovery from waste) compared to the default model.

Efteling Park Map

Chapter C

Morphological Box Example for TU Delft (Campus) Case

Figure C.1 shows that the morphological box created in chapter 6 can also be used to analyze and design SWM strategies for totally different cases than the Efteling such as the TU Delft University Campus. The figure shows the current SWM strategy of the campus based on TU Delft (2019).

Functions	PSP Collection			BTS Collection		Transportation			Central Sorting	Treatment		
Options	**Fractions**	**Separate collect**	**Manual Sorting**	**Fractions**	**Separate collect**	**Decentral pick up**	**Central pick up**	**Return supplier**		**Recycling**	**Biological**	**Thermal**
1	*Residual Waste*	*No*	*PET bottles*	*Residual Waste*	*7 fractions*	*Residual Waste*	*Paper*	*Paper*	*No central sorting*	*Paper and card*	*Local Composting*	*Mass-burn incineration*
2	*Paper*	*2 fractions*		*Paper*	*8 fractions*	*Paper*	*Glass*	*PET bottles*	*MRF sorting*	*Glass*	*Central Composting*	
3	*PET bottles*	*3 fractions*		*Glass*	*9 fractions*	*Glass*	*PET bottles*	*Foil*		*Ferrous metal*	*Bio-gasification*	
4	*Swill*			*PET bottles*	*10 fractions*	*PET bottles*	*Foil*			*Non-ferrous metal*		
5	*PMD*			*Swill*		*Swill*	*Cups*			*Plastic*		
6	*Plastic*			*Fat and oil*		*Fat and oil*	*Garden Waste*					
7	*Cups*			*PMD*		*PMD*						
8				*Foil*		*Foil*						
9				*Cups*		*Cups*						
10				*Garden Waste*								

Not applied in base strategy
Applied in base strategy
Partly applied in base strategy

Table C.1: Morphological box of current TU Delft SWM strategy

Chapter D

Sensitivity Analysis of PSP Collection Combinations

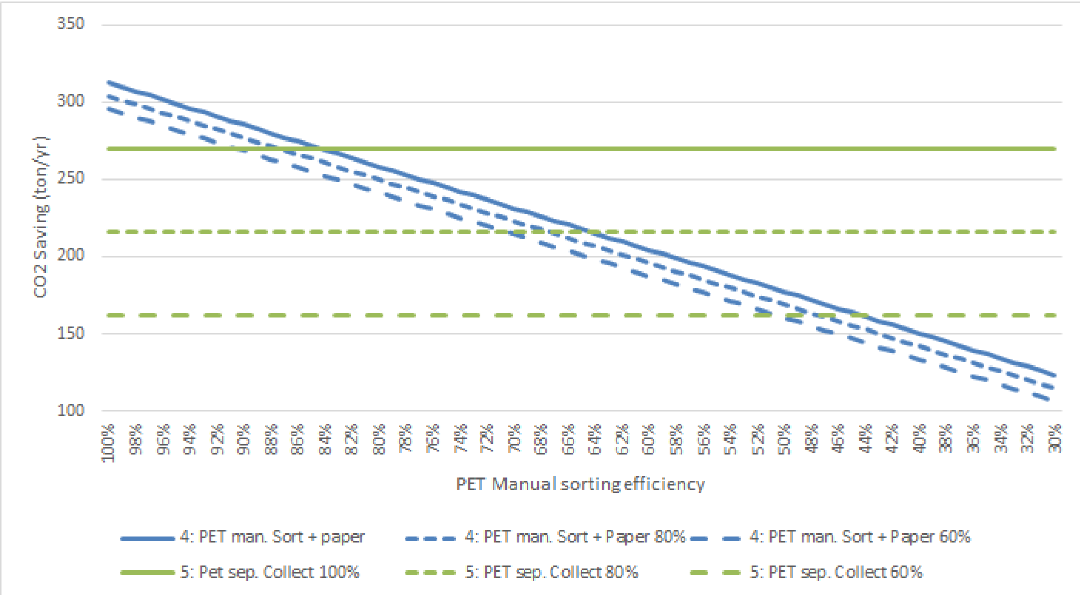

Figure D.1: Sensitivity Analysis of PSP collection options from section 6.2.1

Figure D.1 visualizes the sensitivity analysis that was performed on options #4 and #5 of table 6.6 which contains all possible PSP collection combinations. Option #4 refers to separately collecting paper and manually sorting PET bottles from residual waste while option #5 refers to separately collecting PET bottles. In the sensitivity analysis, the manual sorting efficiency of PET bottles is varied to evaluate the effect of this on the CO_2 saving potential of options #4 and #5. Note that the options #8 and #14 also rely on the manual sorting of PET bottles. However, these options are, for all values of the sorting efficiency, below the CO_2 saving line of option #4. This means that if option #5 results in more CO_2 savings than option #4, it also results in more CO_2 savings than options #8 and #14.

In the case of a manual sorting efficiency of 100%, which means that all of the PET bottles can be separated from the residual waste and subsequently recycled, option #4 is able to achieve the highest level of CO_2 emission savings. However, given that the current efficiency of PET bottle separation via manual sorting is 14,62/(0,15*662,9)=15% (numbers derived from sections 4.2.3 and 6.2) with considerable effort being put in, an efficiency of 100% is deemed to be very unrealistic. When the manual sorting efficiency becomes 84% or lower, option #5 becomes the option with the highest CO_2 saving potential. As one can see in figure D.1, not only the manual sorting efficiency has been varied, the separate collection efficiency of paper for option #4 and PET bottles for option #5 have also been varied. When a lower separate collection efficiency of 80% is assumed, which means that 20% of the paper and PET bottle fractions is still being processed as residual waste, a manual sorting efficiency of 68% or higher is necessary for option #4 to have the highest CO_2 saving potential. This is still very high given the current sorting efficiency. When assuming a separate collection efficiency of only 60% for both paper and PET bottles, the 'switching' value of manual sorting efficiency becomes 51%. This means that when the manual sorting efficiency is equal to 51% or higher, option #4 scores best, when it is lower than 51%, option #5 scores better instead. Since it is deemed to be way easier to achieve a separate collection efficiency of 60% or higher than a manual sorting efficiency of 51% or higher, option #5 was selected as a 'high potential combination' as opposed to options #4, #8 and #14.

Chapter E

WARM Model Factors

Material	Transport for virgin production	Retail transport virgin product	Transport to Recycling Center (Custom)	Transport for recycled production	Retail transport recycled product	Difference recycled and virgin production
Aluminium Cans	0.08	0.03	default (0)	0.03	0.03	-0.04
Steel Cans	0.37	0.03	default (0)	0.33	0.03	-0.04
Glass	0.04	0.03	0.01	0.02	0.03	-0.01
HDPE	0.17	0.04	0.03	0.19	0.04	0.06
PET	0.08	0.04	0.01	0.21	0.04	0.13
PET (return supplier)	0.08	0.04	0.00	0.21	0.04	0.12
Corrugated Containers	0.11	0.06	0.01	0.07	0.06	-0.04
Magazines	N/A	0.02	0.01	N/A	0.02	0.01
Office Paper	N/A	0.02	0.01	N/A	0.02	0.01
Mixed Paper (general)	0.06	0.06	0.01	0.02	0.06	-0.02
Mixed Plastics	0.11	0.04	0.03	0.20	0.04	0.11

Table E.1: WARM transportation emissions to model recycling in TCO_2/ton of material (US EPA, 2019c)

Material	Mass of Methane Generated (kg/ton)	Mass of Methane Leaked (kg/ton)	Mass of Methane Flared (kg/ton)	Mass of Methane Combusted for Energy (kg/ton)	Energy from Combusted Methane (MMBtu/ton)	Electicity Generation[1] (kWh/ton)	Net Electricity to the Grid[2] (kWh/ton)	Net GHG offset[4] (TCO_2E/ton)
Food Waste	59,96	1,2	8,81	49,94	2,37	250,05	220,04	0,07
	""	""	""	""	""	Warmth Generation[1] (kWh/ton)	Net Warmth for useful purposes[3] (kWh/ton)	Net GHG offset[5] (TCO_2E/ton)
Food Waste	59,96	1,2	8,81	49,94	2,37	277,83	158,36	0,03
							Total:	0,10

[1] Energetic conversion efficiency of 36% for electricity and 40% for warmth based on the average of 19 Dutch biogasification installations (Agentschap NL, 2013)

[2] 88% is delivered to the grid and 12% is used by the installation itself based on the average of 19 Dutch biogasification installations (Agentschap NL, 2013)

[3] 57% is deployed for useful purposes, the other part is used by the installation itself or lost based on the average of 19 Dutch biogasification installations (Agentschap NL, 2013)

[4] Based on the average Dutch electricity generation emission factor of 0.3 TCO_2/MWh (PBL, 2019)

[5] Based on the Dutch natural gas emission factor of 1.884 kg CO_2/Nm3 (1Nm3 = 9,769 kWh) (Rijkswaterstaat, 2020b)

Table E.2: Avoided utility GHG emissions from anaerobically digesting food waste with warmth and electricity recovery per short ton (adaptation of US EPA (2019d))

Material Combusted	Energy content (Million Btu per short ton)	Mass Burn Combustion System Efficiency	Emission factor for utility generated electricity (TCO_2E/Million Btu of electricity delivered)*	Avoided utility GHG emissions per short ton combusted (TCO_2E)	Avoided utility GHG emissions per metric ton combusted (TCO_2E)
Aluminium Cans	-0.67	20.3%	0.0879	-0.01	-0.01
Steel Cans	-0.42	20.3%	0.0879	-0.01	-0.01
HDPE	39.97	20.3%	0.0879	0.71	0.79
PET	21.20	20.3%	0.0879	0.38	0.42
Corrugated Containers	14.09	20.3%	0.0879	0.25	0.28
Food Waste	4.74	20.3%	0.0879	0.08	0.09
Mixed Paper (general)	14.14	20.3%	0.0879	0.25	0.28
Mixed Plastics	28.71	20.3%	0.0879	0.51	0.56
Mixed MSW	10.00	20.3%	0.0879	0.18	0.20

* 0.300 TCO_2E/MWh = 0.0879 TCO_2E/Million Btu

Table E.3: Avoided utility GHG emissions from waste incineration with electricity recovery (adaptation of US EPA (2019d))

Chapter F

Waste densities

See section 7.2 of chapter 7 for explanation.

Waste Type	**Density (kg/m^3)**
Residual Waste (unsorted)	150
PMD	60
PET	50
Plastic	50
Paper	120
Swill	1000
cups	80

Table F.1: Waste densities used in formulas 7.5, 7.6 and 7.7 (Stichting Stimular, 2020)