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THE CARBON FOOTPRINT OF WASTE MANAGEMENT SYSTEMS – ANALYSIS AND COMPARISON OF DIFFERENT APPROACHES

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ANALYSIS AND COMPARISON OF DIFFERENT APPROACHES

BY

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ABSTRACT

The emission of greenhouse gases (GHG) and their impact on global warming have been researched broadly for several decades. With an increasing attention in both politics and science, the issue of GHG emissions was found to have an extensive impact on legislation, society and the economy. The transportation sector, the industrial sector, the electricity sector and the waste management sector are considered to be the major contributors to the GHG emissions.

Investigating the waste management sector and its GHG releases, it is of public and private interest, which waste management system – Material Recycling Facility (MRF), Municipality Landfill or Waste-to-Energy Plant (WTE plant) - contributes the most to these emissions.

Therefore, the objective of this study is to evaluate the three WMS concerning their environmental impacts and to compare their performance in terms of their GHG releases, including the three major green house gases: carbon dioxide, methane and nitrous oxide. However, the main focus is on the MRF, for which data was provided by the MRF of the *Rhode Island Resource Recovery Company (RIRRC)* for a real world case study.

For the comparison, the processed amount of waste and the share of composition for each WMS is assumed to be identical. The reference for this amount is given by the waste collected at the curbside of the municipality of Rhode Island within one year. Hence, the compared carbon footprints also include the total amount of GHGs emitted per year from each WMS. For modeling the WMS and the subsequent assessment of the GHGs, the “GaBi 6 Sustainability Software” is utilized.

The results show the total performance of each WMS considering its environmental impacts, emphasizing the MRF of the RIRRC by far as the WMS with the lowest emissions per year. The next WMS in the order is the WTE plant, which however has nearly an eight times higher emission of GHGs as the MRF. The landfill takes the last place in this comparison with a ten times higher amount of emissions per year as the MRF.

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1 Introduction

1.1 Background and Problem Statement

The emission of greenhouse gases (GHG) and their impact on global warming have been researched broadly in literature. With an increasing attention in both politics and science, the issue of GHG emissions was found to have an extensive impact on legislation, society and the economy. Its importance in public rose rapidly since the 1970s when the first significant increase in average temperature of the air and sea at earth's surface was measured.

As a result, many industrial countries signed the Kyoto protocol in 1997, an additional treaty to the already existing United Nations Framework Convention on Climate Change (UNFCCC). Major parts of this treaty involved the agreement of developed countries to legally bind to limitations and reductions in their emissions of greenhouse gases. More than ten years later, in 2011, the waste management sector still contributed nearly 261.04 million tons of carbon dioxide to the total amount of emissions in the United States, which is corresponding to 4 percent. Although, this number might seem to be little, in terms of a general reduction of the GHG emissions worldwide and especially in the United States, this share can significantly change the current gap of required emission reductions (Weitz *et al.*, 2002).

Investigating the waste management sector and its GHG releases, it is of public and private interest, which waste management system – Material Recycling Facility (MRF), Municipality Landfill or Waste-to-Energy Plant (WTE plant) - contributes the most to these previous mentioned emissions. Therefore, an examination of each WMS is required considering its environmental impacts. To provide a real world relevance of such a study, appropriate data for the different WMS has to be collected and analyzed subsequently. The data for a standard MRF will be provided by the MRF of the *Rhode Island Resource Recovery Company (RIRRC).*

Supporting current improvements for environmental concerns by means of an extensive analysis, the underlying problem of this thesis is the comparative assessment of the aforementioned waste management systems.

1.2 Objective and Structure

As an important part of sustainable development, the reduction of waste and thus waste management systems are highly relevant. Considering the problem stated above, the objective of this study is to evaluate the three WMS, MRF, municipality landfill and WTE plant concerning their environmental impacts and to compare their performance in terms of their GHG releases. The main focus is on the MRF, for which data was provided by the MRF of the RIRRC for a real world case study.

This thesis provides an extensive overview of three different waste management systems (WMS), a Material Recovery Facility (MRF), a Municipality Landfill and a Waste-to-Energy Plant (WTE plant), and their related environmental impacts in terms of greenhouse gas emissions. Furthermore, these waste management systems will be modeled by means of sustainability assessment software and their carbon footprint will be measured concerning the three major green house gases, carbon dioxide, methane and nitrous oxide. The results will be subsequently compared with each other aiming to determine the waste management system with the lowest amount of emissions.

While the first section of this chapter presents the background of the study and exposes the concerns that justify research in this field, this second section describes in detail the derived objective of this study and provides an overview of the procedure by which the objectives can be achieved.

The second chapter includes the theoretical foundation of this thesis. Initial point is the presentation of the basic concept of sustainability as well as the history of its development. In the next step, assessment tools for sustainability are analyzed and discussed in detail considering their suitability for achieving the objective of this thesis. Outgoing from that analysis, both the LCA and carbon footprint assessment are considered as the most suitable tools for this study. They are therefore explained as well in detail and the carbon footprint is defined in terms of the objective. Subsequently, several sustainability software is presented, that implements both assessment tools. This software is compared concerning their functions and general availability for an average user. The theoretical foundation ends with an overview of the three regarded WMS, describing each system and its processes in general.

In the third chapter, the previous theoretically described assessment tools are practically applied on a real world case study. Within the case study the main focus is on the MRF of the RIRRC for which primary data is provided. For the WTE plant and the landfill, general systems with standard processes are assumed and the chosen sustainability software mainly provides the data.

In the first step of this chapter, the scope and the general system boundaries of this study are determined. Subsequently the MRF is modeled in the sustainability software and an LCA is performed for it. Simultaneously the software is used for measuring the systems carbon footprint. While in this LCA the MRF is examined on a general level, a second LCA is performed for a particular material that is processed in this MRF regarding more specifically certain process stages of the entire material recovering process chain.

In the last step, the two other WMS are modeled in the sustainability software and their carbon footprint is assessed. Their results are then used for detailed comparison of the three WMS considering their particular emissions.

The procedure for this thesis is illustrated in figure 1.1 below.

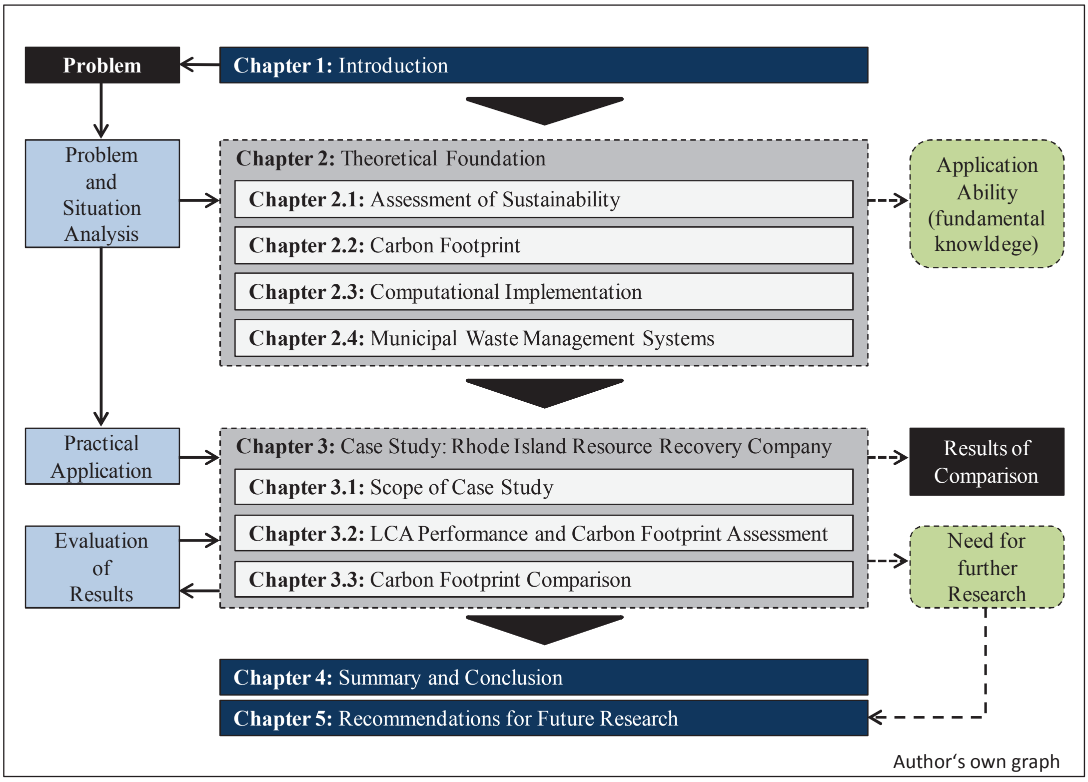


Figure 1.1: Overall procedure of the study

2 Theoretical Foundation

In the beginning of this chapter, the basic concept of sustainability as well as the history of its development is presented. In the next step, a literature review is done on existing tools for the assessment of sustainability. Different tools are therefore regarded with the ambition to find the most suitable for the objective of this thesis. The two chosen tools, the LCA and the carbon footprint assessment are subsequently explained in detail including guidelines for the application of these tools on a real case.

In addition to that, a comparison of different LCA software packages is made considering the one which suits best for performing an LCA of the given WMS and which includes additionally functions for measuring GHGs regarding the carbon footprint.

In the last phase of this chapter, a general overview of the current waste management sector in the United States is presented. Furthermore, the three WMS that are compared later considering their environmental impacts are introduced and a detailed description of them is provided.

2.1 Assessment of Sustainability

2.1.1 Sustainability

The continuous striving for "sustainability" all over the world is a result of the growing levels of resource consumption coupled with a significant increase of the population size that has lead to a high expenditure of natural resources during the last several decades. Many developments, products, production systems and services claim to be sustainable today and the term is widely used in a diverse range of context whether in political debates or in different fields of science. However, there is a lack of definition surrounding exactly what sustainability or sustainable development means. In most cases when the term is used, the definition and the meaning are not clear.

Historical Background

Although the terms "sustainable" or "sustainability" seem to be comparatively new and modern, their roots have been a part of language for thousands of years and can be derived from the Latin word "sus tenere" with the meaning "to sustain" or "to maintain" (Ehnert, 2009). Figure 2.1 illustrates the development of sustainability on a timeline, starting in the 1960s with an ongoing political and economic debate about natural and social boundaries of the worldwide economic growth.

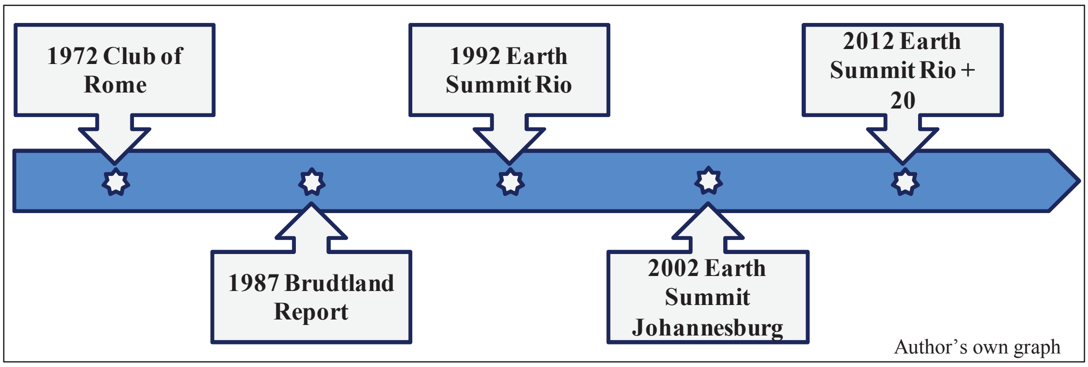


Figure 2.1: Timeline for the development of sustainability

Setting the stage for active pursuit of sustainability, in 1972, the Club of Rome, an informal association of independent leading personalities from politics, business and science presented some challenging scenarios for global sustainability in their report "Limits to growth". In it, they simulated based on a dynamic computer model, interactions of five global economic subsystems, namely: population, food production, industrial production, pollution, and consumption of non-renewable natural resources (Meadows, et. al. 1972). One of their main findings was that the absolute limits of growth on earth would be reached during the next century if the population, industrialization, environmental pollution, food production and the exploitation of natural resources continued to increase at the current rate. However, their results stated simultaneously that there are possibilities to change the tendencies towards an ecological and economical balance that could even upheld in the future. This report gained enormous media attention and led to an increasing consciousness worldwide that environmental problems require international cooperation and joint actions from governments to be solved (Herrmann, 2010).

A few years later in 1987 the terms "sustainable development" and "sustainability" gained further prominence and attention when the United Nations' World Commission on Environment and Development published its report “Our Common Future”, commonly known as the Brundtland report, named after the Commission Chair, Gro Harlem Brundtland. The report presented a new concept called “sustainable development”. The central recommendation of this approach was to meet the challenges of environmental protection and economic development (UNECE, 2014). The commission defined “sustainable development” in their report as "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" (Brundtland p.43).

This report is by far the most cited publication today and a tremendous milestone toward sustainability. Moreover, it found an eager audience at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992, during which documents were approved, notably the comprehensive Agenda 21 that included ambitious commitments by world leaders to ensure sustainable development in many areas and on all levels of society. An additional positive result of the conference has been the establishment of national committees for sustainable development in many countries. Beyond that, the United Nations Commission for Sustainable Development (CSD) was established, ensuring the implementation of the Rio decisions at its annual meetings (UNECE, 2014).

The UNCED on the contrary meets only every ten years. Thus, the second Earth Summit took place in 2002 in Johannesburg with a greater focus on social issues rather than environmental issues. Its success can be viewed as rather limited, because no important agreements were reached.

The last Earth Summit took place in 2012, again in Rio de Janeiro. “The Future We Want” was the outcome document of this conference, which established member-decided sustainable development goals (United Nations 2014).

Besides these historical milestones, several publications have been released during the last decades supporting the need of targeting sustainability in the dimensions of ecology, society, and the economy.

Sustainability and Sustainable Development

Making a clear distinction between the two words “sustainability” and “sustainable development” appears difficult. The majority of the literature supports the thesis that both terms can be described as and measured the same even the comprehensive Agenda 21 uses them interchangeably. However, differ meanings were assigned by the well-known Brundtland report that defines sustainability as a state, which will be achieved through sustainable development. This is a reason why the definition is in some articles criticized by other authors. However, keeping with the common practice, both terms will be used interchangeably in this thesis.

Sustainable development, as it is defined in the Brundtland report and at the UNCED in Rio de Janeiro in 1992, implies that actions of current generations should not impair the opportunities of subsequent generations. Further it states not only to focus on the protection of the environment and the natural resources in the long run, but also on the achievement of social and economic goals. Thus, the definitions imply that sustainability has three dimensions, which it seeks to integrate: economic, environmental and social. Moreover, it is assumed that an ecological balance can only be achieved when economical certainty and social justice is achieved in the same amount, simultaneously. Taking this into account, today's common understanding in literature illustrates the three dimensions as overlapping circles that present these interactions (Figure 2.2).

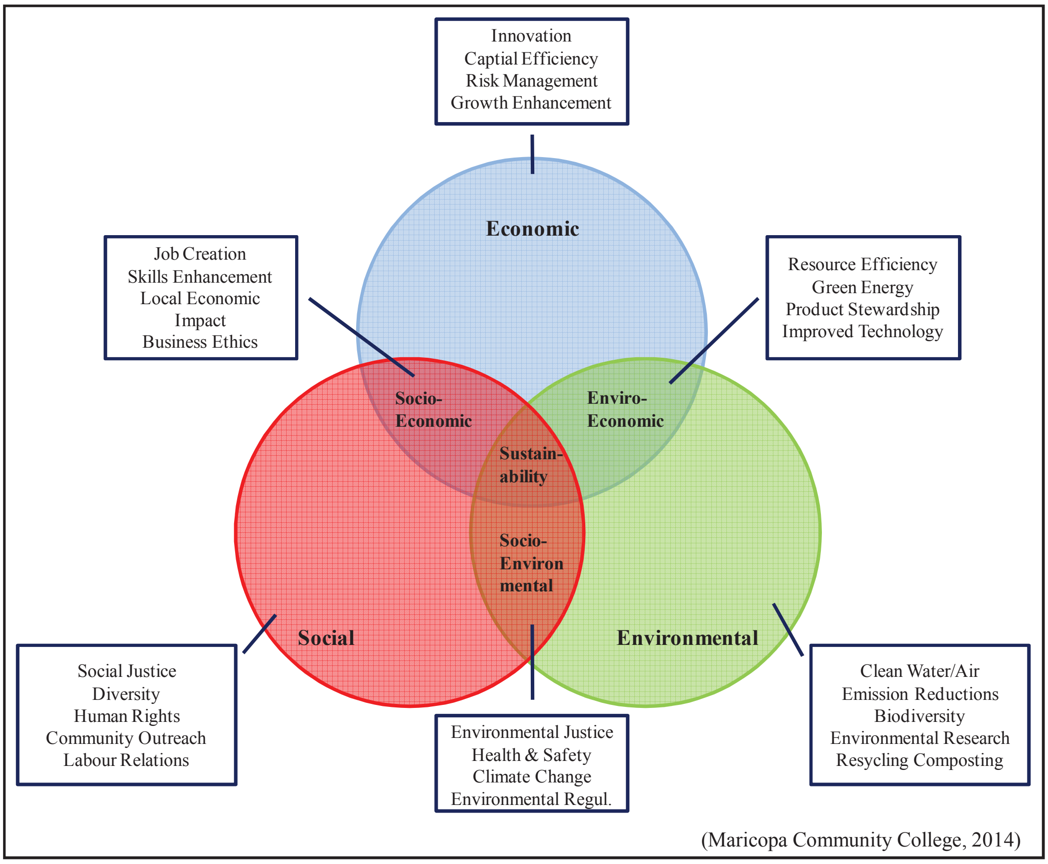


Figure 2.2: Three dimensions of sustainability

For this thesis, the focus is essentially on the environmental dimension with its goal to reduce emissions and to increase the material recovery. Beneficial aspects through interactions with the other dimensions are not taken into consideration.

2.1.2 Tools for Sustainability Assessment

With respect to the previous chapter, the field of sustainability consists of complex and dynamic interactions between environmental, social and economic issues. To get a better understanding of these elements, it is necessary that specific sustainability goals are assessed. A sustainability assessment according to Devuyest et. al. (Devuyst *et al.*, 2001) is defined as "…a tool that can help decision-makers and policy-makers decide which action they should or should not take in an attempt to make society more sustainable."

Developing efficient but reliable tools for this has posed important challenges to the scientific community. These challenges have caused the sustainability assessment to become a rapidly developing area in recent years with increasing numbers of tools. That claims that they can be used for assessing sustainability. Many of these tools have been improved upon today, providing better application guidelines, data and case study experiences (Ness *et al.*, 2007).

Against this background, an overview and discussion on sustainability assessment tools are provided below with the objective to find the most suitable tool for the problem stated in this thesis. The overview is based on the general framework for sustainable assessment tools developed by Ness et. al. (Ness *et al.*, 2007), in which he categorizes these tools adapted from their approaches and focus areas. Within the framework illustrated in Figure 2.3 a broad field of existing approaches that appear most frequently in the literature is covered, but by no means encompasses all the tools that exist for sustainability assessment.

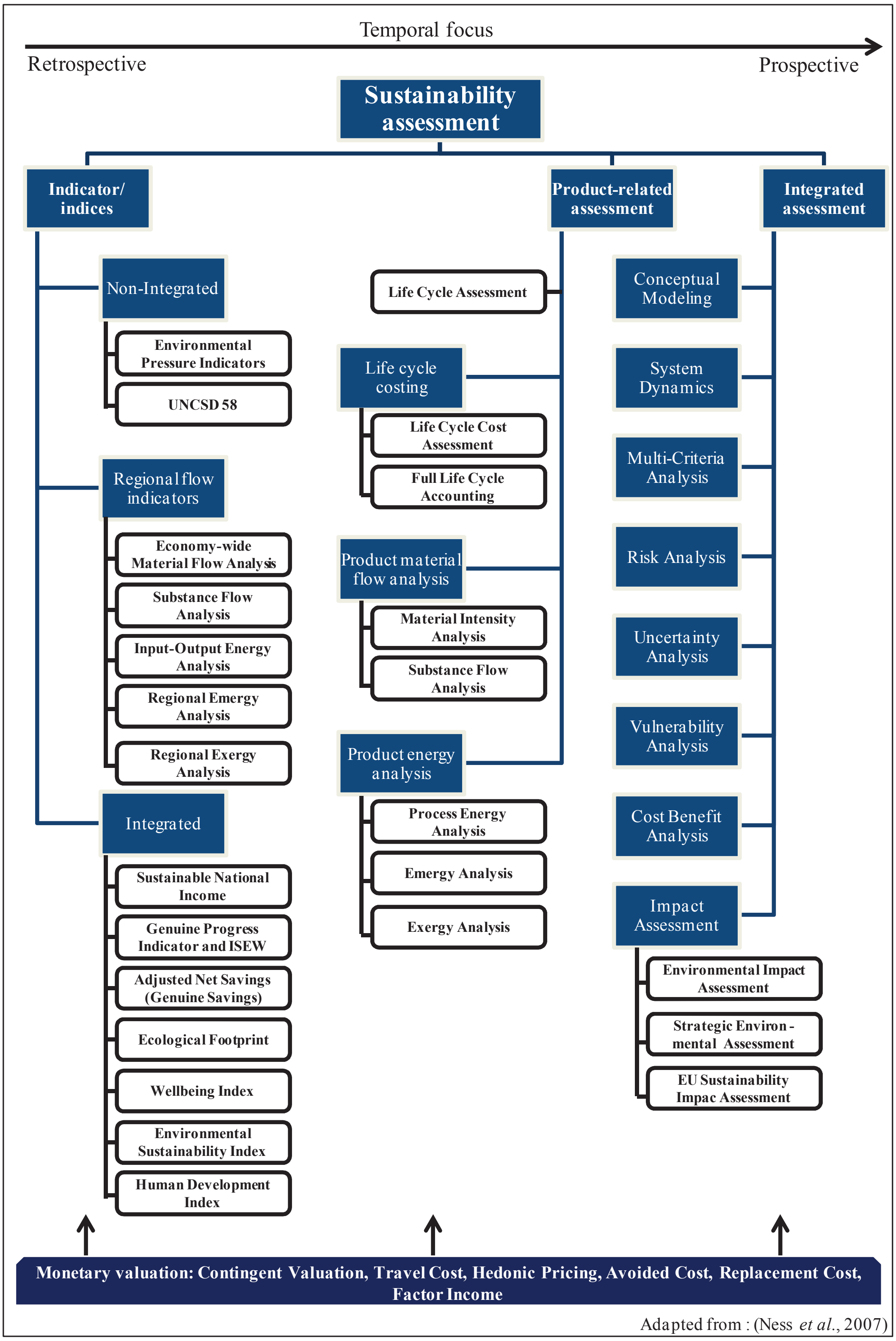


Figure 2.3: Framework for sustainability assessment tools.

The top row shows the general categorization areas, consisting of “indicators and indices”, “product-related assessment tools” and “integrated assessment”. All tools are arranged on a time continuum. Furthermore, an overarching category, added at the bottom of the figure, is used for the case that non-market values are needed in one of the three categories.

Indicators and Indices

This category is further broken down into three sub-categories. The first one includes non-integrated indicators, which do not integrate nature-society parameters. The second sub-category consists of regional flow indicators that focus on analyses of material and energy flows, giving an overview of the structure of resource flows and allowing the identification of inefficiencies within a system. The last sub-category consists of integrated indicators that aggregate the different sustainability dimensions within their tools.

Indicators are progressively recognized as an important and useful tool for public communication and policy making transmitting information on a country’s performance in the fields of society, economy, environment and technological development (Singh *et al.*, 2009).

Their main feature is the ability of summarizing, focusing and condensing the great complexity of the dynamic environment to a manageable amount of substantial information (Godfrey and Todd, 2001). Moreover, indicators analyze, quantify, simplify and communicate otherwise complex and complicated information, by highlighting trends and visualizing phenomena (Wahrhurst, 2002). However “a given indicator does not say anything about sustainability, unless a reference value such as threshold is given to it (Lancker and Nijkamp, 2002)".

Product-Related Assessment

Tools within the second category are product-related assessment tools that focus on material and/ or energy flows of a product, process or service from a life cycle perspective. These tools are closely related to the regional flow indicators of the previous category due to their similar flow perspective that they are built on. The basic difference is that the tools in this category focus on assessing different flows in reference to diverse products or services instead of regions.

They assess the environmental impacts and resource use through the life cycle of a product from cradle to grave, always with the objective to identify particular risks and inefficiencies to support decision-making. Therefore, their main focus is on environmental aspects and they do not integrate any nature-society systems. The only tool in this category which may integrate economic dimensions besides environmental is the life cycle costing (Ness *et al.*, 2007).

Considering the ambition of this thesis, the determination of the carbon footprint of the three different waste management systems (MRF, Municipality Landfill) and of a specific material, this second category turns up as particularly significant with its assessment tools. Especially the fact that the tools mainly integrate the environmental dimension and examine the flows from the life cycle perspective makes them very suitable for the problem. Therefore, the assessment tools of this category are analyzed in detail.

The first tool to look at is the *Life Cycle Assessment (LCA).* It is one of the well-developed and most established tools that have been used in various forms since the late 1960s to evaluate environmental impacts of a product or a service throughout its life cycle.

The International Standards Organization (ISO) established guidelines and principles for the LCA in the 1990s and its methodological framework is defined in the ISO 14040 series. The results of a LCA provide different information for decision-making. These can be used in the field of product development and eco-design, production system improvements or for the eco labeling of products or services. (Cherubini *et al.*, 2009)

The second tool regarded, is the *Life Cycle Costing (LCC).* According to Gluch and Baumann (Gluch and Baumann, 2004), it is an economic approach that sums up "total costs of a product, process or activity discounted over its lifetime". However, LCC includes costs in general and then it can be associated with environmental costs. It is an investment calculation that is used to support decision making, by ranking different investment alternatives.

In the pool of different life cycle costing analyses, only two include environmental costs. These are Life Cycle Cost Assessment and Full Cost Environmental Accounting. (Gluch and Baumann, 2004)

The third tool is the *Product Material Flow Analysis.* As the name already implies, it analyzes all material and/or substance input and output flows of a product through its life cycle stages. A specific version was developed by the Wuppertal Institute for

Climate, Environment and Energy and is called Material Intensity Analysis. (Spangenberg et al.,1999). It considers all the material flows connected to a certain product or a service including the so-called ecological rucksack, which is determined through the difference of all materials required for the complete production process and the actual weight of the product. Thus, this version represents thus the actual material intensity of that given product (Ness *et al.*, 2007).

The last tool considered is the *Product Energy Analysis.* It measures the energy that is needed to manufacture a product or service (Herendeen, 2004). Both direct and indirect energy flows are included in this analysis. Direct energy is the energy used for manufacturing the product or service itself, while indirect energy is the energy that is used for an input as for example the energy used to produce plastic for the packaging industry.

Similar, to the other tools, differences between the Product Energy Analyses exist. While some include for example, the production of energy systems as heating or electricity as in the Exergy Analysis, others do not (Brown and Ulgiati, 2002).

Integrated Assessment

The last category consists of Integrated Assessment tools. They are specifically used to support decisions connected to projects or policies in a certain region. While policy related tools focus on local to global scale assessments, project related tools are used for only local scale assessment.

Within the scope of sustainability assessment, these tools have an ex-ante focus and often are carried out in the form of scenarios. Further, they are predicated on system analysis approaches and integrate both nature and society aspects. This category includes a wide choice of tools that are chiefly used for managing complex issues. (Gough et al.,1998).

A group of tools that definitely requires mentioning in this context is the Impact Assessment, a subcategory of the Integrated Assessment. This small group of forecasting tools is widely used and well developed. Its main field of use is in the improvement of the basis of policymaking and project approval process.

One of the oldest tools within this group is the Environmental Impact Assessment (EIA) that has been used since 1960s for the evaluation of environmental impacts of large development projects, always with the objective to reduce the negative effects (Sadler, 1999). Furthermore, EIA is the basis for another well-developed and known tool in this group, the Strategic Environmental Assessment (SEA). It evolved from the EIA in the 1990s; however, opposite of the EIA, its focus is on the evaluation of environmental impacts of strategic decisions (Partidario, 1999).

Except for two major differences, most of the principles and procedures are the same in both processes. SEA always has to be carried out before EIA, and it is "...performed for conditions that involve less information, higher uncertainty and less concreteness, which is often the case with political decisions; whereas EIA is performed in concrete conditions of a particular project" (Ness *et al.*, 2007).

In summary, an overview covering a broad field of existing sustainability assessment tools has been given. Moreover, individual tools have been explained and a framework for their classification developed by Ness et. al. has been shown. Considering this overview and the background of the objective of this thesis, the second category, with the product-related assessment tools and especially the LCA tool appear to be the most suitable for achieving the goal of this thesis.

The LCA evaluates products, processes and services during each stage of their life cycle and it integrates mainly environmental aspects in its assessment. Furthermore, different articles can be found in the literature, claiming that the determination of the carbon footprint is a part of the LCA. This strengthens the decision for choosing LCA as the most suitable assessment tool. A description of its methodology is given in the next chapter.

2.1.3 Life Cycle Assessment

At the beginning of the 1990s several basic approaches and methods for LCA existed worldwide, which led to varying results in analyses of similar products (Curran, 1993). In 1993, the Society of Environmental Toxicology and Chemistry (SETAC) took a big step forward internationally with its "Guidelines for Life Cycle Assessment – A Code of Practice", standardizing these LCA-methods. The critique of these efforts, especially from national and international standardization committees, led to the composition of the international series of standards the ISO 14040 that defines the methodological framework of LCA.

The strengths of LCA are summarized in three points:

- LCA is product - and service - based and is, therefore, a very appropriate tool to connect ecological aspects with economical.

- LCA represents an integrated approach that balances environmental impacts. It exposes, through the examination of the whole life cycle, shifts of environmental problems (e.g. emissions) into other media (ground, water, air), other phases of life and different locations, as well as temporary shifts.
- LCA provides decision processes with scientifically sound and quantitatively data, so that decisions are more comprehensible and justifiable (Herrmann, 2010).

The methodological framework for performing LCA is explained with respect to the ISO 14040 standards that are accepted worldwide.

An LCA includes a compilation and evaluation of the input and output flows and the potential environmental impacts of a production system during its life cycle (DIN EN ISO 14040:2006-10). For this purpose, the whole product life cycle, from the supply of raw materials to the disposal or respectively recycling, is investigated in relation to the use of energy and materials. Such a life cycle is illustrated in the Figure 2.4 below, which includes further the different system boundaries that can be considered in an LCA.

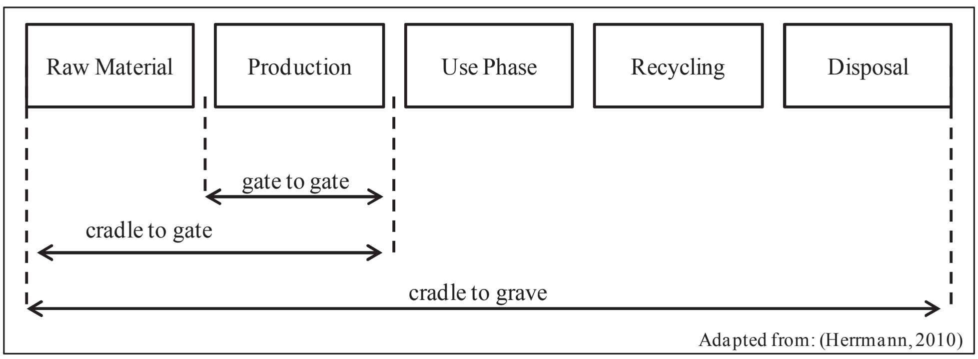


Figure 2.4: Product life cycle phases with system boundaries.

Figure 2.5 shows the four phases that make up an LCA; it also shows that they do not need to be in a successive order. The approach is rather an iterative process. Furthermore, interim results from the inventory analysis, the impact assessment and the interpretation can necessitate a modification of the goal definition.

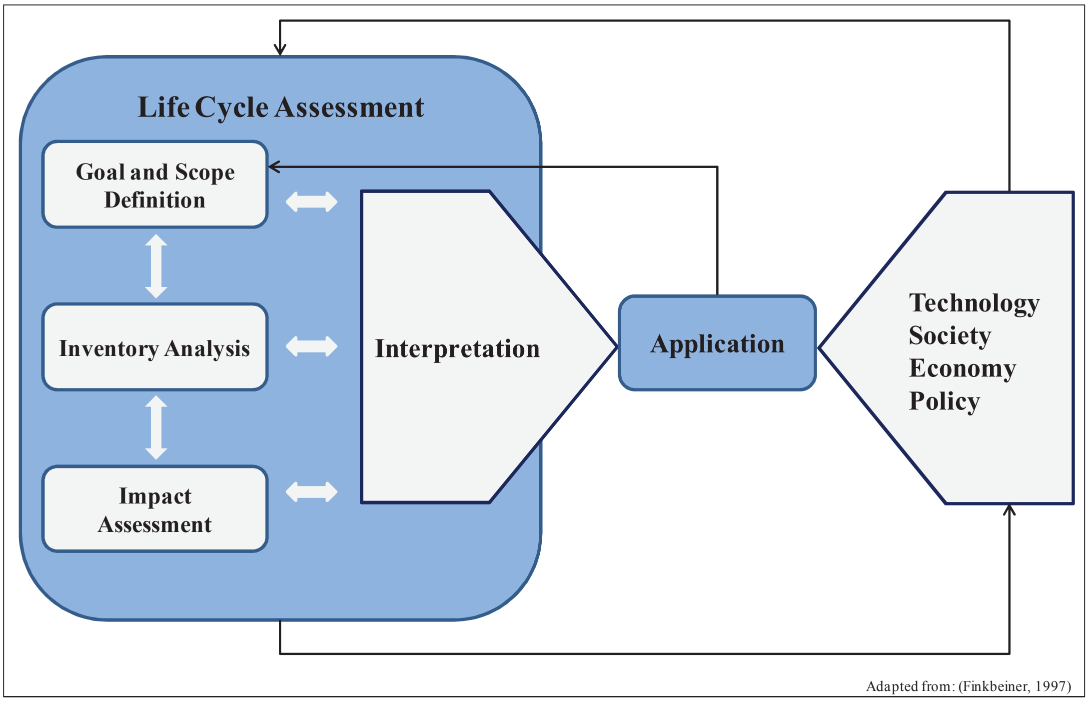


Figure 2.5: Conceptual framework on LCA.

Goal and scope definition

In the first phase, all general decisions for setting up the LCA system are made. This phase is called the goal and scope definition and is of central importance to each LCA. In the goal definition, the reasons for the study as well as the overall goals are defined. In addition, the target group for the LCA report is defined. Whether the LCA will be used to make a comparison between systems is also determined at this stage.

In the scope definition, the product or process system is characterized and all assumptions are detailed. The system boundaries (time, geographic and technical), choice of impact categories and data quality requirements as well as the methodology used to set up the product system are also described.

To describe the product or process, the function of it has to be defined as well as the demands the product or process is supposed to fulfill. This becomes very important when products or processes with a different range of functionalities are to be compared. For this, a functional unit is defined. The functional unit is the quantified definition of the function of a product or process system with a physical unit (Klöpffer, 1997).

Inventory Analysis (LCI)

The inventory analysis includes data acquisition and calculation methods for the quantification of relevant input and output flows of a production system within the determined boundaries (Herrmann, 2010).

All activities that are related to the production of one functional unit need to be analyzed regarding components as raw material extraction, intermediate products, the service or product itself, the use phase and the waste removal at the end. Additional inputs that can be included are energy, transportation or auxiliary products. Typical outputs for an inventory analysis are emissions to air, water and soil, waste heat, co-products and solid waste (Klöpffer, 1997).

The data acquisition in this phase involves collecting quantitative and qualitative data for every process in the system. This can be done by the collection of primary data from plant visits, by using existing, commercially or publically available databases or through the collection of secondary data from the literature. It is important, that the collected data is related to the functional unit and validated. When necessary allocations must be modeled and in some cases, the system boundaries potentially may be redefined (*More about LCA*, 2006).

An option for representing the results of an inventory analysis is the inventory table, a list of all inputs and outputs per functional unit.

Impact Assessment (LCIA)

In this phase, the results from the inventory analysis are used to identify and evaluate the significance of potential environmental impacts of a product or process system as such as the effects on the natural resource use, the natural environment and the human health.

According to the ISO 14044 standard, the LCIA involves several steps. Therefore, certain elements are defined within the range of a study for the LCIA. The selection of relevant impact categories, classification and characterization belong to the mandatory elements, while normalization, grouping and weighting are included in the optional elements of a study (Herrmann, 2010).

Classification is a process where each resource and emission is assigned to one or more impact categories. Impact categories are scientific definitions linking specific substances (*e.g* CO_2, CH_4, etc.) to a specific environmental issue. The issue of global warming for example is represented by the global warming potential (GWP) impact category. Any emission to air that contributes to the global warming potential, such as carbon dioxide or methane, is then classified as contributors. For the case that substances contribute to more than one impact category, they must be classified as contributors to all relevant impact categories (Cherubini *et al.*, 2009).

The next step is the characterization of the results. This means that the results of the impact analyses are converted into the reference unit of the impact category. Regarding the impact category GWP for example, CO_2 is the reference substance for it and its reference unit is defined as “kilograms CO_2 equivalence”. All emissions that contribute to that same impact category (GWP) are then converted likewise to “kilograms CO_2 equivalence” corresponding to their own characterization factor. The determination of these factors is made by different scientific groups and is based on different methodologies and philosophical views on the environmental issues. The two most widely used impact category methodologies are TRACI in the US (developed by the EPA) and CML in Europe (developed by the University of Leiden) (PE International, 2013a).

After characterizing every substance that contributes to the system, all of the characterized quantities can be simply added together. This results in a final number that represents the extent of this environmental impact. Finally, it is done for every impact category of interest, so that these calculated results are collectively referred to as the LCIA results.

The optional elements of the LCIA are performed to facilitate the interpretation of the LCIA results. Since other individuals, organizations and societies may have different preferences for displaying the results and might want to normalize, group, weight or evaluate them differently, it is very important that these actions are transparently documented (Finkbeiner *et al.*, 2006).

Interpretation

First action in this final phase of the LCA is to check, analyze and compare the results from the inventory analysis and the impact assessment to see that they are consistent with the goal and scope definition and that the study is complete. Besides that, two additional steps are performed: the identification of significant issues and the evaluation (Herrmann, 2010).

Significant issues, or respectively data elements that contribute most significantly to the outcome of the results of both the LCI and LCIA for each product, process or service, need to be identified because they guide the evaluation step. They can include, for example, inventory elements such as energy consumption, emissions, or impact category indicators whose amount is of concern.

The aim of the evaluation is to improve the reliability of the study. Methods that are used for the evaluation are the completeness check, sensitivity check and the consistency check (Heijungs *et al.*, 2009).

In conclusion, the goal of the life cycle interpretation phase is to draw the consequences, identify limitations and make recommendations for the intended audience of the LCA.

2.2 Carbon Footprint

The increased emission of GHGs during the last several decades has led to climate changes worldwide, causing serious ecological and economic threats. Extreme weather events that occur regularly today are just one signal for imbalances in natural systems due to warming for example.

With respect to the three dimensions of sustainability mentioned in the chapter before and according to Stern (2006), "the world is running short on time and options" from these high risks related with global warming and climate changes. For this reason strong and immediate local to international actions are needed to stabilize emissions in a justified manner. A significant step in this direction was already done in 1997 when several leading industrial nations agreed to reduce their GHG emissions in the following years, by signing the Kyoto Protocol.

However, it is not enough only to have regulations made by governments. Rather it is necessary that everyone has an understanding about the impacts of GHGs and how these emissions can be reduced. Against this background and following the rule that only measurable is manageable, scientists, governments, the public and the business world have been working for years on developing approaches for measuring (calculating) impacts of GHGs with the one ambition to get a ubiquitous indicator as result that everyone understands.

This chapter deals with exactly one of these approaches. Some claim it as the best one developed, while other says it is just the best-known through media and public debates. Unbiased from that, the approach discussed here is the carbon footprint, which has permeated and is being commercialized in all areas of life and economy.

Many different studies can be found in the literature concerning the term/ concept carbon footprint, but then trying to find a universally valid definition for it raises some problems. In other words, there is little coherence in the existing definitions and calculations of it.

Therefore, an overview of some existing definitions from the scientific literature is given in the first section of this chapter by presenting ideas of what this term/ concept is meant to be, what it measures and what unit is used. Afterwards, these definitions are discussed and an appropriate definition considering the goal of this thesis is derived from them.

In the second section of this chapter, methodological approaches for establishing carbon footprint calculations is explained, followed by a decision on which approach is most suitable for the requirements of the carbon footprint calculations regarding the objectives in this thesis.

2.2.1 Definition

Over the last decade, the term/ concept "carbon footprint" has become enormously popular and is now in a widespread use across media, governments and in the business world. It is used in the public debate on responsibility and abatement action against the threat of global climate change, a topic that is also high up on every political and corporate agenda (Pandey *et al.*, 2011).

Carbon footprint calculations are in a strong demand. Various approaches have been proposed to provide estimates, ranging from basic online calculators to input-and output-based methods or sophisticated life-cycle analyses and tools. However, what exactly is a carbon footprint?

In spite of its pervasive appearance, the term/ concept is not clearly defined. There is rather an apparent lack of academic definitions. Despite the fact that many studies in energy and ecological economics have been published in recent years that have claimed to measure a carbon footprint, the scientific literature is surprisingly void of clarification (Kumar *et al.*, 2014).

According to (Wackernagel, 1996), the roots for this term can be found in the language of Ecological Footprinting, while its common baseline is a specific amount of emitted greenhouse gases that are related to changes in the climate and associated with human production or consumption activities. However, this is where the commonality ends, without any consensus on how to measure or quantify the carbon footprint.

Having a large spectrum of definitions, questions arise whether the carbon footprint should only include carbon dioxide (CO_2) or additional other greenhouse gas emissions like methane (CH_4), for example, or powerful gases as Nitrous Oxide (N_2O) that do not even have any carbon in their molecule.

Another central question is where the boundaries in assessing greenhouse gas emissions should be drawn considering the life cycle of a product or process. Does the carbon footprint, for example, include indirect emissions embodied in upstream production processes or is it sufficient to look just at the direct, on-site emissions? It is also necessary to define how life cycle impacts of goods and services used can be quantified (Wiedmann and Minx, 2008).

Finally, it has to be decided if the carbon footprint should rather be an indicator expressing e.g. the amount of carbon emissions measured in tones or whether it should indicate an impact as e.g. the global warming potential, which is quantified in tons of CO_2 equivalents (t CO_2-eq.) (Pandey *et al.*, 2011).

Several of the questions above have been discussed in detail in the scientific literature previously, especially in the disciplines of LCA and ecological economics. Hence, some answers are already at hand and can be seen in the definitions of the term/ concept carbon footprint summarized in the following Table 2-1. These definitions are based on a literature review from Mai 2014.

Source	Definition
Carbon Trust (2014)	A carbon footprint measures the total greenhouse gas emissions caused directly and indirectly by a person, organisation, event or product. (Carbon Trust 2014)
EPA (2014)	„**Carbon footprint** The total amount of greenhouse gases that are emitted into the atmosphere each year by a person, family, building, organization, or company. A person's carbon footprint includes greenhouse gas emissions from fuel that he or she burns directly, such as by heating a home or riding in a car. It also includes greenhouse gases that come from producing the goods or services that the person uses, including emissions from power plants that make electricity, factories that make products, and landfills where trash gets sent. “ (EPA 2014)
Grub & Ellis (2007)	"A carbon footprint is a measure of the amount of carbon dioxide emitted through the combustion of fossil fuels. In the case of a business organization, it is the amount of CO2 emitted either directly or indirectly as a result of its everyday operations. It also might reflect the fossil energy represented in a product or commodity reaching market.“ (Grub and Ellis 2007)
The Guardian (2010)	The term *carbon footprint* is a shorthand to describe the best estimate that we can get of the full climate change impact of something. That something could be anything – an activity, an item, a lifestyle, a company, a country or even the whole world. (Bernèrs-Lee et. al. 2010)
Time for Change (2014)	The total amount of greenhouse gases produced to directly and indirectly support human activities, usually expressed in equivalent tons of carbon dioxide (CO2). (Rohrer 2014)
Wiedmann (2009)	A 'footprint' indicator should, by its nature, encompass all 'traces' that an activity leaves behind – in the case of a carbon footprint, all greenhouse gas emissions that can be associated directly and indirectly with this activity. (Wiedmann 2009)

Table 2-1: Literature review of definitions for "Carbon Footprint"

Taking all these definitions into account, the next step is to define the term/ concept carbon footprint that is appropriate for this thesis. As mentioned in the prior chapter, LCA is one of the main assessment tools used in this thesis. Considering now the carbon footprint as a part of the LCA, it should reflect all impacts from the aspect of GHG contribution of each life cycle stage of the examined product or process. In other words, all direct (on-site, internal) and indirect emissions (offsite, external, embodied, upstream, downstream) are taken into account, including all substances with greenhouse warming potential and not only those, which are based on carbon. This resulted in the here defined carbon footprint that measures the three major GHGs, carbon dioxide, methane and nitrous oxide. Furthermore, in the cases of the LCA performances it becomes additionally a comprehensive greenhouse gas indicator that displays in the final analysis the Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential, and Human Toxicity Potential (HDP).

Finally, after defining the carbon footprint for this thesis, the only thing missing is a clear definition of the scope and boundaries for the analyzed products and processes, so that all of their life cycle stages can be evaluated correctly. These definitions are given in their respective chapters.

2.2.2 Methodology

The literature provides two methodological approaches for calculating the carbon footprint. Both strive to capture all life cycle impacts and some of their aspects have already been mentioned in the definition before.

The first method is the “bottom-up” or “process analysis” (PA) that has been developed to understand the environmental impacts of individual products or processes from cradle to grave. With the use of specific primary and secondary process data, this method can achieve results with high precision for defined products. For that, emissions sources are broken down into different categories for convenient quantification.

However, a significant drawback of this method is that it suffers from a system boundary problem, which means that often only on-site, most first-order, and only some second-order impacts are considered (Lenzen, 2000). Accordingly, for the case that this methodology is used in order to derive a carbon footprint estimate, truncation errors can be minimized by giving a strong emphasize to the identification of appropriate system boundaries. Furthermore, this method is more accurate for small entities. It runs into further difficulties if carbon footprints have to be established for larger entities such as households or particular industrial sectors.

The second method is the “environmental input-output” (EIO) analysis. It provides an alternative, economy-wide top down approach for calculating the carbon footprint. In this context, economy-wide means that the input-output tables are economic accounts, providing a picture of all economic activities at the meso level. Combining these with consistent environmental account data, carbon footprint estimates can be established in a robust and comprehensive way considering all higher order impacts and setting the whole economic system as boundary. But this completeness comes at the expense of detail (Wiedmann, 2009a).

Another drawback is that when it comes down to assess micro systems such as products and processes, the EIO is limited in its suitability because it assumes homogeneity of prices, outputs and their carbon emissions at the sector level. However, it is rather appropriate for larger entities such as product groups, companies or countries. Similarly, a big advantage is, once an input-output model has been set up, a number of analyses can be carried out in a resource efficient way, requiring a much smaller amount of time and workforce.

An integration of both PA and EIO is called the hybrid approach. It combines the strength of both methods and forms a detailed, comprehensive and robust approach that covers higher-order requirements by the input-output part of the model and allows preserving the detail and accuracy of a bottom-up approach in lower order stages. It embeds process systems inside input-output tables and is therefore the current state-of-the art in ecological economic modeling. Moreover, it is even based on the LCA method (Heijungs and Suh, 2006).

All things considered the choice of the method is depending on the purpose of the inquiry and the availability of data and resources. The EIO is superior for establishing a carbon footprint calculation in macro and meso systems. An input-output analysis for industrial sectors, individual businesses and larger product groups can be easily performed in this context. (Foran et. al 2005) Looking on the contrary at micro systems like an individual product, a relative small group of individual products or a particular process, the PA has clear advantages.

For the processes and products reviewed in this thesis, both methodological approaches illustrated above seem to be useful. The EIO can be for example used for establishing a carbon footprint calculation for a complex process as the MRF, while the PA is useful when it comes to the calculations for particular recyclable materials.

However, according to the ISO 14044 LCA is the premier methodology in determining the carbon footprint and the hybrid approach is claimed to be the main part within the LCA that is responsible for its determination (Wiedmann, 2009a).

Taking this into account, the regarded products and processes for this thesis are primarily modeled in LCA software, which is used for calculating their carbon footprint as well. In addition, more specific calculations such as those for the different recyclable materials that are recovered in the MRF, are performed in excel. These calculations consider in the same way as those performed in the LCA software all impacts of the whole life cycle and uses the strength of the hybrid approach, instead of the PA approach.

The implementation of the LCA as well as the hybrid approach for calculating the carbon footprint can be seen in the case study in Chapter 3.

2.3 Computational Implementation

The following chapter reviews existing LCA software packages for the computational implementation of footprint assessment. To begin, specifications of four LCA software packages are compared with the goal to identify the most suitable package for the requirements of this thesis. Subsequently, the chosen software package is specified.

2.3.1 LCA Software Packages

As introduced in Chapter 2.1.3, LCA has gained general acceptance as a tool with a wide range of uses in recent years. Environmental labeling, product environmental improvement, eco-design, policy evaluation and carbon footprint assessment, are just a few of these. The increased acceptance of LCA, led to the development of software tools and databases for performing LCA. Many of these software tools are available for purchasing or licensing.

One important parameter for choosing a LCA software package is the data, considering the volume, quality, accuracy and relevance, available for the user. The two most comprehensive international LCI databases are the “Ecoinvent Database” developed by the Swiss Center of Life Cycle Inventories and the “GaBi Database” developed by the PE International. (Umberto, 2014)

Besides the databases, the ease of use of the software package is another parameter that has great importance. Does the package for example run on Windows? Are exports of results to Excel or any other MS Office program possible? Is it clearly set up? Does it perform impact assessment and how are the graphical outputs diagrammed? How accurate and consistently does the software generate the results? Moreover, what kind of support is provided with the package? (G. Rice *et al.*, 1997)

Keeping these parameters in mind and with respect to the requirements for performing LCA and carbon footprint assessment in this thesis, the four software packages chosen for comparison are:

- Gabi 6 Sustainability Software
- openLCA
- Sima Pro 8
- Umberto NXT LCA

Each of the software packages uses at least one of the two databases mentioned previously.

The abilities of the compared software packages are essentially similar, each having the basic function to complete energy and mass balances on a product or process specified by the user and then also allocating energy uses and environmental releases on some common basis, usually mass. Nevertheless, the software packages differ in some specifications; each has its merits and its drawbacks. The main specifications regarded in the comparison are:

- Carbon Footprint Assessment: according to the ISO 14044, LCA is the premier methodology in determining a carbon footprint. The software package should be able to disclose the carbon footprint (including the main GHG), reveal reduction potentials and highlight negative trade-offs as for example the shifting of environmental burdens from one stage of the life cycle to another.

- Impact Assessment: one of the most useful tools associated with any LCA software; a package is without it, essentially, a database with a spreadsheet attached.
- Graphical Representation of Results: very useful for the purposes of clarification and report writing.
- Sensitivity Analysis: analysis and comparison of the effects on the results by altering the process details slightly.
- Cost: an essential decision criterion for choosing one of the software packages.
- Flow Diagrams: extremely useful for showing what is included and what is excluded from the system boundaries.
- Limitations (input/ output parameters; geographically): Some of the LCA software packages have restrictions on the number of inputs and outputs available to or from a process. Furthermore, the compared software packages are of European origin, therefore it occurs that objects in a process are labeled in the same language as the LCA software has its origin.

The whole comparison and further information about the software packages can be seen in the following Table 2-2.

Software name	GaBi 6 Software	openLCA	Sima Pro 8	Umberto NXT LCA
Supplier	PE International GmbH University of Stuttgart, LBP-GaBi	GreenDelta	PRé Consultants B.V.	ifu Hamburg GmbH
Language	English, German	English, German	Spanish, French, Italian, German, English	English, German
Main database	ecoinvent v3; GaBi Databank	openLCA Databank; on purchase: GaBi + ecoinvent v3 available	ecoinvent v3	ecoinvent v3; GaBi Databank optional
Supports full LCA	Yes	Yes	Yes	Yes
Carbon Footprinting	Yes	limited	Yes	Yes
Sankey (Flow) Diagramms	Yes	Yes	Yes	Yes
Graphical impact assessment	Yes	Yes	Yes	Yes
Auto sensitivity analysis	Yes	No	Yes	Yes
Restriction input / output	Depending on License	Yes	Depending on License	Depending on License
If commercial, free trials available?	30 days free trial + **free student version**	---	Demo Version	14 days free trial
Cost	Quote on Request	Free	Business Licenses: \$8.000 - \$16.000 Educational Licenses: \$2.400 - \$4.200	Quote on Request [1]

Table 2-2: Review and comparison of existing LCA software packages

In conclusion, all of the compared packages have the same basic functions for performing LCA. The differences are only in the method, speed, flexibility and information each package has when performing this function. For this thesis, the main decision criterion for choosing one of the packages is the price, its availability and if it has a tool included for carbon footprint assessment.

[1]For more information on the software packages, see Appendix1

OpenLCA is a free software package that uses a smaller database, but for using databases such as “Ecoinvent version 3” or “GaBi Database” one would have to purchase the database. A similar problem occurs with the Sima Pro 8 software package, which offers a free trial version that includes lean versions of the mentioned databases, but it is only available for a 30 day trial period. Umberto NXT LCA and GaBi 6 are the two software packages that are free available and as educational versions. In comparison, GaBi 6 education software offers larger databases and more LCI profiles than those from Umberto NXT LCA. For this reason, the Gabi 6 education software is used in this thesis for performing LCA. In the next chapter, this software package is discussed.

2.3.2 GaBi 6 Education Software Package

GaBi 6 is a sustainability software developed by PE International, a sustainability software and consulting company based in Leinfelden-Echterdingen, Germany. PE International is originally a spinoff of the University of Stuttgart that was founded in 1991. Today, it is the international market leader in strategic consultancy, extensive services and software solutions in the field of sustainability. Worldwide more than 1,500 companies and institutes put their trust in its consultancy and software, including market and branch leaders such as Bayer, Daimler, Siemens, Toyota and Volkswagen (PE International).

With its GaBi 6 software for product sustainability, PE International offers one of the market-leading software solutions with the ability to model every element of a product or system from a life cycle perspective. It supports business applications such as LCA, life cycle costing (LCC), life cycle reporting and life cycle working environment.

Moreover, it offers users a unique choice of high-quality databases. These include the "GaBi Databases" containing more than 7,000 ready-to-use LCI profiles, the "Ecoinvent Databases" and the "U.S. LCI Databases". In addition, PE International offers customized datasets that suit the needs of the customer. (PE International)

The Gabi 6 education software is a free option available for students and teachers and it includes the same functions as the professional GaBi 6 product sustainability software. The two packages differ only in the databases they use. While the professional version includes all databases, the educational version includes only lean versions. However, the databases are comprehensive enough to fulfill the requirements to perform a LCA of recyclable materials, a machinery of a MRF, as well as, a MRF itself, in this thesis.

2.4 Municipal Solid Waste Management

This chapter begins with a brief look at the United States waste management sector, in particular, regarding developments during the last several decades and future trends. Furthermore, it provides a detailed overview of the following three waste management systems (WMS), Material Recovery Facility (MRF), Incineration Plant, and Landfill.

Each system is analyzed concerning its structure and its sources for emitting GHGs (environmental parameters) with respect to the objective of this thesis to perform a LCA on the WMS and to calculate their carbon footprints in the next chapter.

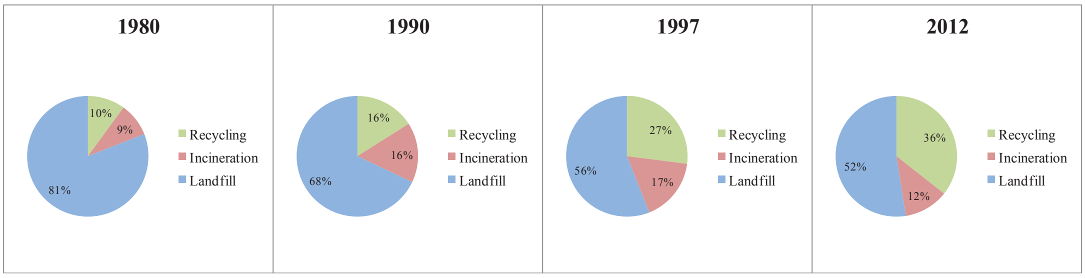
For the general understanding it needs to be mentioned that these analyses are based on WMS in the United States.

2.4.1 Waste Management Sector USA

The waste management sector is responsible for the collection, treatment and recovery of municipal solid waste (MSW). Its primary objective is to fulfill these responsibilities as efficiently as possible to avoid undesirable residues from MSW and to limit their impacts on the environment (Entreprises pour l'Environnement, 2010).

The necessity for achieving this objective is strengthened due to the fact that landfills for example are still accounted for approximately 18.1 percent of total U.S. anthropogenic methane (CH_4) emissions in 2012, which is the third largest contribution of any CH_4 source in the United States. This might seem to be a lot, but compared to 1990 when landfills represented nearly 90 percent of the GHGs from the waste sector, it was reduced to 80 percent in 2012 (EPA and Division, 2014b).

This reduction is a result of significant changes that took place in the U.S. waste management sector during the last several decades. Figure 2.6 presents exactly these changes on a timeline from 1980 to 2012.



(U.S. Environmental Protection Agency, 2012)

Figure 2.6: Changes in WMS in the U.S. from 1980-2012.

At the beginning of the 1970s recycling was rarely practiced, the combustion of waste was executed without any recovery of energy and MSW management primarily consisted of landfilling without the collection of gases or any control.

Today, the waste management sector in the United States distinguishes itself through well-developed resource recovery facilities, incineration plants with energy recovery and landfilling with gas recovery, control, and utilization (Weitz *et al.*, 2002).

Furthermore, environmental regulations and technological advancements that are more energy efficient and protective of human health have made great contributions in the reduction of environmental impacts in recent years. Summarized in numbers, that means a reduction of the total quantity of GHG emissions from the waste management sector from 60 million metric tons carbon equivalence (MMTCE) in the 1970's to only 8 MMTCE in 2012 (Weitz *et al.*, 2002).

However, the companies that work in this sector take a paradoxical position because even though they control other people' and companies' waste, they themselves have environmental impacts.

In this context, it is essential to determine the scope of responsibility for these impacts, regardless of whether it is during the transportation phase (transport, collection) or the waste treatment (recycling, combustion, etc.). In addition, the companies from the waste sector have to negotiate with waste producers to have an influence on the quantity and quality of waste they receive.

Finally it can be said, that the greatest opportunities for the waste management sector to reduce atmospheric emissions in the future is in the continuous improvement of their treatments. A special focus should be thereby on the technological advancement of recovering treatments, so that end-of-life products can be either recovered as material through reuse, recycling or composting or as energy through landfill gas recovery or incineration with energy recovery.

2.4.2 Material Recovery Facility

The first serious recovery of materials from MSW in the United States started in the early 1980s. Around that same time, the first MRF was established in Groton, Connecticut. The facility was primitive compared to the MRF standards used today and only a few materials could be recovered. Nevertheless, it set the basis for an increasing development in the field of recycling. While at the beginning of the 1990s only 100 MRFs existed in the United States, nearly 1,320 MRFs were identified in 2011 from which 563 were residential MRF types and the other 760 non-residential MRF types (Waste Management Recycling Service, 2011). Furthermore, the amount of material recovered increased from 10 percent in the 1980s to 36 percent in 2012 (U.S. Environmental Protection Agency, 2012).

A reason for this rapid increasing interest in recovering materials is due to environmental regulations from the government that put a greater responsibility on waste management companies to reduce environmental impacts from MSW. Another reason to reduce MSW going to the landfill is the rising costs of solid waste disposal in recent years. For a long time it was not economically attractive for the waste management sector to recycle, but that attitude has changed the moment land-filling became more expensive.

Structure

MRFs are specialized plants that receive, sort, process and store recyclable materials before they are shipped and marketed to end-users. Concerning their size and configuration, the EPA split them into three categories, small, medium and large.

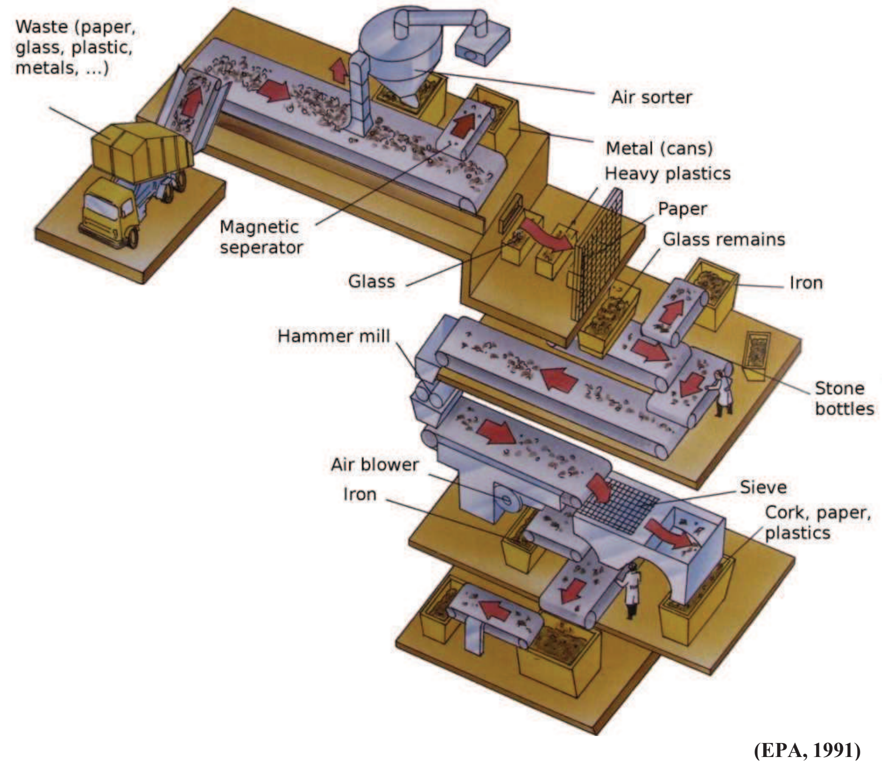
Small MRFs are less automated. Manual labor is used instead of sorting equipment and the daily amount of recyclables handled is normally less than 10 tons per day. Facilities that handle more than 10, but less than 100, tons of recyclable material per day belong to the medium sized category. Their equipment is, to the greatest possible extent, automated including, picking lines, sorting machines, balers and conveyors, which are necessary to move and process material faster through the facility. The last category includes large MRFs operating up to 500 tons of recyclables per day. They operate at full capacity with highly automated equipment and are often located in very large cities (EPA, 1991), Besides the categorization for size and configuration, MRFs are distinguished in two types of facilities depending on the type of waste they handle.

The first one is the so-called "Dirty MRF." It receives comingled (mixed) waste material that requires labor-intensive sorting activities to separate the recyclables from the mixed waste. One drawback of this type of MRF is that it increases the likelihood of contaminates to the recyclables captured. To avoid that problem and to meet the required technical specifications established by end-users, some of the sorted recyclable materials (mainly paper products) may undergo further processing. The remainders of these sorting and cleaning processes are sent as a mixed waste stream either to a landfill or are otherwise disposed.

The second type of MRF is called a "Clean MRF." These facilities accept only recyclable materials and can be even further distinguished by those, that accept source-separated recyclables consisting of two streams: mixed containers (typically ferrous metal, aluminum, non-ferrous metals, glass and plastics) and mixed papers and other facilities that accept a single stream consisting of comingled recyclables (Recycling Marketing Cooperative for Tennessee, 2003). Although theoretically all the materials coming into a "Clean MRF" should be recyclable, analyses have shown that those systems also include some residues that are not recoverable and which cannot be properly recognized by the sort mechanisms in the MRF. The amount of residues depends heavily upon the processing efficiency of the facilities and in some instances on how well the community has separated its recyclables previously.

In the final analysis, both types of MRFs have its merits and drawbacks. While a "Dirty MRF" is capable of a higher recovery rate, because it ensures that nearly 100 percent of the waste stream is subjected to the sorting process, it's processes are considerably more labor-intensive and usually more expensive than those from a "Clean MRF". Furthermore, "Clean MRFs" significantly reduce the potential for material contamination.

Considering the MRF regarded in the case study in chapter 3, the focus of this thesis is on "Clean MRFs" with a single stream (Recycling Marketing Cooperative for Tennessee, 2003). A conceptual structure of that one is shown in the following Figure 2.7.



(EPA, 1991)

Figure 2.7: Structure of a standard MRF.

GHG Emission Source

Recovering materials contributes greatly to the reduction of GHG emissions by displacing virgin raw materials in manufacturing processes and thereby avoiding environmental releases associated with the extraction of raw materials and its followed materials production (Weitz *et al.*, 2002). Taking this into account the amount of GHG emission sources at a MRF are rare. No source is attributed to the waste itself. Emitted GHG come from the consumption of energy associated with the sorting and separating operations (Entreprises pour l'Environnement, 2010). Table 2-3 summarizes further parameters with an environmental impact.

Table 2-3: Direct and indirect activities associated with recycling that contributes to solid waste output, energy use, and releases to air and water.

Environmental Parameter	Solid waste output	Energy use	Air releases
	Waste from the aquisition of fuels used by:	**Engergy represented by the fuels actually consumed by:**	**Releases from the combustion of fuels by:**
	- recycling collection vehicles, utilities to generate electricity used to operate recycable materials processing equipment	- recycling collection vehicles	- the MSW collection vehicles
	- residuals transport vehicles and residuals landfill equipment	- the utility	- the equipment used to process recyclable materials
	- vehicles transporting processed recycables materials to market	- equipment used to process recyclable materials	- the residuals transport vehicles and residuals landfill equipment
	- reject materials from recyclable materials processing	- the residuals transport vehicles and landfill equipment	- the vehicles transporting processed recyclable materials to the market
		- vehicles transporting recyclable materials to market	

Adapted from: (Denison, 1996)

2.4.3 Waste-To-Energy Plants

For many centuries, incineration of waste was a common method for disposal. It took a long time to be done for the purpose of generating energy. In 1975, the first commercial waste-to-energy plant opened its doors in the United States, more precisely in Saugus, Massachusetts. The plant is still operating today, of course having been updated.

Besides their generation of energy, those facilities reduce the volume of trash up to 90% through their high temperature combustion, minimizing the need for valuable landfill space. This is requested especially in areas where land for sanitary landfills is scarce. Furthermore, the high combustion temperature allows the breakdown of hazardous substances such as pathogens and toxic chemicals. Simultaneously to the whole process, emissions are controlled strictly by systems that meet or exceed the most stringent state and federal standards. However, some still confuse modern waste-to-energy plants with incinerators of the past that only attempted to reduce the volume of the trash without any pollution control equipment (Integrated Waste Service Association, 2014).

According to the U.S. Environmental Protection Agency, the 89 waste-to-energy plants that produce electricity have even "less environmental impact than almost any other source of electricity" (EPA *et al.*, 2014b). This statement is strengthened by results from current studies, which show that waste-to-energy facilities contribute to the reduction of the amount of GHGs that enter the atmosphere. An example therefore is a megawatt of electricity generated through the combustion of solid waste which is at the same time a megawatt of electricity avoided from conventional, *e.g.,* coal or oil-fired, power plants, creating a net savings of emissions of greenhouse gases, *i.e.,* carbon dioxide. Another example is, when a ton of solid waste is delivered to a waste-to-energy facility, the amount of methane that would have been generated if it were instead sent to a landfill is avoided. Considering that some of this methane might be collected and used to generate electricity, a portion of it would not be captured and be emitted to the atmosphere.

Taking all this into consideration when deciding either to use or not use a waste-to-energy plant, all benefits of it must be weighed against the significant capital and operating costs, potential environmental impacts, and technical difficulties of operating such a plant (Stauffer, 2014).

Structure

Three different types of waste-to-energy plants exist in the U.S. mainly distinguishable by their incineration processes and the waste they combust. Mass Burn Facilities are the most common types of waste-to-energy facilities. Waste used in this type of plant does not necessarily have to be sorted before it enters the furnaces. Modular Systems are smaller then Mass Burn Facilities and can be moved from site to site due to their portability. They are designed to burn unprocessed, mixed MSW. The last type is the Refuse Derived Fuel System that shreds incoming MSW, sorts out non-combustible materials and produces a burnable mixture suitable as a fuel in a dedicated furnace. Below, the conceptual structure of a generalized waste-to-energy plant is explained with its basic functions and technologies used (EPA *et al.*, 2014b).

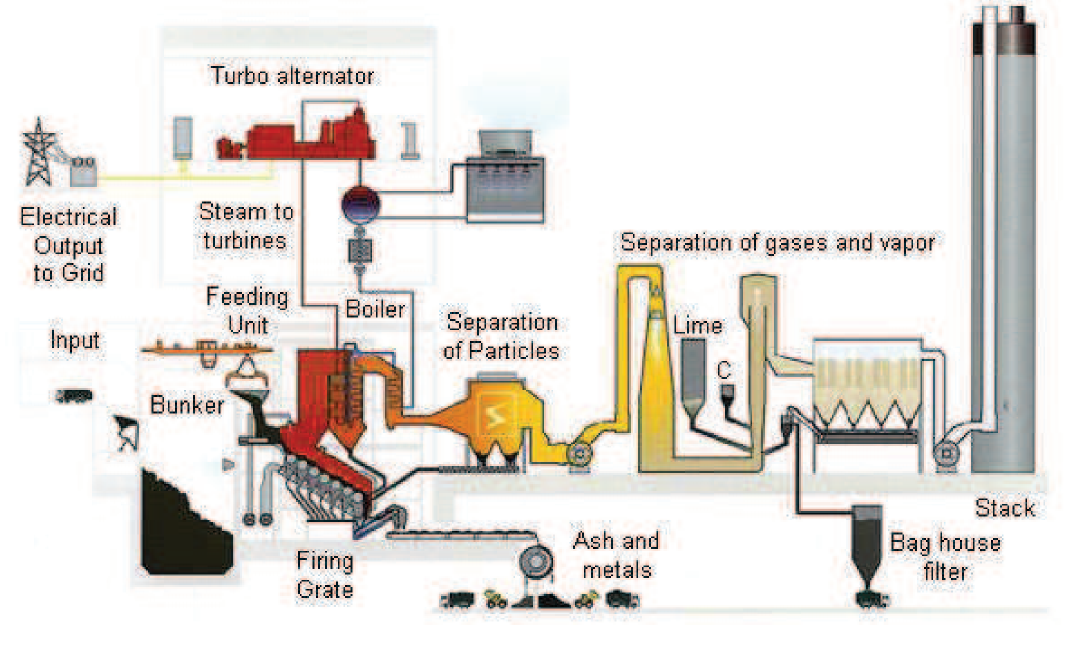
The first step in every incineration process is the delivery of the trash to the receiving building where it is deposited onto the floor or into a large concrete pit. At this point the majority of recyclables are removed from the trash received; however, to avoid any loss of recoverable material most waste-to-energy plants have integrated a recycling program. Depending on the plant, the trash is then either loaded directly into the furnaces or is first shredded to produce a fuel before putting it into the boilers. The required air for the combustion processes in the furnaces is obtained from within the receiving building. This ensures that a continuous flow of air gets into the building creating a so-called "negative pressure", which prevents dust and odors from escaping (Integrated Waste Service Association, 2014).

The next step in the process is the combustion itself. Extremely high temperatures during this process lead to the complete destruction of bacteria, viruses, rotting food and other organic compounds found in household garbage that could potentially affect human health. Generated heat from burning the trash boils water that flows inside the boiler tubes where it turns the water into steam that can be used directly in a heating system or a factory. In most cases, however the steam is used to turn a turbine-generator to generate electricity (Stauffer, 2014).

In the final step, after the ash with its incombustible residues cools down, magnets and other mechanical devices pull metals from the ash for recycling, a crucial step considering that waste-to-energy plants extract thousands of tons of metals from its ash. The remaining ash is, in most cases, disposed on landfills.

Additional technologies that are essential for the whole combustion process are those, that control the environmental impacts. Today's air quality (emission) control systems work on very high standards, minimizing the amount of GHGs emitted and potential contaminants that have an impact on the environment. Included in these systems are, for example, giant vacuum cleaners consisting of hundreds of fabric filter bags or electrostatic precipitator, which capture small particles of fly ash. Finally, these systems are continuously advanced to meet, or in the best case to exceed, the strictest federal requirements set by EPA (Integrated Waste Service Association, 2014).

The following Figure 2.8 displays a waste-to-energy plant as described above. For the calculations of the carbon footprint in chapter 3, the incineration processes are assumed to take place in a Mass Burn Facility.



Adapted from: (Yokogawa, 2014)

Figure 2.8: Structure of a standard Waste-to-Energy plant.

GHG Emission Source

The combustion of MSW contributes to the reduction of GHG emissions. On the one hand, it diverts MSW from landfills where it would otherwise produce CH_4 as it decomposes. On the other hand, energy generated from waste combustion results in avoiding emissions from the production of an equivalent quantity of energy from a fossil fuel-fired power generator (Weitz *et al.*, 2002).

Nevertheless, any burning process produces carbon dioxide and nitrous oxides that are released to the environment, despite the advanced emission control systems. Furthermore, Table 2-4 shows additional environmental parameters, which have an impact on the environment during this combustion process.

Taking all this into account, a carbon footprint for this waste management system is calculated in the next chapter.

Table 2-4: Direct and indirect activities associated with waste-to-energy plants that contribute to solid waste output, energy use, and releases to air and water.

Environmental Parameter	Solid waste output	Energy use	Air releases
	• Utility-related wastes (e.g. coal ash) • Ash residue and scrubber wastes that are outputs of the combustion process	**Energy represented by the fuels actually consumed by:** -the MSW collection vehicles - the utility - the incineration and associated equipment - the ash transport vehicles and ash landfill equipment	**Releases from the direct combustion of fuels by:** -the vehicles - the utility - the incinerator and associated equipment - the ash transport vehicles and ash landfill equipment - releases directly from the incinerator arising from combustion waste

Adapted from: (Denison, 1996)

2.4.4 Municipality Landfill

The last regarded waste management system is the municipality landfill. It is historically the oldest form of waste treatment and the most common method of organized waste disposal utilized all over the world. Yet, continuous advancements and environmental regulations have changed the structure of landfills significantly. In the 1970s most landfills in the United States were operated without any gas collection or control; however, this is no longer conceivable today (EPA *et al.*, 2014a).

Modern landfills are well-engineered facilities that are strictly regulated by the EPA and the state's environmental agency, with consideration of location restrictions, composite liners requirements, groundwater monitoring requirements, closure and post closure care requirements, etc. (Government Printing Office, 2012).

The primary source of the trash received at a landfill is household waste. Besides that, they can also receive non-hazardous sludge, industrial solid waste, and construction and demolition debris while other materials might be banned from the disposal such as chemicals, batteries, motor oil, or pesticides (RIRRC, 2013).

A major drawback of a landfill compared to the other waste management systems is that it is a finite resource. Once it is filled up, operations are ceased and the landfill is closed, albeit the maintenance and monitoring of it have to stay active for many years, using additional financial resources.

Structure

Similar to the other waste management systems, different types of landfills exist. Three main types are distinguished concerning the waste they receive. The MSW landfill is a highly engineered disposal facility, which must meet or exceed the strict state regulations to ensure environmentally safe and secure disposal. It receives non-hazardous waste that is disposed for long-term care and monitoring. At Construction & Demolition landfills, non-hazardous materials that are produced in the process of construction, renovation and/or demolition of structures are disposed. The last type, Inert landfills, are for the disposal of earth and earth-like products such as cured asphalt, rock, bricks, yard trimmings etc. (Advanced Disposal, 2014).

In terms of the design of a standard landfill, it consists of different layers, using different types of liners to keep the waste separate from the surrounding natural environment. Typically, liners consist of plastic, clay or sand, depending on the type of landfill they are used at and are designed to keep leachate, water that comes in contact with waste, from passing through the landfill. Besides that, each landfill today is equipped with an advanced system for collecting gases like methane and carbon dioxide that are continuously produced at landfills (RIRRC, 2013). For longevity of the landfill, compactors and bulldozers try constantly to get as much trash in the smallest amount of space possible. Further explanations about the design of a standard landfill can be taken from the Figure 2.9 below.

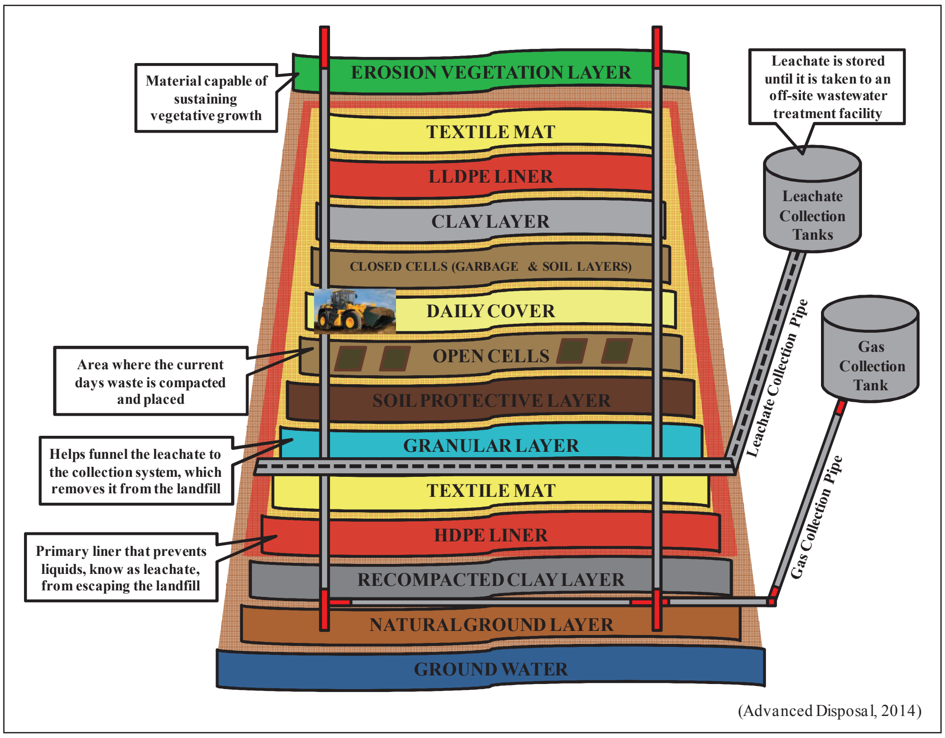


Figure 2.9: Structure of a landfill

GHG Emission Source

Although there have been several improvements in landfill design and management, which has led to a substantial reduction of GHG emissions, organic waste decomposition still produces a proportionally large amount of landfill gases comprising of methane (18.1% of U.S. total CH_4 emission in 2012) and carbon dioxide. As mentioned above, parts of it can be captured and recovered to produce energy. Other parts are destroyed through combustion that turns methane into carbon dioxide, which has 21 times less impact on the greenhouse effect. However, all of the produced landfill gas cannot be captured and therefore parts of it are emitted to the atmosphere. Table 2-5 shows additional parameter with an impact on the environment considering land-filling.

Table 2-5: Direct and indirect activities associated with land-filling that contribute to solid waste output, energy use, and releases to air and water.

	Solid waste output	Energy use	Air releases
Environmental Parameter	• Waste from the aquisition of (e.g. oil) fuels used by MSW collection vehicles and landfill equipment • Landfilled materials itself	• Energy consumed in the aquisition of fuels used by MSW collection vehicles and landfill equipment • Energy represented by the fuels themselves consumed by the vehicles and equipment	• Releases from combustion of fuels themselves in the vehicle equipment • Volatilization to the air of products of waste decomposition, in the form of landfill gas

Adapted from: (Denison, 1996)

3 Case Study: Rhode Island Resource Recovery Center

Within this chapter, tools such as LCA and carbon footprint measurement that have been discussed in detail in the theoretical foundation previously are now applied in practice on real processes of an existing and currently operating MRF in Rhode Island. Primary goal is to perform an LCA of the MRF and exemplarily an LCA of a particular material. Furthermore, the environmental impacts of this MRF, the exemplarily chosen material, and two other WMS are evaluated with particular focus on the GHGs emitted to the air.

The MRF regarded in this case study is part of the Rhode Island Resource Recovery Center (RIRRC), which is located in Johnston, Rhode Island (RI). It was created in 1974 by the Rhode Island General Assembly to do the state's work, but it is neither a department in the government, nor is it dependent on any government financing.

RIRRC handles almost all of the state's trash and recyclables from the towns, cities and some RI businesses, providing safe, environmentally compliant, and affordable recycling and solid waste services for the community. Everyday 350-400 trucks bring waste to the sanitary landfill and 85-90 bring recycling to the MRF.

Considering its size, the MRF belongs to one of the largest in New England with 61 employees and a maximum process rate of approximately 800 tons per day. However, the current amount processed per day is only 450 tons, leaving room for more.

While this case study is only focusing on the RIRRC, the final results of the models can be considered as reliable for most of existing MRFs, which process a similar amount of recyclables.

The first step is the definition of the scope, which is important with respect to the performance of both LCA and carbon footprint measurement later. It includes the determination of system boundaries, necessary data for calculations and lists the impact categories that should be considered.

In the next step, the processes of the RIRRC and a particular recyclable material that passes the different steps within the RIRRC are modeled in the sustainability software GaBi 6 and in Excel spreadsheets, which are subsequently used to determine the carbon footprints.

3.1 Scope of the Case Study

Setting the scope and boundaries is the most important step in the beginning to determine what exactly will be regarded in the system. In this case study the scope is virtually given through the boundaries of the RIRRC itself. It is limited to recyclables 'produced' from households in the municipality of Rhode Island and limited to waste generated within one year. In other words, it includes all the necessary information needed for performing the LCA of the RIRRC and calculating its carbon footprint afterwards.

3.1.1 System Boundaries

Figure 3.1**: Scope for the case study** illustrates a detailed overview of the scope and boundaries of this case study and also provides at the same time a conceptual framework of the recycling process of the RIRRC. This process consists essentially of three parts: the collection of recyclable waste, the MRF and the recovered raw materials at the end. To get a better understanding, which material and processes are

being further examined in this study, they are highlighted with colors and simultaneously labeled with “Module” in the scope. The focus is thereby on the first two parts, while the third part is only considered for performing a LCA of one particular recycling material.

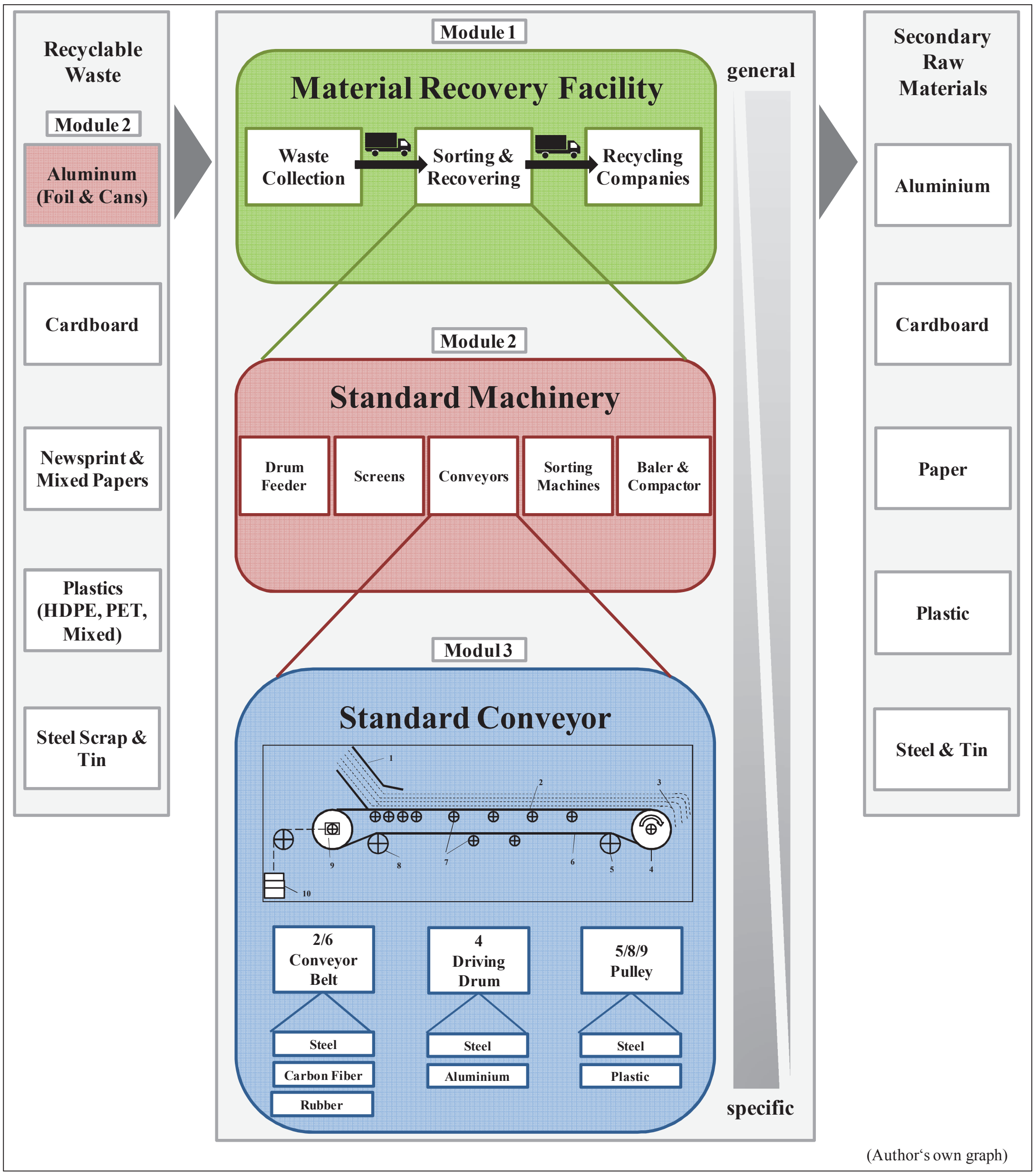


Figure 3.1: Scope for the case study.

Regarding the first part of this recycling process, it is necessary to look at the materials, which should be considered in the system. As mentioned before the RIRRC handles most of the states trash and recyclables. Therefore, the first system boundary set in this case study is a regional one determining that only recyclable waste produced in the municipality of Rhode Island is taken into account. Based upon the data set provided by the RIRRC this recyclable waste consists, of aluminum (foil and cans), cardboard, news print and mixed papers, plastics (HDPE, PET, mixed), tin and steel scrap.

Within that listing, aluminum is highlighted meaning that a closer look was taken. This is done with respect to the next chapter, in which LCAs are performed It would go far beyond the scope of this thesis to perform one for each material. Hence, a LCA of aluminum is performed to represent all the other recyclable material.

In the next step, the second and main part of this study is reviewed concerning its scope and boundaries. This part is initially subdivided into three levels, in which each level includes a different approach. The first level represents the waste management sector with its different WMS. Assuming, for example, that a decision has to be made as to what kind of WMS should be created in a certain geographical area, examinations would be made on this upper level to compare different alternatives and their possible advantages and disadvantages on an economic and ecological basis. Therefore, the systems are viewed as black boxes taking into consideration only the main process steps of each WMS and the associated general parameters such as energy consumption, GHG emission, solid waste production and costs.

The first step for each of the compared WMS in the process is the curbside collection of the recyclable waste at the households in the municipality of Rhode Island, which is then either brought to the MRF, a Waste-to-Energy plant or a Landfill.

In the next step a closer look is taken at the main processes of each WMS such as the separating process at the MRF, the incineration process at the Waste-to-Energy plant or the disposal of the materials at a Landfill. However, the examination of these processes considers only general parameters as mentioned above; a more detailed assessment of the machinery used in these different processes is addressed in the next level.

The final step of this process chain is either the recovery of secondary raw materials through the MRF, the production of energy through the incineration of waste or the production of energy through the collection of gases from the landfill.

The necessary information for all of these examinations is based on the data set provided from the RIRRC, which includes only recyclable materials. Therefore the center of attention is on the MRF and its processes and its examinations are focused on environmental impacts outgoing from the system rather than on economical factors.

The second level is consulted, for example, when a benchmark for a certain WMS exists and it is recognized that the system requires improvements to reach it. In light of examining environmental impacts, these improvements can include the reduction of GHG emissions, the amount of energy consumed or any other aspect that has negative impacts for reaching the benchmark.

Finding weak points within the system that need to be improved assumes that a closer look has to be taken at the processes and machinery used. Hence, this second level considers, in particular, the technical aspects.

The sorting process of recyclables at a MRF is complex and requires different machinery. Drum Feeders, Screens, Conveyors, Sorting Machines, Balers and Compactors are the most common ones. Considering the RIRRC machine park, conveyors constitute nearly 60 percent of all machines. A look at this level is taken in the LCA of the aluminum waste, in which GHG emissions are allocated to certain machineries within the process of the MRF.

An even closer technical analysis is done at the third level, in which the materials and parts used for the construction of a machine are analyzed concerning their environmental impacts during their life phases. However, this level is due to its enormous complexity excluded from the examinations in this thesis.

In conclusion, two different LCAs are performed in the scope of this case study, beginning with the center of attention, the performance of the LCA of the MRF, followed by the performance of the LCA of aluminum waste.

Furthermore, a Waste-to-Energy plant and a Municipal Landfill are modeled within the GaBi 6 sustainability software and evaluated considering their GHG releases. Subsequently, those two WMS are compared with the MRF in terms of their carbon footprint.

3.1.2 Data Acquisition and Estimations

The quality of the data used in performing a LCA or a carbon-footprint measurement has a significant influence on both assessments results. Therefore, determining the data quality requirements is an essential step at the beginning of each study, keeping in mind that quality is often a tradeoff between feasibility and completeness.

In general, the quality of a data set can only be assessed if the characteristics of the data are sufficiently documented. Hence, the data quality corresponds to the documentation quality where issues such as the data acquisition, time reference, geographical reference, precision, completeness, consistency and reproducibility need to be considered (Neugebauer, 2012).

Regarding the data acquisition, it can be distinguished between data that is measured, calculated or estimated and primary data or secondary data, which is taken from literature and databases. The data used for performing the LCAs and for the measurement of the carbon footprints in this thesis is based, as earlier mentioned, primarily on the data set provided by the RIRRC. This data set includes necessary information about the recyclable materials collected and their amount as well as a list that is broken down into different categories accounting the consumption of different energy sources. Regarding the electricity consumption, for example, a whole list of the different processes and machines used within the MRF is provided, showing exactly how much each requires. Furthermore, information about the consumption of propane for running the power forklifts, the annual oil consumption for heating the MRF and the diesel consumption for running all wheel loaders is provided (Björklund, 2001).

Considering the time reference of the data, it has to be mentioned that the data set provided is two years old. Major changes that have occurred in the RIRRC (*e.g.* changes in consumption) since the data collection are not provided and, therefore, are not taken into account. However, technologies and processes associated with the LCA and carbon footprint are based on secondary data from the databases of GaBi and can be considered as the state-of-the-art, which is used for the modeling.

To illustrate the geographical reference, electricity will be used as an example. Electricity is the main energy source for most of the machines and processes and it is at the same time an important input parameter in the inventory analysis of LCA as well as in the measurement of carbon footprints. The data used in this case study for the electricity supply is therefore based on data from U.S. power plants.

However, while the amount of electricity consumed at the MRF is provided, information is missing from what type of power plant supplied it. Depending on the geographical location, the supply can differ considerably. Is the supplied electricity, for example, mainly generated from coal-fired or nuclear power plants or is it supplied from renewable energies, such as solar plants or wind power stations. Depending on the type of power plant chosen for the supply, the results in both the LCA and carbon footprint measurement can vary significantly.

Regarding the MRF of the RIRRC, it is assumed that the electricity consumed is a mix supplied from different power plants of the east cost of the USA. The respective data of this electricity mix is provided through literature, online databases and the sustainability software GaBi 6, in which the MRF is modeled. The same applies to the respective data of the other energy sources, such as propane, oil and diesel. They are all based on data from the U.S. and, if possible, even on data from the east coast where the MRF is located.

With respect to the next chapter in which LCA and carbon footprint measurement are addressed, some data is missing in view of modeling the MRF. As previously, mentioned the process begins with the curbside collection and ends with the transport to further recycling companies. Both process steps are related to transport and, thus, also with the consumption of fuel. Because of the lack of data in this context, realistic estimations need to be made. The necessary steps for the estimation of the curbside collection are displayed in Figure 3.2 below.

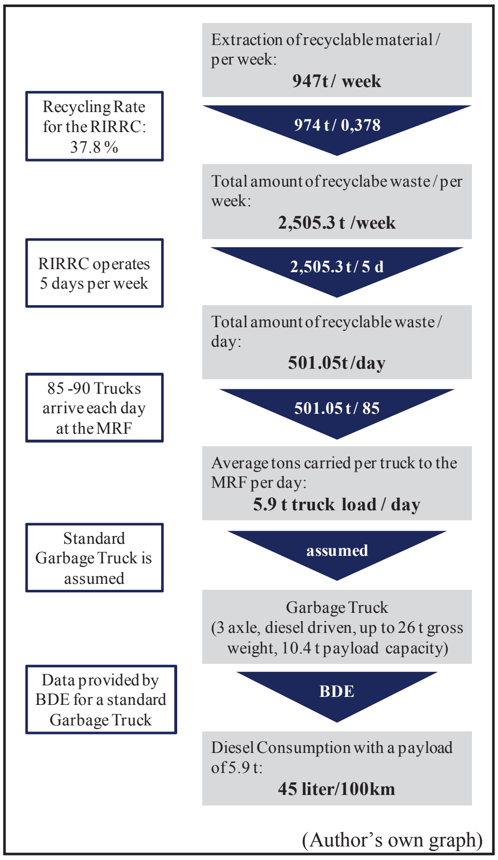


Figure 3.2: Estimation for the curbside collection and transport to the MRF

The initial point for the estimate is the weekly amount of recyclables extracted from the arriving waste at the MRF. This amount, 947 tons in total, is provided by the data set from the RIRRC and encloses all recyclable materials. Considering that the MRF has a recycling rate of 37.8 percent the next step in the estimation can be calculated. It is the total amount of waste arriving at the MRF per week, which is 2,505.5 tons (RIRRC, 2011).

Also included in the information provided by the RIRRC is that the MRF operates five days per week, which allows the average amount of recyclable waste arriving per day to be determined as 501.05 tons. According to the RIRRC Guide (RIRRC, 2013) the average amount of waste processed in the MRF is indicated as 450 tons, which lets the calculated amount seem realistic.

Continuing the estimation of the curbside collection, the data set provides the information that 85-90 trucks arrive at the MRF per day. Taking the 85 trucks into account, it can be estimated that a particular truck delivers about 5.9 tons of waste every day to the MRF. Hence, the only eligible truck for the curbside collection is a standard garbage truck with 3-axles, a payload capacity of 10.4 tons, with an average diesel consumption of 45 l/ km. Research on an American standard garbage truck has proved difficult with minimal information available. Therefore, comparable data for this type of garbage truck is provided by the “Bundesverband der deutschen Entsorgungswirtschaft” (Federal Association of German Waste Disposal (BDE, 2009), which has done more substantial research.

The high consumption of diesel by the garbage truck is related to the fact that the curbside collection is a continuous alternation between stopping and starting and that only short distances (from house to house) are driven.

In order to estimate the total diesel consumption for the transportation to the RIRRC within a year, a further assumption is required regarding the distances each truck drives. For curbside collection, urban settings are more or less needed. Hence, all cities in Rhode Island with a population bigger 15,000 people are taken into account. In the next step, the distances from each of those cities to the RIRRC in Johnston, Rhode Island is researched and an average is calculated.

With this information, the total diesel consumption for the transport of the waste to the RIRRC can be estimated in respective chapters where it is needed as an input for either the LCA or the carbon footprint measurement.

The second estimation that is required is for the last process step of the MRF is the transport of the recovered materials to other recycling companies. Figure 3.3 illustrates the methodological approach of this estimation.

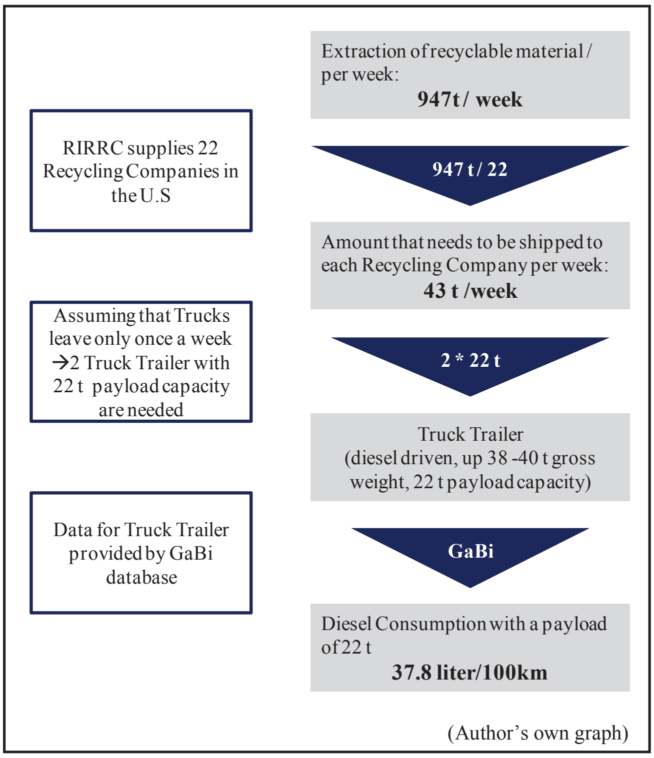


Figure 3.3: Estimation for the transport to the recycling companies.

The initial point for this estimation is the amount of recyclable material that is extracted per week. Within the data set provided by the RIRRC, 22 recycling companies are listed to which the RIRRC ships their recovered materials. However, there is no information considering the quantities that are shipped to each. Therefore, it is assumed that only trucks leave once a week, shipping quantities of 43 t to each of these companies. This requires two truck trailer with a payload capacity of 22 tons and an average diesel consumption of 37.8 l/100km each. The data for this truck type is provided by the GaBi database.

With this estimation, it is now possible to calculate the total diesel consumption for the transport from the MRF to its customers within one year. Similar to the previous transport estimation, this calculation is done in its respective chapters. The assumptions needed for the distances each truck drives are comparable to those done for the first transport problem. In this estimation, the distances from the RIRRC to the particular customer (recycling company) are researched and then an average of all distances is calculated and used.

Further missing data, within the data set of the RIRRC, is the energy consumption of land-fills and waste-to-energy plants in general. While some of this data is provided by the GaBi databases, the remaining data is taken from literature and online databases. A closer examination of this data takes place in the respective chapters. The same applies to the data that is used for the LCA and the determination of the carbon footprint of the aluminum can.

Finally, all the data used will be assessed regarding its consistency, reliability and accuracy.

3.1.3 Impact categories

As mentioned previously in Chapter 2.1.3, mandatory elements such as the selection of relevant impact categories, classification and characterization have to be determined for the LCIA within the first step of each LCA study, the goal and scope definition. Also in the beginning steps, the impact assessment method used for performing a LCA needs to be chosen.

Two common methodologies that help classify and characterize substances according to the extent they fit into a list of environmental impact categories are TRACI and CML that have also been mentioned before. While TRACI (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts) is developed by the

U.S. Environmental Protection Agency and is primarily used in the US, the CML methodology is developed by the University of Leiden and mainly used in Europe.

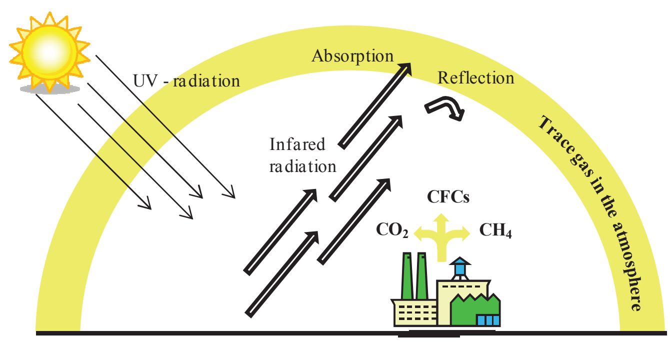
LCAs within this case study are to the greatest extent performed in the sustainability software GaBi 6, which includes both methodologies. However, although the data used for the performance base on products and processes from the U.S. and the MRF examined is also in the U.S., the impact assessment method chosen is the CML. The principal reason for this is that the available student version of GaBi, due to its origin, is based on European principles rather than on American. Nonetheless, it is important to note that the differences between both methodologies concerning their impact categories do not significantly influence the results. Furthermore, CML's focus is on environmental impact categories that are expressed in terms of emissions to the environment and its categories are based on IPCC factors. Hence, CML is considered as the more appropriate methodology to use in this case study (PE International, 2013a).

The number of impact categories is commonly chosen at the beginning of an LCA study and the number strongly depends on the goal of the study. The focus of this case study is, not only, the performance of a LCA of recyclable material, the MRF and the different conveyor belt types, but also, the determination of the carbon footprint of all three entities. Therefore, a selection of impact categories that covers the environmental effects of the analyzed systems and includes within its categories the most important GHGs is explained below (Herrmann, 2010). The selection consists of following five impact categories:

Global Warming Potential (GWP)

The first environmental impact category and by far the most important considering this case study is the GWP. It is an index that measures the contribution to global warming of a substance that is released into the atmosphere. These gases, mainly emitted through human activities, are summarized as GHGs and enhance the natural mechanism of the greenhouse effect (OSRAM, 2013).

The effect occurs by short-wave radiation from the sun that encounters the earth's surface, which is either partly absorbed leading to direct warming or partly reflected as infrared radiation. Unfortunately, the reflected part is absorbed by greenhouse gases in the troposphere and is re-radiated in all directions, including back to earth that resulting in a warming effect at the earth's surface. Figure 3.4 illustrates the principal process of the anthropogenic greenhouse effect and includes furthermore GHGs such as carbon dioxide, methane and CFCs that are considered to be caused or increased mainly by human activities. Additionally, analyses of the greenhouse effect should, in general, regard the possible long term global effects (PE International, 2013a).



Adapted from: (Dominik and Stadlmann, 2012)

Figure 3.4: Principal process of the anthropogenic greenhouse effect.

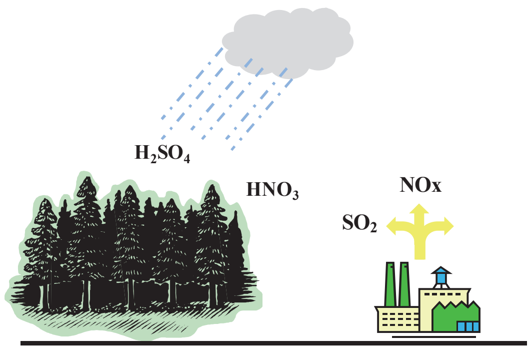
The reference substance for the GWP is carbon dioxide, meaning that the green house potential of any emission in this impact category is given in relation to CO_2 and calculated in carbon dioxide equivalents (CO_2-eq.). Additionally, because the residence time of the emissions in the atmosphere is incorporated into the calculation, a time range for the assessment has to be specified. Usually, a period of 100 years is assumed (Herrmann, 2010).

Acidification Potential (AP)

The next regarded impact category is the Acidification Potential (AP). Acidification is in terms of the environmental media, understood as an increase in the concentration of H^+-ions in air, water and soil. Major contributors to that acidification are gases such as sulphur dioxide and nitrogen oxide and their respective acids (H_2SO_4 and HNO_3). Compounds of these gases, especially those originating from anthropogenic emissions, react in the air with water vapor and form sulfuric and nitric acid, which fall subsequently down to the earth as "acid rain", snow or even as dry deposits and damage soil, water, living organisms and buildings.

Considering the damaging effect of acidified soil, nutrients are washed out and toxic cations are released attacking roots of trees. Thus, there is a failure to supply the organisms with nutrients and simultaneously a disturbance of the water balance of the roots. This damages the ecosystems enormously, whereby forest dieback is the most well known impact (OSRAM, 2013).

An important detail to consider during acidification analysis is that although it is a global problem, the regional effects of acidification can vary. Figure 3.5 below shows basic impact paths of acidification.



Adapted from: (Dominik and Stadlmann, 2012)

Figure 3.5: Impact paths of acidification.

The reference substance of the impact category AP is sulphur dioxide and it is measured in sulphur equivalents (SO_2-eq.) (OSRAM, 2013).

Eutrophication Potential (EP)

Eutrophication, specifically nutrient enrichment, refers to an accumulation of nutrients in a particular location. Thereby, it is distinguished between the discharge of nutrients into the water (aquatic) and into the soil (terrestrial). Wastewater, fertilizers used in agriculture and air pollutants all contribute to eutrophication.

A result of aquatic eutrophication is an increased growth of algae, which prevents sunlight from reaching deeper depths of water, leading to a reduction in photosynthesis and a lower production of oxygen. Plus, oxygen is necessary for the decomposition of dead algae. Thus, these two effects result in a decreased oxygen concentration in the water, which can ultimately lead to the devastation of fish stocks and to putrefaction (anaerobic decomposition), which simultaneously lead to the production of methane and hydrogen sulphide. The combination of all these effects can lead to the destruction of an eco-system.

Regarding terrestrial eutrophication, it is often observed that plants growing in the effective soil have an increased susceptibility to diseases and pests. Furthermore, an enrichment of nitrate is also possible. This is when the nutrification level exceeds the amount of nitrogen needed for a maximum harvest, which can subsequently result, in the case of leaching, in an enhanced content of nitrate in the groundwater. From there, the nitrate can also end up in the drinking water. From the toxicological point of view, lower levels of nitrate are harmless. However, it often reacts to nitrite, which is toxic to humans.

The Figure 3.6 below displays the causes of eutrophication. The reference substance in this impact category is phosphate and the EP is measured in phosphate equivalents (PO_4-eq.)

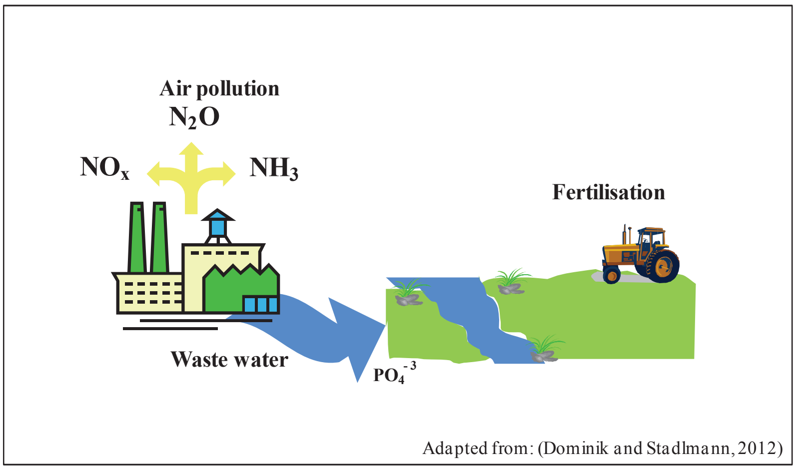


Figure 3.6: Causes for eutrophication.

Human Toxicity Potential (HTP)

Methods for the impact assessment of toxicity potentials are still to some extent in the development stage. HTP assessment intends to estimate the negative impact of a process on humans. It is a calculated index that reflects the potential harm of a unit of chemical released into the environment, which is based on both the inherent toxicity of a compound and its potential dose. Most of these by-products such as arsenic, sodium dichromate and hydrogen fluoride are mainly caused by the production of electricity from fossil sources. These substances are potentially dangerous to humans through ingestion, inhalation and even contact. A main issue in this impact category is the cancer potency. HTP is measured in 1,4-dichlorobenzene equivalents ($C_6H_4CL_2$ – eq.).

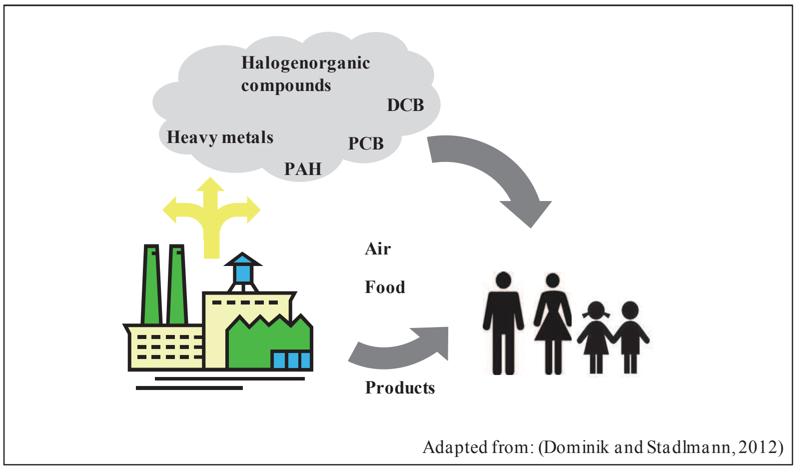


Figure 3.7: Human toxicity potential (HDP).

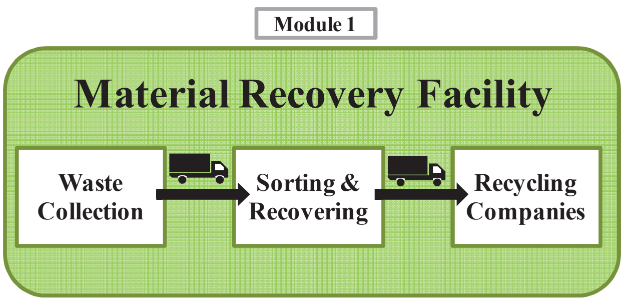
After selecting the relevant impact categories, the LCI results have to be assigned to one or more impact categories. This is done in the next chapter when the respective LCAs are performed. The final step is the characterization, which describes and quantifies the environmental impact of the analyzed systems. Therefore, characterization factors that are included in the selected impact category methods (in this case CML) are used for converting the results of the LCI into the reference units of the respective impact category.

3.2 LCA Performance and Carbon Footprint Assessment

The first part of this Chapter forms the focus of this entire thesis. An LCA study of the MRF of the RIRRC is performed and its carbon footprint is determined. The LCA of the MRF is thereby, as previously described in the scope of this case study, at a general level performed. The results of the carbon footprint assessments are the initial point for the subsequent comparison of the MRF with the two other WMS, the landfill and the waste-to-energy plant, in the next Chapter 0.

In the second part of this Chapter, an LCA for the aluminum waste that is processed in the MRF is performed for all other commodity types and additionally its carbon footprint is determined for this phase of its life. While the LCA for the MRF is modeled and performed in the GaBi 6 sustainability software, the LCA for the aluminum waste is performed in both the software and Excel spreadsheet. The reason for this is to analyze each process stage the aluminum waste runs through in the MRF to assess a precisely carbon footprint, which discloses the main contributors to emissions of GHGs within the entire process.

3.2.1 Material Recovery Facility



The scope and system boundaries for the MRF have been determined in general in the previous chapter, but are further specified here in the respective step of the LCA. This study quantifies all significant inputs and outputs of the material recovery system including input categories, such as the mass of recyclable waste identified in the system and the energy consumed. A significant output, environmental releases, are essentially related to air for the determination of the carbon footprint. Furthermore, these releases will be sub-divided into process-related, fuel-related and transportation-related data categories.

This LCA was mainly performed with the educational version of the GaBi sustainability software, which also allows the GHGs concerning the carbon footprint to be measured. However, it is important to note that some steps of the LCA performance needed to be simplified due to both lacks of information and data considering the whole process of the MRF and limitations within the modeling software. This essentially refers to the modeling, whereby each simplification is mentioned at each particular part, as well as, the reason for it.

Goal Definition

The goal of this LCA study is, on the one hand, to provide the RIRRC with general up-to-date LCI data and, on the other hand, to demonstrate the performance of the MRF considering its carbon footprint compared with other existing WMS (Waste-to-Energy Plant, Land-fill). Therefore, a range of specific and selected environmental impacts is assessed, but other aspects such as economic and social factors are not considered.

The intended audience for this study is the RIRRC itself, decision makers in the waste management sector of Rhode Island, as well as the general public.

Scope Definition

While usually the scope of an LCA comprises a “cradle-to-grave” LCI, starting with the extraction of the raw material for the product, including the production of it, and ending after its recovery and recycling, the scope of this study focuses on the later part of the life cycle of a product or material. The later section of the life cycle begins with the curbside collection and transport of the recyclable waste to the MRF, the process within the MRF itself and ends with the transport of the recovered material to further recyclers.

Table **3-1: Summary of system boundaries** summarizes the system boundaries with regard to the general processes/ quantities that are considered in the study.

Product System Boundaries

The examined process is a standard material recovery process at the MRF of the RIRRC that is located on the East Coast of the United States, more precisely in Johnston Rhode Island. The energy consumed during this process is supplied by power plants from this geographical area and the technology used in the process is assumed as the state-of-the-art for the U.S.

Furthermore, it is important to mention that in a waste LCA a ‘zero burden’ approach is usually considered, indicating that the embedded environmental load of a material, before it becomes a waste, is excluded from the modeling (Gentil *et al.*, 2009).

Table 3-1: Summary of system boundaries

Included	Excluded
• Creation of recyclable waste in the household • Curbside Collection • Transport to the RIRRC • Separating and Sorting process in the MRF • Energy and fuel inputs • Transport of recovered material from the RIRRC to further recycling companies	• Embedded environmental load of a material before it becomes a waste • Production of trucks, roads, containers, garbage bins, MRF building • Maintenance and operation of equipment • Human labor • Waste disposal (i.e. land-filling)

Additionally to the summarize of the system boundaries in

Table **3-1**, a system flow chart is presented below in Figure 3.8 illustrating the system boundaries in the context of all life cycle phases a product has.

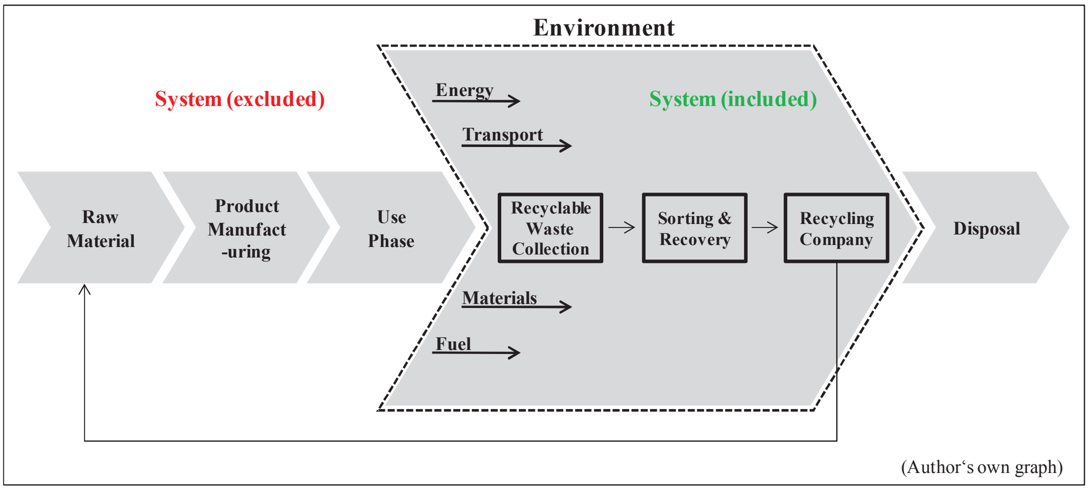


Figure 3.8: Process flow chard indicating the system boundaries in the context of all life cycle phases.

Data Collection, Software and Databases

While the generalized data has been described in Chapter 3.1.2, in this part, the data used specifically for this LCA is expanded upon. Thereby, the data provided by the RIRRC can be sub-divided in the following categories for the process:

- Fuel and energy use,
- Recyclable waste collected,
- Recyclables extracted
- Emissions to air (in parts also water and soil).

Wherever possible, the primary data provided by the RIRRC is used in this LCA study. In cases where primary data is not available, secondary data readily available from life cycle databases, previous LCI studies or from literature is used for the analysis. The sources for secondary data are documented. In the absence of secondary data, approximations based on general information from the RIRRC were used to close the data gaps.

Functional unit

The definition of the functional unit is a special issue for LCA studies of WMS, since they differ from the LCA of products. While in a product LCA, the functional unit is usually defined in terms of the system output, *i.e.* the product; the functional unit in this context must be defined in the terms of systems input (Cherubini *et al.*, 2009). Therefore, the functional unit chosen is the amount of total recyclable waste produced within a year in the municipality of Rhode Island.

Life Cycle Impact Assessment Methodology & Impact Categories Considered

The LCIA methodology (CML) as well as the meaning and significance of the impact categories investigated in this case study are discussed in detail, in the previous Chapter. For the purposes of a comparison of the carbon footprint of the WMS later, the following impact categories were determined:

- Global Warming Potential (GWP) (100 years; includes carbon dioxide, CO_2, and other GHG relevant emissions),
- Acidification Potential (AP),
- Eutrophication Potential (EP), and
- Human Toxicity Potential (HTP).

Life Cycle Inventory and Process Modeling

To begin with, an inventory analysis of each process step within the MRF is done and particular results for the impact categories and the carbon footprint are presented. After that, the process is assessed in total and the results are displayed.

It is important to notice that all results presented in this chapter are absolute values considering the previously determined functional unit. Regarding, for example, the total amount of CO_2 emitted from the MRF in the context of the carbon footprint assessment, this result is not referred to as a certain comparative value (i.e. one ton recycled material processed) but it is referred to as the total amount of recyclable waste processed in the MRF.

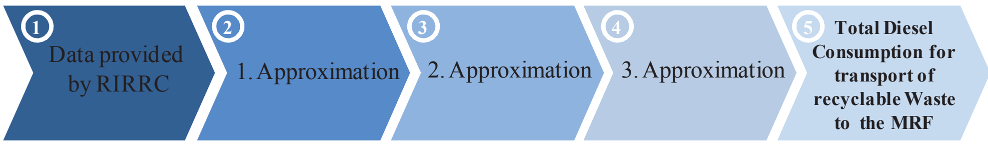
Curbside Collection and Transport to the MRF

The first step in the process is the curbside collection of the recyclable waste within the municipality of Rhode Island and its transport to the MRF afterwards. Because of missing data in this case, approximations have already been made in Chapter 3.1.2, to close this gap of data. Taking these approximations into consideration, a standard garbage truck is estimated to have a diesel consumption of 45 liters/ 100 km. Outgoing from that, the total amount of diesel consumed for the whole transportation to the MRF within a year can be approximated.

Table **3-2** illustrates each particular step taken to reach a realistic result. Additionally, variables are integrated for each step, which are used later within the formulas for the calculations. Furthermore, the table displays, besides the total amount, information to the amounts of each commodity type recycled.

Table 3-2: Approximation of the total diesel consumption of the transport of recyclable waste to the RIRRC per year.

Commodity Type		① Extracted recyclables (t) per year	② Recyclable waste collected (t) per year	% of total amount of waste per year	③ Amount of waste trucks driving to MRF per year	④ Total kilometers driven to MRF	⑤ Total diesel consumed (liters)
i	Variables	v	w		x	y	z
1	Aluminum (Foil & Cans)	1,104	2,920.63	2%	495	31,356.73	14,110.53
2	Tin	2,880	7,619.05	6%	1,291	81,800.16	36,810.07
3	Steel Scrap	7,20	1,904.76	2%	323	204,50.04	9,202.52
4	News Print	19,200	50,793.65	43%	8,609	545,334.41	245,400.48
5	Mixed Paper	4,800	12,698.41	11%	2152	136,333.6	61,350.12
6	Cardboard	10,800	28,571.43	24%	4,843	306,750.61	138,037.77
7	HDPE	2,400	6,349.21	5%	1,076	68,166.8	30,675.06
8	PET	2,880	7,619.05	6%	1,291	81,800.16	36,810.07
Total		44,784	118,476.19	100%	20,081	127,1992.51	572,396.63



The first step in the calculations is again the extracted recyclables in tons per year. With a given recycling rate of 37.8 percent and the following formula below, the total recyclable waste collected and transported to the MRF is calculated.

①
$$\sum_{i=1}^{8} w_i\,(t) = \sum_{i=1}^{8} \left(\frac{v_i\,(t)}{0{,}378}\right)$$

The next step is the determination of the total amount of garbage trucks driving to the MRF per year. Basis for this calculation is the approximation in Chapter 3.1.2 of the average payload of a standard garbage truck, which is estimated with 5.9 tons. The formula for this calculation is the following:

$$\sum_{i=1}^{8} x_i = \sum_{i=1}^{8} \left(\frac{w_i\ (t)}{5{,}9\ (t)}\right) \quad (2)$$

After knowing the amount of garbage trucks driving to the MRF per year, the total mileage driven of all of these trucks can be calculated. As mentioned previously, a curbside collection requires urban settings for a curbside collection, therefore only cities within Rhode Island with a population size bigger than 15,000 people are taken into account.[2] From these cities, distances are determined to the RIRRC in Johnston, Rhode Island and the average distance is calculated. Furthermore, it is assumed that the garbage trucks are located in each city while they are not collecting waste, meaning they always do a round-trip.

The average distance from each city to the RIRRC is calculated as 31.672 km (19.68 miles); considering the round-trip it is a total distance of 63.344 km (39.36 miles). With this information and the formula below, the total amount of kilometers driven is calculated.

$$\sum_{i=1}^{8} y_i(km) = \sum_{i=1}^{8} x_i * 63.344\ (km) \quad (3)$$

The last step in the calculation of the total amount of diesel consumed per year for the whole transport of recyclable waste to the MRF is the multiplication of the total kilometers driven with the quantity of liters needed for running a standard garbage

[2] Further information considering the distance matrix with cities in Rhode Island with a population bigger 15,000 people can be seen in Appendix A2.

truck. The following formula was used to determine the later value, resulting in 45 liters for 100 kilometers.

(4)

$$\sum_{i=1}^{8} z_i(l) = \sum_{i=1}^{8} y_i(km) * \frac{45\ (l)}{100\ (km)}$$

Thus, the total diesel consumption is 572,396.63 liters per year.

After obtaining the data from

Table **3-2**, the first process step is modeled in the sustainability software GaBi. Thereby, it is important to note that due to limitations in the LCI database of the student version, certain commodity types have to be summed up in one category within the model. This affects the two commodity types: “News Print” and “Mixed Paper,” which are summed up in the category “Waste Paper” and the two plastic types “HDPE” and “PET,” which are summed up in the category “Packaging Waste (plastic).” The model for the transport from GaBi is displayed in below.

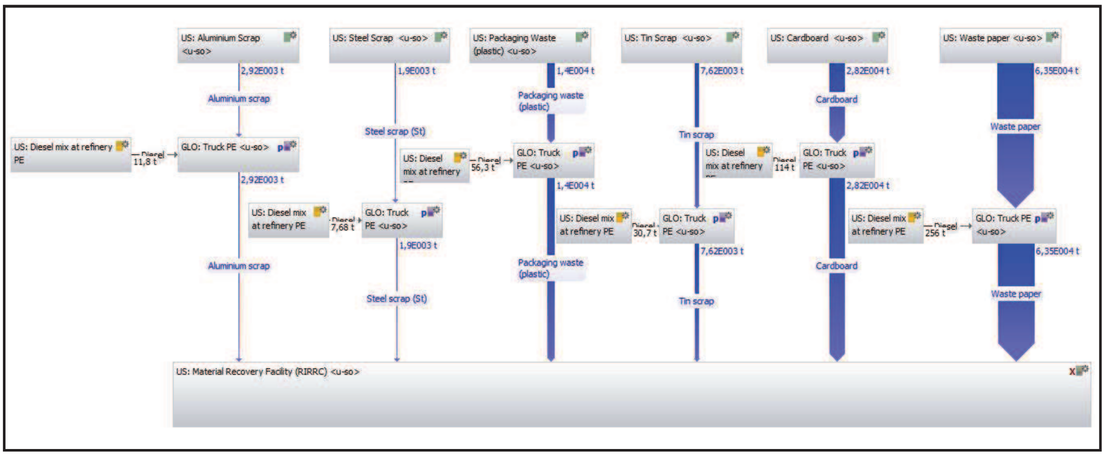


Table 3-3: Curbside Collection and Transport to the MRF of the RIRRC.

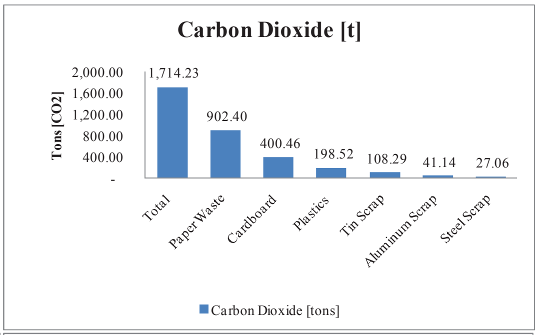
With the entered data for the different commodity types, GaBi provides first a result for the carbon footprint and the impact categories considering the whole transportation of recyclable waste within one year to the MRF.

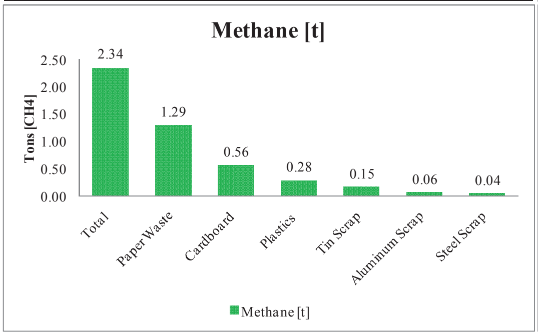
Carbon footprint – Curbside Collection and Transport to the MRF

As previously stated, the three major GHGs (CO_2, CH_4 and N_2O), defined for the carbon footprint assessment in this thesis and case study, are regarded, which further form the basis for the subsequent impact categories.

The following results present an absolute value of the emissions released to the air from the total amount of recyclable waste collected and transported to the RIRRC within one year. Presenting the total amount of each GHG and particular GHG amounts for the transport of each commodity type, these results are illustrated in the Figure 3.9 below. The results are displayed in Pareto diagrams that represents the results in a descending order, highlighting the most important contributors to each emission.

Commodity Type	Carbon Dioxide [t]	Methane [Kg]	Nitrous Oxide [kg]
Aluminum Scrap	41.14	0.06	0.527
Steel Scrap	27.06	0.04	1.21
Plastics	198.52	0.28	2.525
Tin Scrap	108.29	0.15	1.374
Cardboard	400.46	0.56	5.091
Paper Waste	902.40	1.29	11.473
Total	1,714.23	2.34	21.346





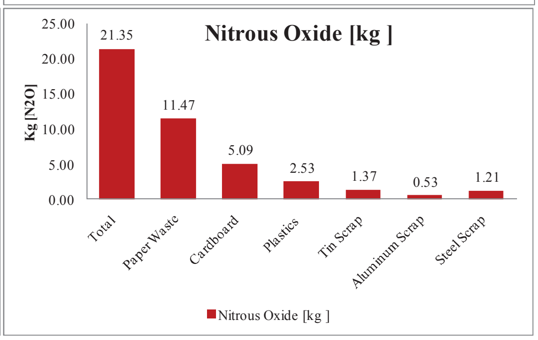


Figure 3.9: Total amount of GHGs emitted considering the transportation of recyclable waste to the RIRRC within one year.

The total carbon dioxide emitted within a year from the transportation of recyclable waste to the RIRRC amounted to 1,714.32 tons. For methane, the total amount emitted was 2.34 tons; the majority of these emissions came from the consumption of diesel by the trucks. The total amount of nitrous oxide emitted was 21.35 kg.

Taking into consideration these results and the percentage each commodity type is of the total waste (from

Table 3-2), the materials, forming the largest part of the recyclable waste, also emit during their transportation the largest amount of GHGs. For all three GHG types, the largest amount is emitted by transporting waste paper and the lowest amount is emitted by steel scrap. The according impact categories are not shown at this point.

Recovering and Sorting Process at the MRF

The next process step is the sorting and material recovering process at the RIRRC. In Chapter 2.4.2 this extremely complex process has been described, in general, for a standard MRF. However, on this level of examination, specific processes within the MRF are not further regarded. Inputs that are important for this assessment and need to be considered are essentially the annual energy and fuel consumptions. Table 3-4 below displays a general overview about these consumptions at the MRF. The data is provided by the RIRRC.

Table 3-4: Annual consumption of energy and fuel in the MRF of the RIRRC.

Annual Consumption	
Energy/ Fuel	**Amount**
Energy for running MRF	750,019 kwh
Oil consumption	4,695 gal
Propane for power forklifts	4,180 gal
Diesel for running wheel loaders	9,075 gal

(RIRRC)

From these annual consumptions, the energy and fuel consumptions for each particular commodity type are calculated based on its percentage of the whole recyclable waste processed per year. The results are illustrated in

Table 3-5.

Table 3-5: Annual consumption of energy and fuel allocated on the commodity types.

Commodity Type	Amount per year extracted (t)	Total amount of recyclable waste per year (t)	% of total Amount per year	Oil consumed (gal)	Propane consumed (gal)	Diesel consumed (gal)
Aluminum (Foil & Cans)	1,104	2,920.63	2%	115.74	103.04	223.71
Tin	2,880	7,619.05	6%	301.93	268.81	583.60
Scrap Metal	720	1,904.76	2%	75.48	67.20	145.90
News Print	19,200	50,793.65	43%	2,012.86	1,792.07	3,890.68
Mixed Paper	4,800	12,698.41	11%	503.22	448.02	972.67
Cardboard	10,800	28,571.43	24%	1,132.23	1,008.04	2,188.50
HDPE	2,400	6,349.21	5%	251.61	224.01	486.33
PET	2,880	7,619.05	6%	301.93	268.81	583.60
Total	44,784	118,476.19	100%	4,695	4,180	9,075

(RIRRC)

Based on this provided data, the process of the MRF is modeled in GaBi. The conceptual model with all its inputs is displayed below in Figure 3.10. Outputs regarded in this process are the three defined GHG emissions and the extracted recyclable materials. For the modeling part, it is important that the objects chosen conform with the geographical requirements of the process. In this case, the objects have to be based on U.S. data.

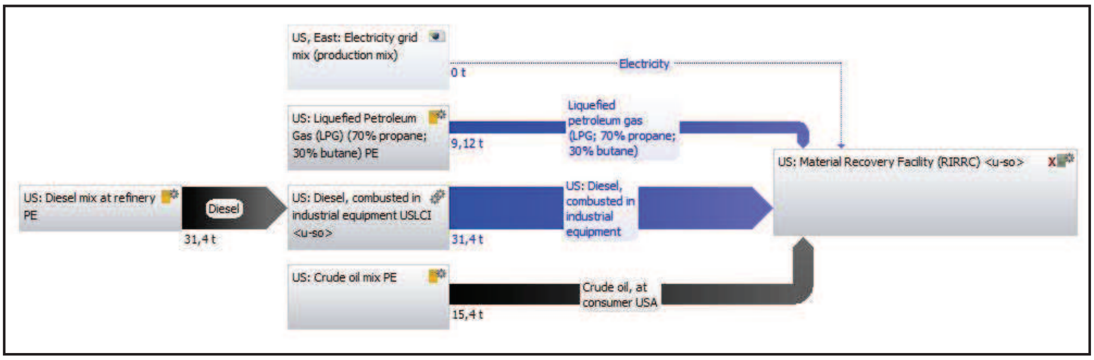


Figure 3.10: Conceptual model for the MRF.

Furthermore, especially the sources of electricity supply can vary depending on the geographical area. The electricity supplied in this case is an electricity grid mix, produced from different types of power plants from the east of the U.S.. The data for that is provided by the GaBi databases and is hence secondary data. Figure 3.11 illustrates an overview of this electricity grid mixture.

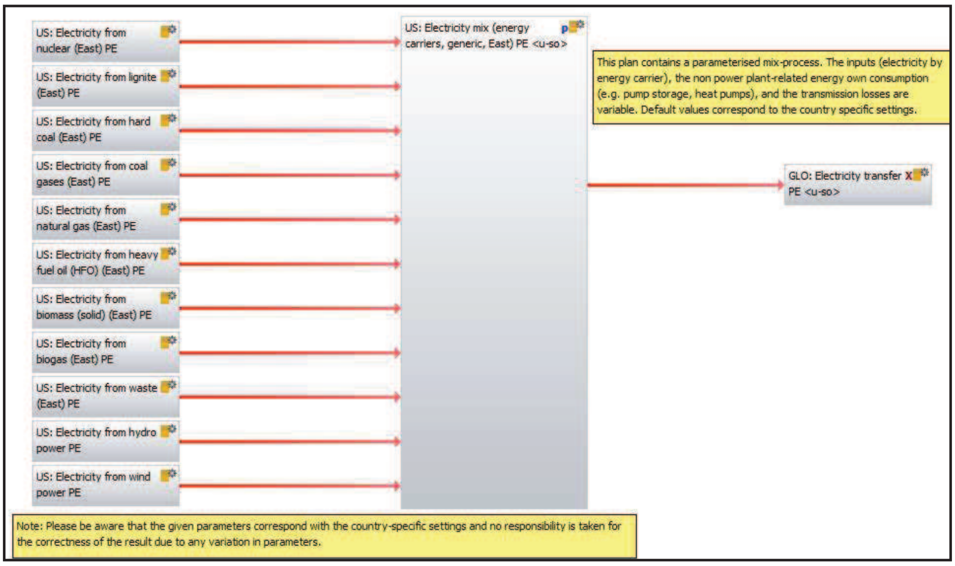
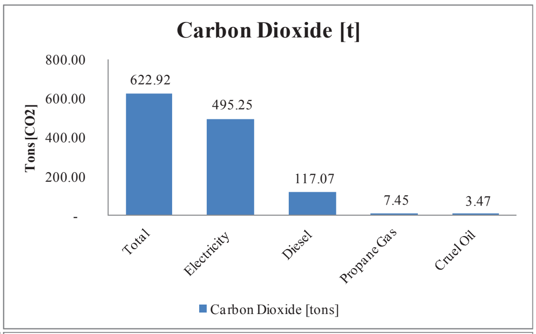


Figure 3.11: US, East electricty grid mix (production mix) used in the model of the MRF.

Carbon Footprint – MRF

As in the previous process step only the GHGs emitted from the energy and fuel consumptions at the MRF that form the carbon footprint are regarded, whereas the impact categories are viewed later for the whole process. Once more, these results are absolute values considering the functional unit. The total amount of each emission released into the air is displayed in Pareto diagrams in Figure 3.12 below.

Energy and Fuel consumption	Carbon Dioxide [t]	Methane [t]	Nitrous Oxide [kg]
Diesel	117.07	0.16	0.39
Propane Gas	7.45	0.05	0.16
Electricity	495.25	1.15	9.28
Cruel Oil	3.47	0.06	0.07
Total	622.92	1.42	9.91



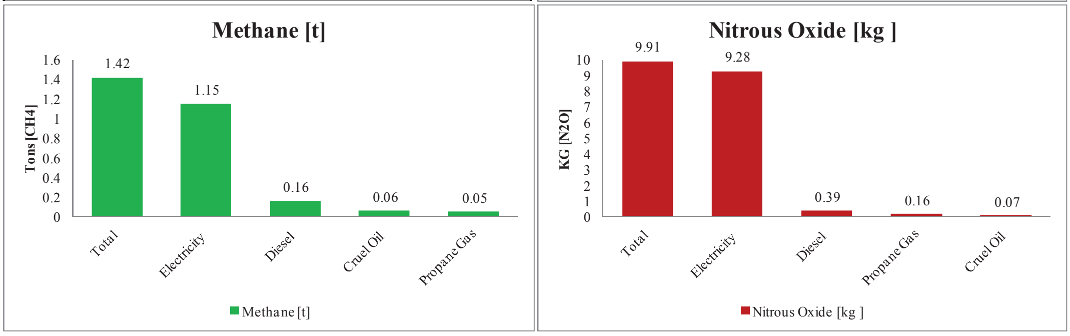


Figure 3.12: Total amount of GHGs emitted considering the consumption of energy and fuel for processing the recyclable waste at the MRF of the RIRRC within one year.

Examining the Pareto diagrams, it is apparent that the consumption of electricity emits by far the largest amount of each GHG type. Of the total 622.92 tons of carbon dioxide output, the electricity consumption alone constitutes 495.25 tons. The same applies for the release of Methane, in which the electricity consumption forms 1.15 tons, nearly 81 percent of the total amount (1.42 tons) emitted. For the last GHG, Nitrous Oxide, 9.28 kg out of 9.91kg is released by the electricity consumption. These amounts of emissions from the electricity consumption are substantial, considering that they are indirect emissions that, although linked to the activity of the MRF, physically occur at sites and operations controlled by companies other than the RIRRC.

The emissions concerning the consumption of oil and propane gas in this process are not significant.

Transport from the MRF to the Recycling Companies

The final step in the recovering process is the transport from the RIRRC to its recycling companies. Therefore, it has to be mentioned that only the companies within the U.S. were taken into account.

Similar to the transport to the MRF, a lack of data existed concerning the amount of diesel consumed within a year for the trucks leaving the MRF. Furthermore, information was missing about the exact locations of the recycling companies and data about the amount and type of extracted commodities that are supplied to each particular company.

A first estimation, concerning the required truck size and the amount of trucks leaving the RIRRC each week, has been done in Chapter 3.1.2. Additionally, research has been done on the locations of each of the 21 recycling companies the RIRRC supplies, in which the distances from the RIRRC to each company has been determined.[3] The exact steps for calculating the total amount of diesel consumed is displayed in the following Figure 3.13.

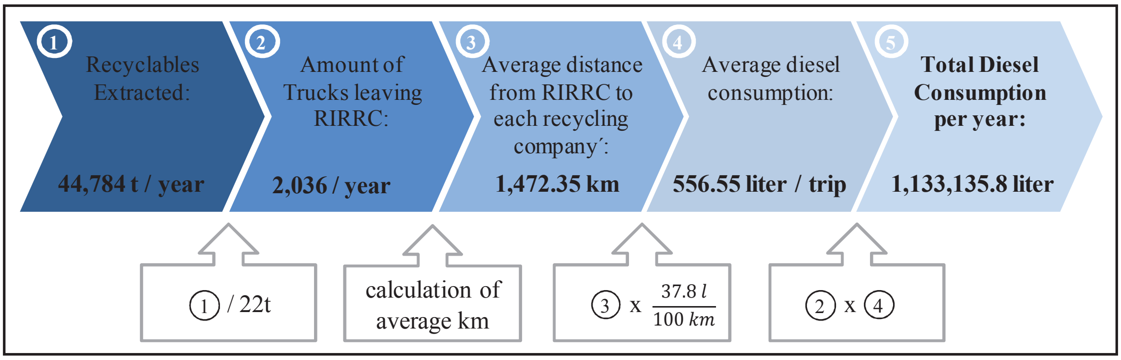


Figure 3.13: Approximation to determine the total diesel consumption of the trucks that leave the MRF to the recycling companies.

[3] For more information see Apendix A3.

Taking both the data about the total amount of recyclables extracted per year and the data for the previously estimated truck payload capacity of 22 tons into account, the amount of trucks needed per year is calculated. In the next step, the average distance from the RIRRC to each company is multiplied with the diesel consumption of the estimated truck (37.8l /100km) to define the average diesel consumption per trip; no round-trip is assumed. The final step in this approximation is the multiplication of the total amount of trucks leaving the MRF and the average diesel consumption per trip, resulting in a total diesel consumption of 1,133,135.8 liters for this type of transportation per year.

Taking this data and information into consideration, the transportation is modeled in Gabi and is shown in the following figure. Inputs for this process are the diesel consumed and the extracted recyclables the trucks carry. Outputs regarded are the three GHG types (CO_2, CH_4 and N_2O) that are assessed for the carbon footprint.

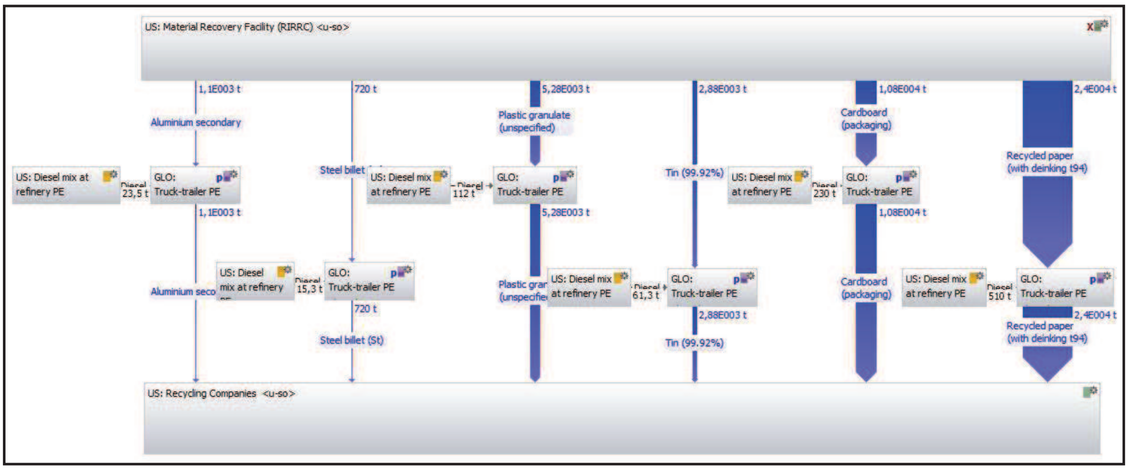


Figure 3.14: Conceptual model for the transportation leaving the MRF to the recycling companies

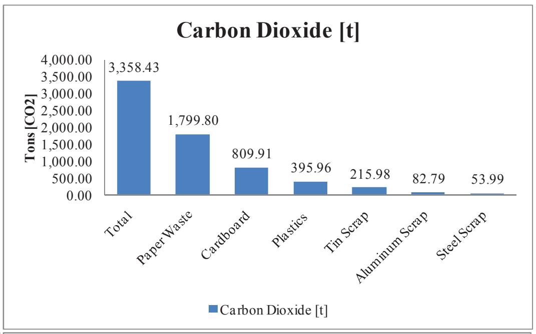
Carbon footprint – Transport from the MRF to the Recycling Companies

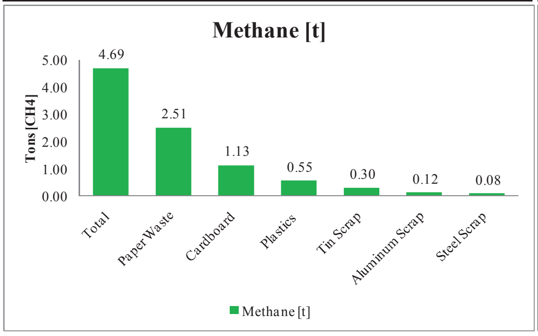
Similar to the presentation of the carbon footprint results of the previous processes, the GHGs emitted to the air are displayed in Pareto charts in the Figure 3.15 below. Furthermore, within those charts, not only are the total amount of each emitted GHG provided, but, also, information about how much the transportation of a particular commodity type contributes to each GHG release.

The transportation of paper waste to its recycling companies constitutes by far the greatest share of each emission. Considering the carbon dioxide emissions, it contributes 1,799.80 tons to the total of 3,358.43 tons per year. Methane contributes 2.51 tons of the total 4.69 tons released, originating mostly from the production of diesel that is consumed by running the trucks. For the nitrous oxide emission, the transportation constitutes nearly 54 percent (18.52 kg) of the 34.55 kg that is totally released.

The next biggest contributor to the carbon footprint, in this descending order, is the transportation of cardboard that is closely followed by the transportation of plastics. The impacts of the transportation of the ferrous and non-ferrous metals on the carbon footprint are minimal due to the low amounts carried.

Commodity Type	Carbon Dioxide [t]	Methane [t]	Nitrous Oxide [kg]
Aluminum Scrap	82.79	0.12	0.85
Steel Scrap	53.99	0.08	0.55
Plastics	395.96	0.55	4.08
Tin Scrap	215.98	0.30	2.23
Cardboard	809.91	1.13	8.33
Paper Waste	1,799.80	2.51	18.52
Total	3,358.43	4.69	34.55





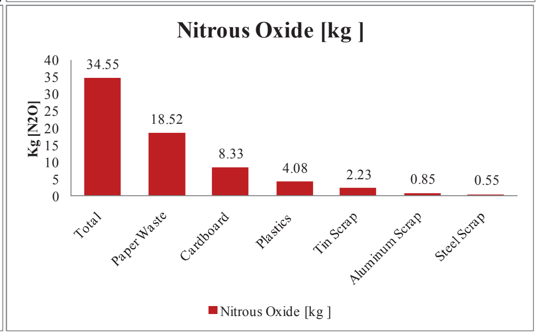


Figure 3.15: Total amount of GHGs emitted considering the transportation of recyclable waste from the RIRRC to its recycling companies within one year.

Complete Process – MRF

Finally, after examining each process step itself and assessing the carbon footprint for each process, the whole process is regarded. Representing the total amount of recyclable waste collected in the municipality of Rhode Island and processed in the MRF within one year, an inventory analysis is illustrated in Figure 3.16 showing all input and output flows for the system.

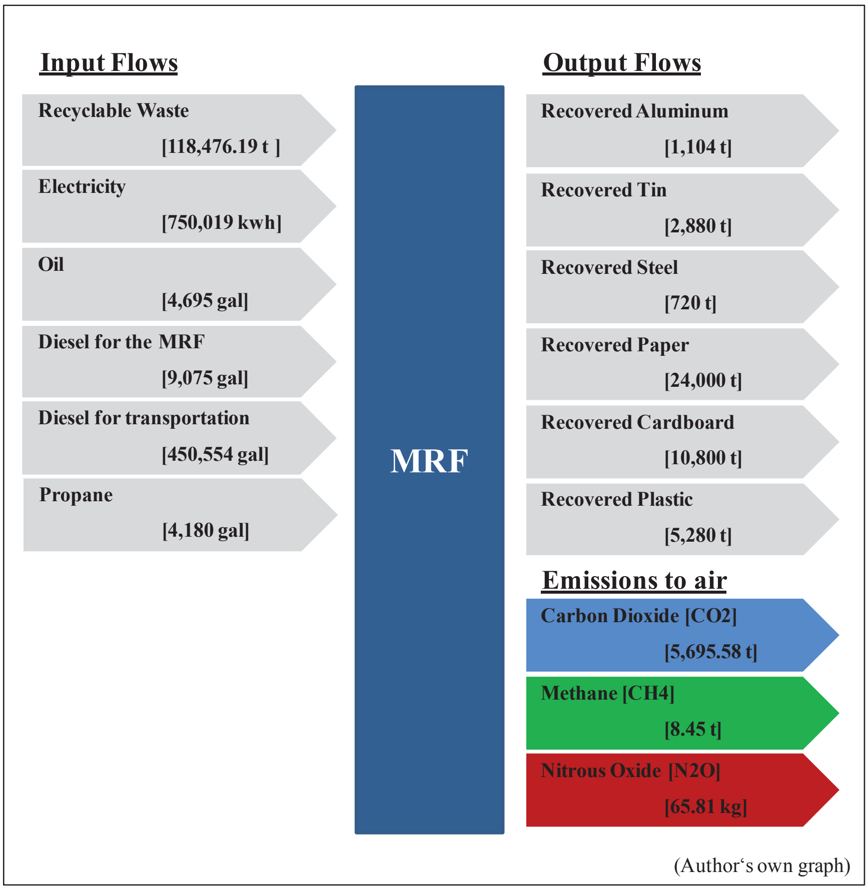


Figure 3.16: Inventory analysis with all inputs and outputs of the whole system. Flows are representative for processing the total amount of recyclable waste in the MRF within one year.

Hence, the inputs are the energy and fuels consumed and the collected recyclable waste. Outputs are the recovered materials, which are transported to the recycling companies and the emissions of the three GHGs considering the carbon footprint assessment.

For the final model[4], the previous processes are linked with each other in the sustainability software GaBi 6. The model is subsequently used for the calculation of the environmental impacts, which is done in the next step, the LCIA.

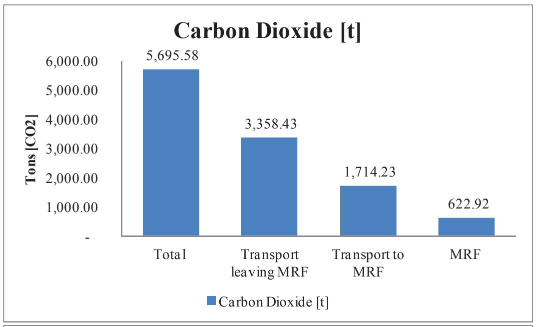
[4] Complete model for process of the MRF see A 4

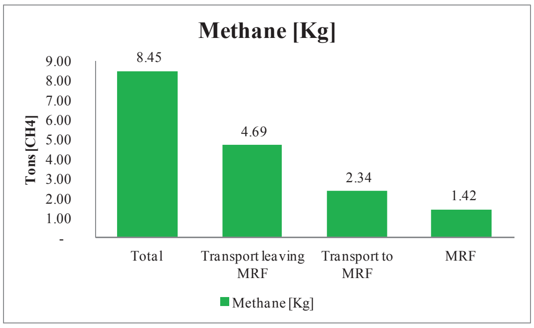
Life Cycle Imapct Assessment Results

In this part the LCIA results are presented for processing the total amount of recyclable waste (118,476.19 tons) within one year at the MRF of the RIRRC in Johnston, Rhode Island, USA. Unlike the LCI, that only reported the sums of individual emissions for the carbon footprint, the LCIA includes methodologies for combining these different emissions into impact categories. Therefore, characterization factors are used, integrated within the GaBi 6 sustainability software, to calculate the LCIA results. These characterization factors originate from the impact assessment method CML 2001 that was chosen in the beginning of the study and is a widely applied method. However, before the results of the impact categories are described in detail, the result for the carbon footprint assessment of the MRF of the RIRRC is analyzed below.

Figure 3.17 displays the results for the complete carbon footprint assessment, showing each process and its associated emissions and the total amount of GHGs released.

#	Process	Carbon Dioxide [t]	Methane [t]	Nitrous Oxide [kg]
1	Transport to MRF	1,714.23	2.34	21.35
2	MRF	622.92	1.42	9.91
3	Transport leaving MRF	3,358.43	4.69	34.55
	Total	5,695.58	8.45	65.81





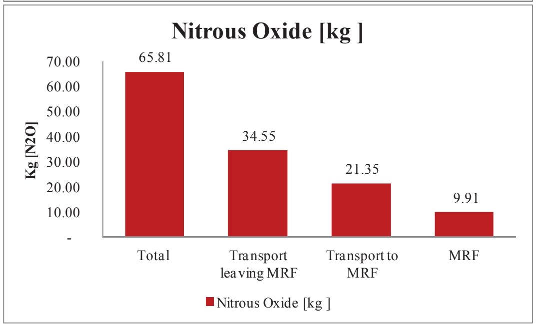


Figure 3.17: Carbon footprint of the MRF of the RIRRC

As shown in the carbon footprint assessment, carbon dioxide is by far the GHG with the largest amount emitted, releasing 5,695.58 tons per year from processing the complete recyclable waste in the MRF. However, the carbon dioxide Pareto diagram displays that the transportation to the MRF (1,714.23 tons) and the one leaving the MRF (3,358.43 tons) is the main cause of this high amount of emission, whereas the MRF itself with its own consumption of energy and fuel contributes a remarkably small amount (622.92 tons) to the total emission.

The differences between the two types of transportation can be explained through the average distances that have been assumed for each route. While the average distance assumed for the transportation to the RIRRC (63.344 km) is calculated with distances from cities of Rhode Island to the MRF, the average distance for the transportation leaving the RIRRC to the recycling companies (1,472.35 km) is calculated with distances distributed all over the U.S.. This explains the significant difference of carbon dioxide released during transportation to and away from the MRF, which originates primarily from the consumption of diesel of the trucks.

To get an impression of this relatively large amount of carbon dioxide emissions, the Figure 3.18 below illustrates equivalency results.

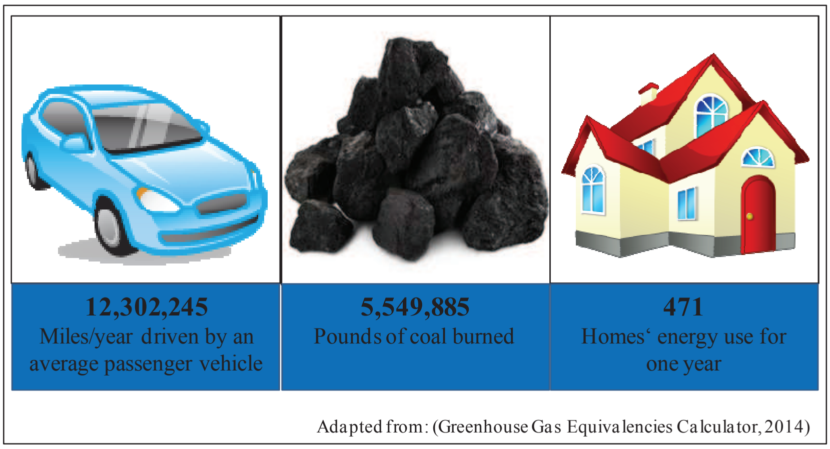


Figure 3.18: Equivalency results for the carbon dioxide emission assessed for the carbon footprint

These results are provided by the GHG Equivalencies Calculator from the EPA, which was also used to review the results assessed from GaBi for the carbon footprint (*Greenhouse Gas Equivalencies Calculator*, 2014).

Considering the other two Pareto diagrams of methane and nitrous oxide, it becomes apparent that the main contributor to these emissions is similar carbon dioxide. The total amount of methane emitted during the whole process is 8.45 tons, with the two transportation processes contributing the largest amount. However, it is important to mention that the trucks themselves emit only a small amount of methane during their trips. The largest amount comes from the diesel production at a refinery that the trucks, in turn, consume. This diesel production at a refinery is also an object included in the GaBi model along with its related emissions. The data used for these GHG assessments are provided by the GaBi databases.

The amount of nitrous oxide (65.81 kg) emitted might appear insignificant compared to the other two GHGs; however, regarding its environmental impact, this amount is anything but small. Its significance becomes apparent the moment it is converted into carbon dioxide equivalents, which is essentially done in the GWP impact category. However, before the impact categories are described, equivalency results for both the amount of methane and nitrous oxide emitted per year from the RIRRC is illustrated in the following[5].

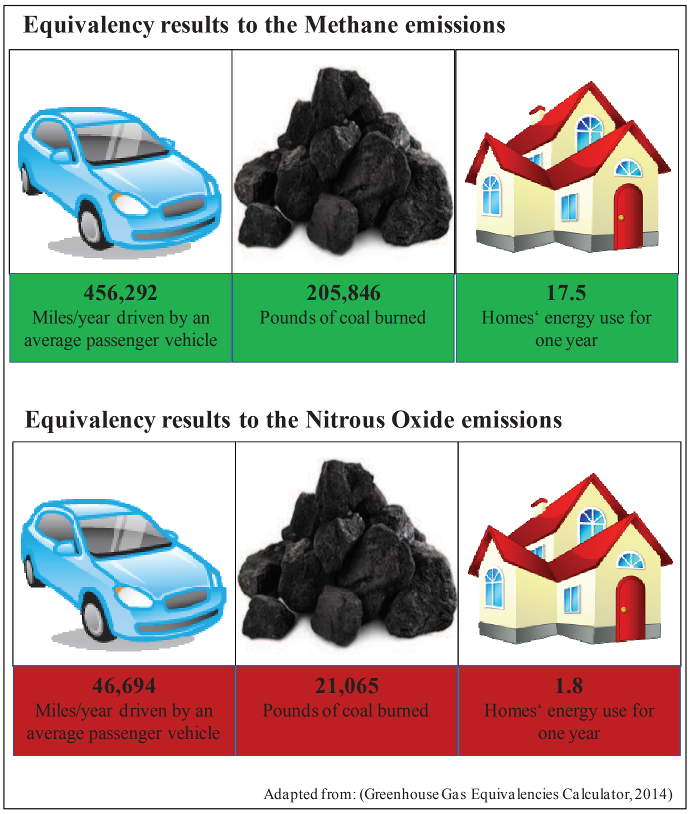


Figure 3.19: Equivalency results for the methane and nitrous oxide emissions assessed for the carbon footprint.

[5] For more information see (*Greenhouse Gas Equivalencies Calculator* (2014))

Now, the impact categories regarded below for this study have been defined in the scope and goal definition and were previously described in Chapter 0 in detail. All results presented are obtained from the GaBi 6 sustainability software (educational version), which used the CML assessment methodology for the calculation of these balances. The basis for all these calculation has been the complete model of the MRF. The results, however, illustrate the impact of each particular process step to give a better overview. Moreover the balances are presented in Pareto charts

Global Warming Potential (100 years)

The Global Warming Potential (GWP) measures the emission of different GHGs such as CO_2, CH_4 and N_2O and is expressed as kilogram of CO_2 – equivalents. These GHGs are found to cause an increase in the absorption of radiation emitted by the sun and reflected by the earth, magnifying the natural greenhouse effect.

The total GWP related to the processing of the 118,476.19 tons of the total collected recyclable waste in the municipality of Rhode Island within one year at the RIRRC is 6,091,382.37 kg CO_2 – equiv. A breakdown of the GWP impact by each greenhouse gas displays that almost 96 percent of the net GWP comes from CO_2, 3.66 percent from CH_4 and 0.034 percent from nitrous oxide (N_2O).

A further breakdown of the results by individual production stages is shown in Figure 3.20, presenting that 59.4 percent of the GWP impacts come from the transportation leaving the RIRRC to the recycling companies. The next largest contributor is the curbside collection and transportation to the RIRRC with 29.7 percent share of the net GWP. The process within the MRF contributes only 10.9 percent to the net GWP.

The share of GWP from direct greenhouse gas emissions is approximately 65 percent and comes mainly from the burning of fuels during the transportation and at the MRF itself, while indirect CO_2 emissions account for another 15 percent of the net GWP impact (mainly from electricity production).

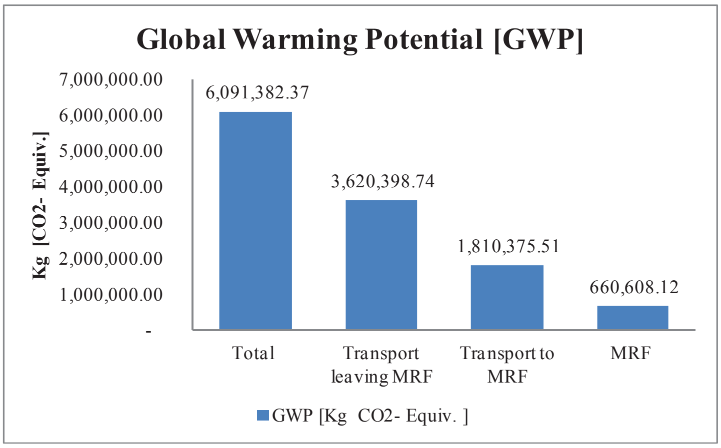


Figure 3.20: Global warming potential results for processing recyclable waste in the RIRRC

Acidification Potential

The Acidification Potential (AP) measures GHG releases, which cause acidifying effects to the environment and is expressed as kilogram SO_2- equivalents.

Nitrogen oxides (NO_x), sulfur dioxide (SO_2) and ammonia emissions are the major acidifying emissions that lead to ammonium deposition. These gases are known as highly reactive and are mainly released from fossil fuel combustion at power plants as well as at industrial facilities. The AP related to the processing of the 118,476.19 tons of the total collected recyclable waste in the municipality of Rhode Island within one year at the RIRRC amounts to kg 25,890.15 SO_2 – equiv. The relative share of this acidification potential indicator from NO_x emissions to air is nearly 10 percent, from SO_2 emissions to air is 23 percent and the largest contributor with nearly 57 percent is

Nitrogen monoxide, also known as nitric oxide, which is mainly a by-product of the combustion of fuels as, for example, in an automobile engine.

This explains, regarding Figure 3.21, that by breaking the emissions down by their process stages, the two transportation routes are responsible for the largest amount (together 87 percent) of the total acidification potential result. The other 13 percent are contributed by the MRF and particularly the production of electricity for running the MRF.

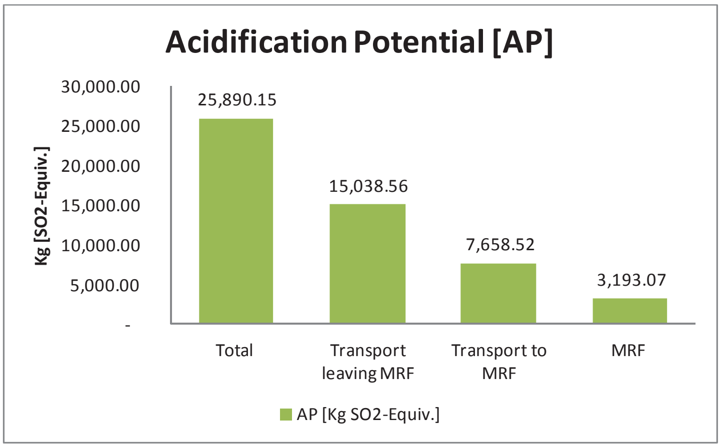


Figure 3.21: Acidification potential results for processing recyclable waste in the RIRRC

Eutrophication Potential

The EP is a measure of GHG releases that cause eutrophying effects to the environment and is expressed as kilogram of Phosphate - equivalents. Large inputs of nitrogen and phosphorus are essentially the reason for eutrophication of aquatic systems (most often due to of over-fertilization).

The EP related to the processing of the 118,476.19 tons of total collected recyclable waste in the municipality of Rhode Island within one year at the RIRRC amounts to kg 5,661.78 Phoshpate – equiv. The EP from emissions to air (mainly NO_x emissions) contributes 92.6 percent of the total impacts. The remaining 7.4 percent of the EP is caused by emissions to water (mainly hydrocarbons releases to water).

Breaking the impact down by contributions from the three different process stages, as previously done (Figure 3.22), it becomes apparent that the transportation processes are again primarily responsible for the eutrophication impacts results, with individual contributions of 61.5 percent and 31.8 percent. The share of the MRF is relatively small, forming only 6.7 percent of the total EP result.

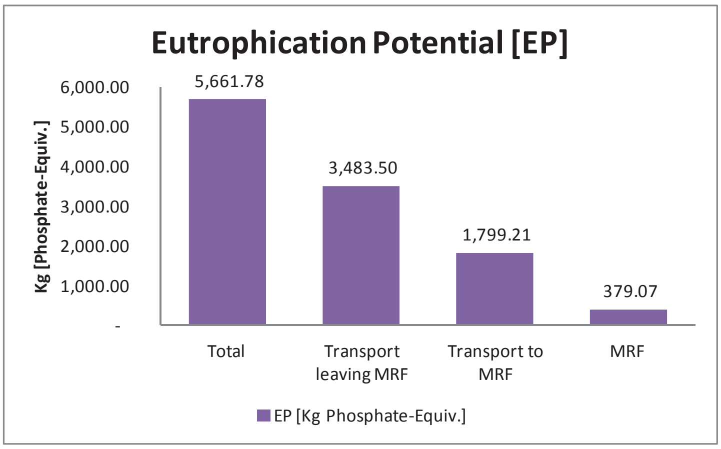


Figure 3.22: Eutrophication potential results for processing recyclable waste in the RIRRC

Human Toxicity Potential

The Human Toxicity Potential (HTP) measures emissions that are potentially dangerous to humans through ingestion, inhalation and even contact. A main issue in this impact category is the cancer potency. HTP is, thereby, measured in 1,4-dichlorobenzene (DCB) equivalents ($C_6H_4CL_2$ – equiv. or DCB – equiv.) Most of these by-products, such as arsenic, sodium dichromate and hydrogen fluoride, are mainly caused by the general combustion of fossil fuels.

The HTP related to the processing of the 118,476.19 tons of total collected recyclable waste in the municipality of Rhode Island within one year at the RIRRC amounts to kg 137,005.25 Phoshpate – equiv.

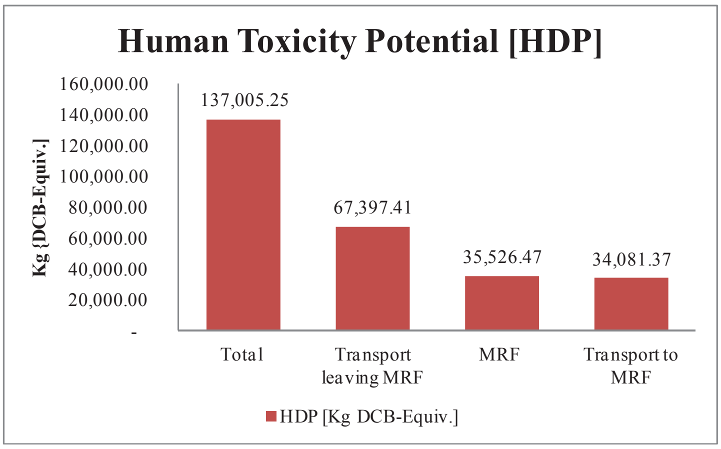


Figure 3.23: Figure 3.24: Human toxicity potential results for processing recyclable waste in the RIRRC.

Figure 3.23 shows the impact broken down by the different process stages, displaying again that the transportation leaving the MRF to the recycling companies is the biggest contributor to the total HDP results. However, compared to the other three impact categories previously presented, this time the MRF itself is the second largest contributor considering the HDP results. A reason for that can be found in its electricity consumption and the fact that the production of electricity is especially known for the release of by-products such as arsenic, sodium dichromate and hydrogen fluoride, which are all related to the HDP.

Finally, Table 3.5 summarizes the LCIA results for processing the 118,476.19 tons of the total collected recyclable waste in the municipality of Rhode Island within one year at the RIRRC, in Johnston Rhode Island (U.S.)

Impact Assessment Category	Unit	Transport to MRF	MRF	Transport leaving MRF	Total
Global Warming Potential (GWP)	[Kg CO2- Equiv.]	1,810,375.51	660,608.12	3,620,398.74	6,091,382.37
Acidification Potential (AP)	[Kg SO2-Equiv.]	7,658.52	3,193.07	15,038.56	25,890.15
Eutrophication Potential (EP)	[Kg Phosphate-Equiv.]	1,799.21	379.07	3,483.50	5,661.78
Human Toxicity Potential (HTP)	[Kg DCB-Equiv.]	34,081.37	35,526.47	67,397.41	137,005.25

Table 3-6: LCIA results for processing 118,476.19 tons of recyclable waste (total amount collected in the municipality of Rhode Island) within one year at the RIRRC.

Sensitivity Analysis

The sensitivity analysis can be used at many stages throughout the assessment of the environmental impacts of a process or a material. Its major purpose is to identify and focus on the key data and assumptions that have most influence on a result. This is generally secondary data, which are derived by referenced literature, and that are related to resources and emissions pertaining a specific process, with a specific technology and a specific production equipment.

In the best cases, primary data are added to secondary data to provide qualitative information, regarding for example system boundaries and allocation rules, to define if such data are able to characterize the investigated system. Therefore, primary data from the RIRRC is added in this study to the secondary data that is mainly taken from literature or the GaBi 6 databases. However, the usage of secondary data and approximations involves significant uncertainty in a LCA study. This essentially occurs because their accuracy and reliability, and their collection method may not be known (Cellura et al., 2011).

Between data used in the LCA and data needed to represent the examined system there are three significant correlations that have to be highlighted, the temporal, the geographical and the technological.

The ‘temporal correlation’ represents the degree of accordance between the year of the study and the year of the available data. Due to the fact that some industrial technologies develop very quickly, the use of old secondary data in current studies can significantly distort the results. However, the secondary data, which is essentially taken from the GaBi 6 databases in this study, provides up-to-date data, so the results should not significantly be distorted by that (International Energy Agency, 2001).

The ‘geographical correlation’ represents the degree of accordance between the production conditions in the area of the study and those ones in the geographical area to which the secondary data are referred. This concerns particularly the production of energy and fuel in this study, which is consumed by the MRF of the RIRRC. In the models, this correlation is ensured by using especially secondary data that is referred to the similar geographical area as the system (MRF) itself.

The last correlation, the ‘technological’, describes the representativeness of secondary data for a specific technology, company or process of production. This correlation has specific relevance for the determination of the carbon footprint of the other WMS in the next chapter, but has a rather less importance for the sensitivity analysis in this section (Cellura *et al.*, 2011).

For the performance of the sensitivity analysis, the assumptions and calculations for the MRF are generated and modeled in the GaBi 6 sustainability software, whereby all of the data and assumptions made can be clearly identified and furthermore the formulas that lead to the results for which sensitivity is to be investigated are included.

The parameter that is from essential relevance in modeling the MRF of the RIRRC is the waste processed within one year (functional unit), which has a great influence on the GHGs emitted within the same time. This parameter was approximated from primary data that was provided for the total amount of recyclables extracted per year and a specific recycling rate. However, this approximation implies a small degree of uncertainty. Therefore, a sensitivity analysis is performed in the following in order to assess the effects on the GHG emissions that are relevant for the carbon footprint of the MRF by processing different amounts of waste per year.

The sensitivity analysis varies the parameter between the known maxima of waste being processed within a year and the minimum, meaning that no waste is processed within the year and only the consumptions of the MRF building, some equipment and their related emissions are regarded.

The starting point of the analysis is regarding the process at its minimum, with no waste processed within the whole year. Thereby, only the energy and fuel consumption for the building and some equipment are regarded, while the transport of waste to the MRF and leaving the MRF is excluded. Table 3-7 illustrates all these consumptions below.

Table 3-7: Annual consumption of the MRF with no waste being processed.

Annual Consumption	
Energy/ Fuel	**Amount**
Energy for lighting the MRF building	34,497.9 kwh
Energy for air conditioning	83,400 kwh
Oil consumption (heating)	4,695 gal
Propane for power forklifts	348 gal
Diesel for running wheel loaders	756.25 gal

(assuming 48 weeks/ 5 days per week/ 8 hrs per day)

Table 3-7, includes the annually energy consumption for lighting the facility, the energy consumption for running the air conditioning and heating and some small amounts of propane and diesel for running power fork lifters and wheel loaders, which need to be maintained and moved sometimes. With the provided data, the GHG emissions for the MRF can be determined, considering that no waste is processed. Subsequently the results can be compared to the real process of the MRF. The assessment for the carbon footprint is also done with the GaBi 6 sustainability software for which the modeled process can be seen in the Figure 3.25 below.

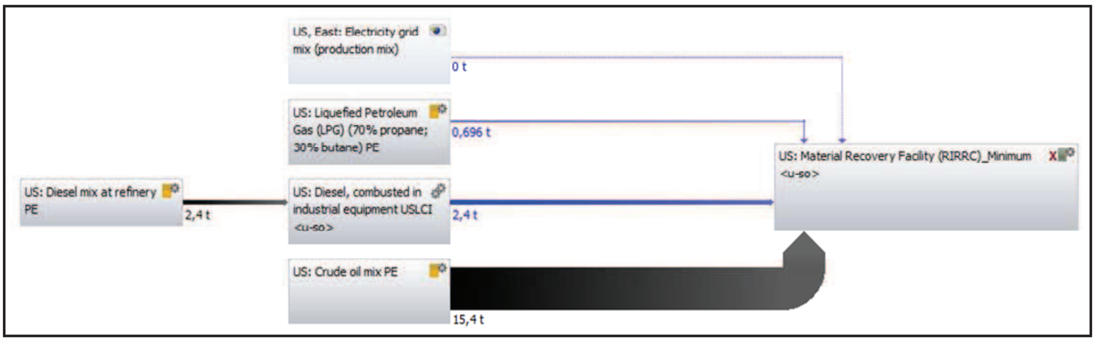
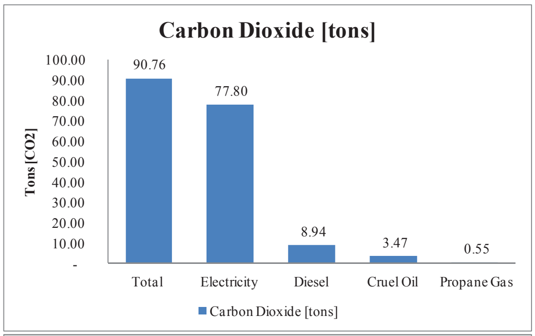
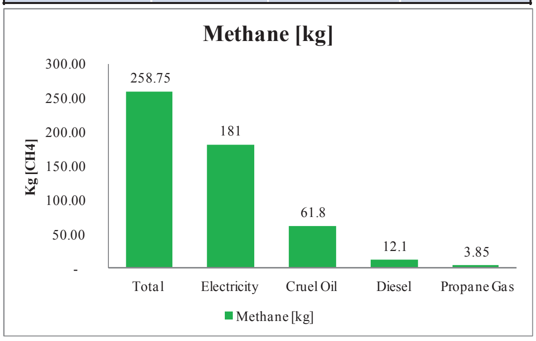


Figure 3.25: Annual consumption of the MRF modeled in the GaBi 6 sustainability software.

The results for the emissions considering the carbon footprint assessment are shown in the diagrams below.

Energy and Fuel consumption	Carbon Dioxide [t]	Methane [kg]	Nitrous Oxide [kg]
Diesel	8.94	12.1	0.03
Propane Gas	0.55	3.85	0.01
Electricity	77.80	181	1.46
Cruel Oil	3.47	61.8	0.07
Total	90.76	258.75	1.57





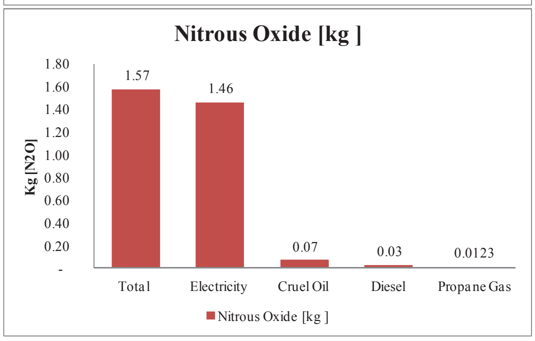


Figure 3.26: Carbon footprint of the MRF of the RIRRC with no waste being processed within one year

Regarding the Pareto diagrams in Figure 3.26, which show the emissions of the MRF within one year without processing any waste, we can see enormous differences to the emissions for the regular process. The total carbon dioxide emissions (90.76 tons) are only 1.6 percent of the emissions before (5,695.58). The reasons for this is that on the one hand no transport of waste is going to the MRF and no transport is leaving the

MRF with recovered materials to the recycling companies, which saves a lot of carbon dioxide emissions. On the other hand, less energy and fuel is consumed by the MRF itself, because the machinery does not run and no waste is processed.

This significant less amount of emissions applies in the same way to the other two GHGs, methane and nitrous oxide. With no waste processed, the amount of methane emitted within one year is 258.75 kg, which is nearly 3 percent of the amount emitted from the regular process (8.45 tons/year). The amount of nitrous oxide emitted (1.57 kg/year) is approximately 2.6 percent of the amount emitted during the regular process in one year. This first step of the sensitivity analysis provides thus an impression of the lowest possible bound of GHG emissions of the MRF within one year, when no waste is processed at all.

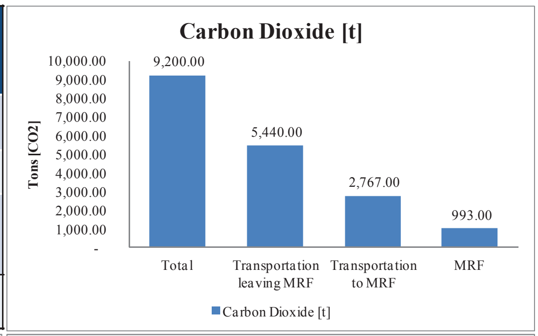
In the next step of the sensitivity analysis the maximum bound will be analyzed, regarding that the machinery of the MRF are working to capacity and the transport are fully stretched. This considers that the MRF processes a total amount of 800 tons recyclable waste per day. To begin with, the Table 3-8 below illustrates the total amount or recyclable waste processed within one year broken down to its commodity types and its annually consumptions of energy and fuels.

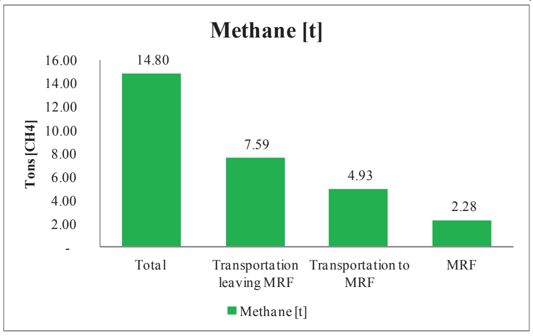
Table 3-8: Annual consumption of the MRF processing the largest possible amount of waste.

Commodity Type	Amount per year extracted (t)	Total amount of recyclable waste per year (t)	% of total Amount per year	Oil consumed (gal)	Propane consumed (gal)	Diesel consumed (gal)
Aluminum (Foil & Cans)	1,789.12	4,733.12	2.47%	187.55	166.99	362.53
Tin	4,667.27	12,347.27	6.43%	489.26	435.63	945.72
Scrap Metal	1,166.82	3,086.82	1.61%	122.32	108.91	236.43
News Print	31,115.11	82,315.11	42.87%	3,261.74	2,904.18	6,304.82
Mixed Paper	7,778.78	20,578.78	10.72%	815.43	726.05	1,576.21
Cardboard	17,502.25	46,302.25	24.12%	1,834.73	1,633.60	3,546.46
HDPE	3,889.39	10,289.39	5.36%	407.72	363.02	788.10
PET	4,667.27	12,347.27	6.43%	489.26	435.63	945.72
Total	72,576.00	192,000.00	100%	7,608.00	6,774.00	14,706.00

Outgoing from that data collection and knowing that the MRF itself consumes approximately 1,215,464.87 kWh for processing 192,000 tons recyclable waste per year, the parameters can be adjusted in the model of the GaBi 6 sustainability software. The model is subsequently used to assess the GHG emissions of the MRF for the case that it works to capacity the whole year through. While the model can be seen in Appendix 5, the results for the carbon footprint assessment are illustrated in Figure 3.27 below.

#	Process	Carbon Dioxide [t]	Methane [t]	Nitrous Oxide [kg]
1	Transport to MRF	2,767.00	4.93	35.70
2	MRF	993.00	2.28	16.00
3	Transport leaving MRF	5,440.00	7.59	56.00
	Total	9,200.00	14.80	107.70





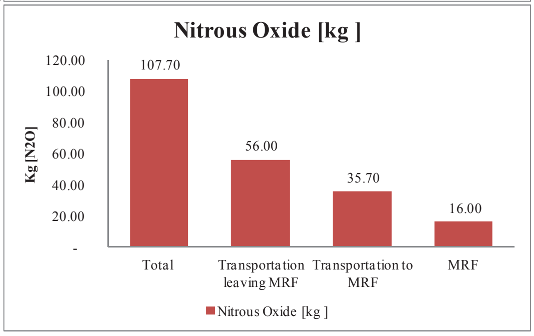


Figure 3.27: Carbon footprint of the MRF of the RIRRC processing the largest possible amount of waste within one year.

While regarding the Pareto diagrams of the three different GHG emissions and comparing these with the results from the regular process, it can be said that with a doubling of the recycling waste processed at the MRF, the GHGs released also approximately double. In the regular process, an amount of 118476.19 tons was processed within a year and emitted an amount of carbon dioxide of 5,695.58, whereas the MRF working to its capacity would emit 9,200.00 tons of carbon dioxide within one year. This applies as well for the other two GHGs methane and nitrous oxide. The amount of methane released for the regular process was 8.45 tons, for this process with a maximum of waste processed at the MRF it is 14.8 tons. For nitrous oxide the amount raises from 65.81 kg per year to an amount of 107.70 kg per year by processing the maximum amount of waste at the MRF.

In conclusion, the sensitivity analysis examined the two extreme scenarios that either no waste at all is processed at the MRF during the year or that every day throughout the year the maximum amount of waste is processed. In the first scenario the amount of emissions decreases extremely to nearly a hundredth of the regular process, showing that the emissions assessed for this scenario origin primary from the energy and fuel consumption of the facility building. Whereas, the second scenario in which the amount of waste processed is approximately double as large as the regular process, certain linearity can be examined, showing that the emissions for this process also doubled.

The sensitivity analysis provided on the one hand a range of possible emissions for processing waste at the MRF of the RIRRC and illustrated on the second hand that by changing the parameters for the waste processed to its minimum and maximum the emissions decreases or increases greatly. With these results that varied to a large degree, it can be stated that the variable parameter has a high degree of accuracy and reliability.

Conclusion and Interpretation

This study provides the RIRRC and decision makers within the waste sector of Rhode Island with an up-to-date LCI and LCIA of primary curbside collection and the transportation of recyclable waste in the municipality of Rhode Island in one year and its processing at the MRF of the RIRRC. Moreover, within this study, the carbon footprint was assessed of the entire process of the MRF. The audience is, thus, provided with an overview of the total performance of the MRF in the context of environmental impacts and, in particular, GHG releases. Additionally, this study quantifies all the significant inputs and outputs needed for a carbon footprint comparison with the other two WMS regarded in the next chapter.

Comparing the results of this study with the goals defined in the beginning, it can be stated that majority of the goals have been reached. Regarding the results in particular and in the context of the carbon footprint assessment, it becomes apparent that the transportation in this entire process is the greatest contributor to GHG emissions.

However, these results have to be examined critically. Although a lot of the data used for modeling the process was provided by the RIRRC, approximations needed to be made to close certain data gaps. These were particularly made in the context of both the transportation of the recyclable waste to the RIRRC and when leaving it to the recycling companies. Another approximation that was necessary to make was the number of weeks the MRF runs per year, which had an influence subsequently on further approximations, such as the consumption of fuels and energy.

Furthermore, the data provided by the RIRRC included only an average amount of recyclables extracted per week and a general recycling rate, but no specific rates concerning the different recycled commodity types. All those listed uncertainties concerning the data set had an influence on the results presented in this study.

However, the obtained results in this study with the given data input are consistent and reliable. The accuracy of the results for the environmental impacts, especially the carbon footprint from the calculations of the GaBi 6 sustainability software, was further reviewed and cross-checked with other assessment tools, including the GHG equivalency calculator of the EPA (*Greenhouse Gas Equivalencies Calculator*, 2014) and an assessment tool for GHG emissions provided by the German Federal Environment Agency (Umweltbundesamt, 2014).

In conclusion, this study provides an overview of the general performance of the RIRRC concerning environmental aspects such as the emissions of GHGs. Thereby, all results are related to the total amount of recyclable waste processed within one year in the RIRRC. For comparison with other MRFs, it is, therefore, required that the results are broken down to a reference value, such as 1 ton of recyclable waste that is processed in the MRF. Since this does not contribute to the thesis, and no comparison with a different MRF is made, it is not necessary at this point.

3.2.2 Aluminum waste

After an LCA for the entire MRF was performed in the previous chapter, an LCA for the aluminum waste is performed to represent all other types of waste that are processed within one year in the MRF of the RIRRC. The scope and system boundaries are essentially the same as those that have been determined in the previous chapter for the MRF and if needed, they are further specified in the respective step of the LCA.

This study quantifies all significant inputs and outputs required for processing the amount of aluminum waste at the MRF. Input categories, such as the composition of the aluminum waste, are identified in the system along with the energy and fuels consumed. Environmental releases are only related to air and are assessed for both the carbon footprint and the impact categories considered. Furthermore, these releases are sub-divided into process-related, fuel-related and transportation related data categories.

As mentioned before, the LCA has been performed with both the educational version of the GaBi 6 sustainability software, which allows to measure the GHGs concerning the carbon footprint, and an Excel spreadsheet. However, it is important to note that some steps of the LCA performance needed to be simplified due to a lack of information and data considering the whole process of the MRF and limitations within the modeling software.

Goal Definition

While the goal of the previous LCA study of the MRW was to provide the RIRRC with general up-to-date LCI data and to demonstrate the MRFs general performance considering its carbon footprint, the goal of this study is to disclose main contributors to GHGs emissions within the entire process and identify weaknesses within the system. Therefore, a range of selected environmental impacts is assessed, while other aspects such as economic and social factors are not considered.

The intended audience for this study is the RIRRC, decision makers in the waste management sector of Rhode Island and the general public.

Scope Definition

Usually the scope for an LCA of a particular aluminum product (*e.g. aluminum can*) comprises a "cradle-to-grave" LCI, beginning with the extraction of the raw material bauxite, including the alumina and the subsequent primary aluminum production, the production of the aluminum product and ending with its recycling. However, the scope of this study focuses only on the last part of the life cycle of this commodity type, its recovering and recycling process. The regarded process stages, therefore, are similar to the previously described stages in the LCA of the entire MRF. The only difference is that the process at the MRF is more closely examined considering the consumption of energy and fuels of particular machineries used for processing the aluminum waste. Table 3-9 summarizes the system boundaries with regard to the general process and quantities that are considered in the study.

Product System Boundaries

The system boundaries are analogous to those from the previous LCA of the entire MRF. This also applies to the energy consumed during this process, which is supplied by power plants from the geographical area of the MRF, and the technology used in the process is assumed to be the state-of-the-art for the U.S.

Furthermore, the LCA for the aluminum waste is also considered as a 'zero burden' approach, indicating that the embedded environmental load of a material before it becomes waste is excluded from the modeling (Gentil *et al.*, 2009).

Table 3-9: Summary of system boundaries

Included	Excluded
• Creation of aluminum waste in the household • Curbside Collection • Transport to the RIRRC • Separating and sorting process in the MRF • Energy and fuel inputs • Transport of recovered aluminum from the RIRRC to its recycling companies	• Embedded environmental load of material before it becomes a waste • Production of trucks, roads, containers, garbage bins, MRF building • Maintenance and operation of equipment • Human labor • Waste disposal (i.e. land-filling)

Additionally to the system boundaries in Table 3-9, a system flow chart is presented below in Figure 3.28 illustrating the system boundaries, for an aluminum product's life cycle phases.

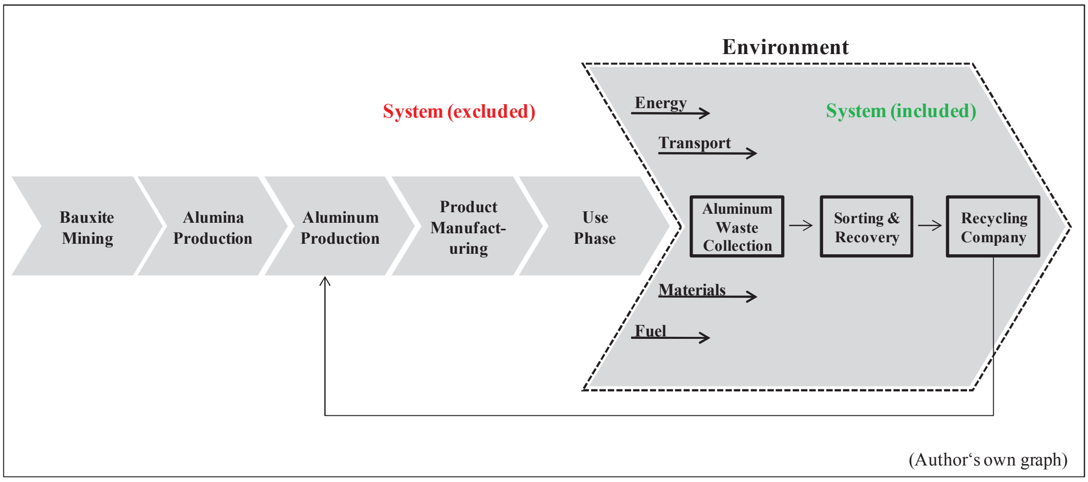


Figure 3.28: Process flow chart indicating the system boundaries in the context of all life cycle phases

Data Collection, Software and Databases

While the provided data has been described in Chapter 3.1.2 in general, in this part, the data used specifically for this LCA is enlarged upon. Thereby, the data provided by the RIRRC can be sub-divided into the following categories for the process:

- Fuel and energy use,
- Aluminum waste collected,
- Aluminum extracted
- Emissions to air

In this LCA study, the primary data provided by the RIRRC is used whenever it is possible. If primary data is missing, available secondary data from life cycle databases and previous LCI studies is used for the analysis. In the absence of secondary data, approximations based on general information from the RIRRC were used to close the data gaps.

Functional unit

Similar to the previous LCA, the functional unit has to be defined in the terms of systems input. The functional unit chosen is, therefore, the amount of total aluminum waste produced within one year in the municipality of Rhode Island and subsequently processed in the RIRRC.

Life Cycle Impact Assessment Methodology & Impact Categories Considered

Both, the LCIA methodology (CML) and the impact categories that are investigated in this case study are the same as the previously performed LCA in Chapter 0 and include the following four:

- Global Warming Potential (GWP) (100 years; includes carbon dioxide, CO_2, and other GHG relevant emissions),
- Acidification Potential (AP),
- Eutrophication Potential (EP), and
- Human Toxicity Potential (HTP).

However, it need to be notified that although this LCA essentially considers several processes within the whole process chain, the impact categories are only determined for the total process. The reason for this is that the main focus is on assessing the GHG emission of particular processes concerning their consumption of certain energy sources and fuels.

Inventory Analysis and Process Modeling

Usually the first step in an inventory analysis is to look at each process step within the system and to analyze their inputs and outputs related to the previously collected data. Because the approximations considering the transportation process used in this LCA are analogous to those made for the previous LCA, the data has only to be adjusted to the amount of aluminum waste transported.

A model of the whole recovery facility was designed, based on a site plan from the RIRRC itself, video material about the recovering process from the RIRRC and the usage of information from standard MRFs[6]. This model is the initial point for the inventory analyses, which is essentially done in an Excel spreadsheet that breaks down the entire process chain of the aluminum recovery into individual processes, displaying the path of the aluminum within the MRF. Furthermore, the model allocates emissions to the individual processes, highlighting later in the carbon footprint assessment those processes with high releases of GHGs.

The data for all machines running within the MRF and their dependent energy and fuel consumptions are provided by the RIRRC. However, some information and data are missing for particular process steps. Those gaps are closed through approximations.

For this LCA, it is also important to note that all results presented are absolute values considering the previous determined functional unit. This means that all results are referring to the total amount of aluminum waste processed in the MRF within one

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[6] The conceptual model of the whole process of the MRF from the RIRRC can be seen in Appendix A6.

year. Figure 3.29 shows the inventory analysis with all the necessary data for the subsequent modeling of this whole process.

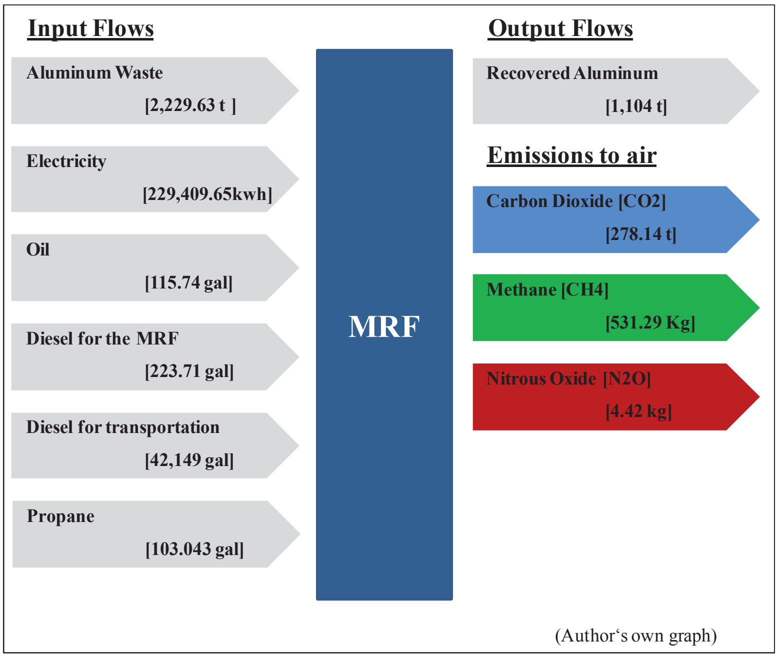


Figure 3.29: Inventory analysis LCA aluminum waste

All inputs are based on the provided data for the total amount of waste being recycled at the MRF within one year. Aluminum waste, thereby, constitutes a very small share to this amount, with only 2.5 percent. This percentage was used for calculating the shares of the particular fuels for the subsequent modeling, whereas calculating the amount of electricity consumed during the entire process is depended to the several process steps that are needed to recover the aluminum. As previously mentioned, this break down of the entire process chain, which additionally illustrates the assessment of the GHGs allocated to each process, is done in an Excel spreadsheet, which can be seen in Appendix A7. However, the entire process is also modeled with the provided data in the GaBi 6 sustainability software, which is used in the next step, the impact assessment, to crosscheck the results obtained from the Excel spreadsheet. The model from GaBi 6 is illustrated below in FIGURE.

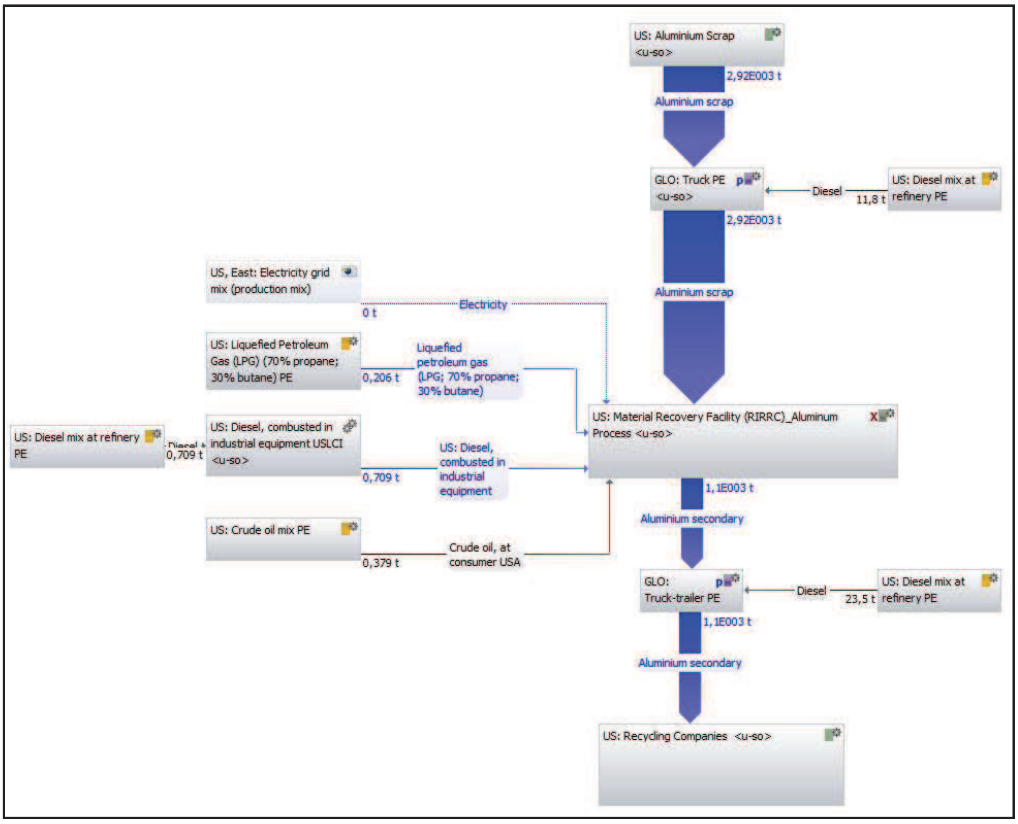


Figure 3.30: GaBi model for the entire process of the aluminum waste.

Lifecycle Impact Assessment Results

At this stage of the LCA, results are presented for the carbon footprint assessment of both the particular process steps and the combined GHG emissions in their related impact categories. The results are based on the total amount of aluminum waste (2920.63 tons) processed within the MRF in one year and are calculated using the Excel spread sheet and the GaBi 6 sustainability software. The impact assessment method used is, as previously determined in the goal and scope definition, the widely applied CML 2001 method.

To begin with, the results for the carbon footprint are presented and explained in detail. While each particular process step was examined in the excel spread sheet, the processes are summarized for the presentation of the results into the following categories: screens, conveyors, sorting machineries, baler and compactor, heating and transportation. Additionally, each category provides information about the amount of GHG emitted for a certain energy or fuel consumed by this category. A detailed listing of the particular processes that are summarized in each of these categories is provided in Apendix A7.

These categories have also been previously mentioned in Chapter 3.1.1, in the general scope definition, in the context of examination levels for this case study. While in the LCA of the RIRRC the entire process, considering its general inputs and outputs such as the total energy and fuel consumptions was examined, this LCA examined the process in more detail, regarding one material and its related process steps. However, before each GHG is considered respectively to its contribution to the carbon footprint, Table 3-10 gives an overview of all GHGs assessed for one year related to their particular process categories.

Table 3-10: Overview of all GHGs assessed within one year related to their particular process categories and energy source.

Processes	CO2 [t]				CH4 [Kg]				N2O [kg]			
	Eletricity	Propane	Diesel	Oil	Eletricity	Propane	Diesel	Oil	Eletricity	Propane	Diesel	Oil
Screens	30.99	0.00	0.00	0.00	72.31	0.00	0.00	0.00	0.58	0.00	0.00	0.00
Conveyors	22.46	0.00	0.00	0.00	52.41	0.00	0.00	0.00	0.42	0.00	0.00	0.00
Sorting Machinery	25.64	0.00	0.00	0.00	59.82	0.00	0.00	0.00	0.48	0.00	0.00	0.00
Baler and Compactor	72.32	0.00	0.00	0.00	168.74	0.00	0.00	0.00	1.36	0.00	0.00	0.00
Heating	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.56	0.00	0.00	0.00	0.00
Transport	0.00	0.06	126.64	0.00	0.00	0.42	177.02	0.00	0.00	0.00	1.39	0.00
Total of each category	151.41	0.06	126.64	0.03	353.29	0.42	177.02	0.56	2.84	0.00	1.39	0.00
Total	278.14				531.29				4.23			

Predictably from looking at the results of the carbon footprint assessment of the entire MRF, carbon dioxide is also in this assessment the emission with the largest amount

(278.14 tons). The GHG with the second largest amount is methane with 531.29 kg, whereas only 4.23 kg of nitrous oxide is emitted from the whole process.

The first GHG considered in detail is the carbon dioxide, its assessment results are illustrated in the Figure 3.31 below.

Processes	CO2 [t]			
	Eletricity	Propane	Diesel	Oil
Screens	30.99	0.00	0.00	0.00
Conveyors	22.46	0.00	0.00	0.00
Sorting Machinery	25.64	0.00	0.00	0.00
Baler and Compactor	72.32	0.00	0.00	0.00
Heating	0.00	0.00	0.00	0.03
Transport	0.00	0.06	126.64	0.00
Total of each category	151.41	0.06	126.64	0.03
Total	278.14			

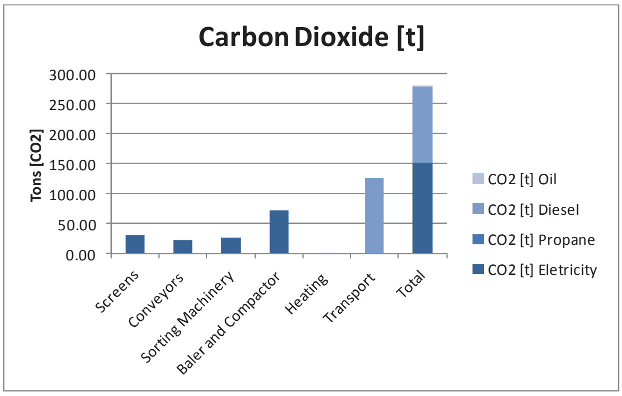


Figure 3.31: Carbon dioxide emissions for processing aluminum waste in the MRF of the RIRRC within one year.

The diagram illustrates the different categories, displaying the carbon dioxide released from a particular energy or fuel consumed by a particular process. Regarding, for example, the transportation category that emits 126.67 tons of carbon dioxide per year, it has two fuels contributing to this amount, primarily the consumption of diesel with 126.64 tons of CO2 and a nearly negligible emission of 0.06 tons from propane. The next biggest contributors to the carbon dioxide emission are the balers and compactors at the end of the process, which consume enormous amounts of electricity. This consumption releases 72.32 tons of carbon dioxide. Surprisingly, the emissions from the consumption of electricity by the running conveyors are the smallest (22.46 tons), although they are the most common process in the entire MRF.

The next considered GHG in the carbon footprint assessment is methane and its results are illustrated in Figure 3.32 below.

Conveyors	CH4 [Kg]			
	Eletricity	Propane	Diesel	Oil
Screens	72.31	0.00	0.00	0.00
Conveyors	52.41	0.00	0.00	0.00
Sorting Machinery	59.82	0.00	0.00	0.00
Baler and Compactor	168.74	0.00	0.00	0.00
Heating	0.00	0.00	0.00	0.56
Transport	0.00	0.42	177.02	0.00
Total of each category	353.29	0.42	177.02	0.56
Total	531.29			

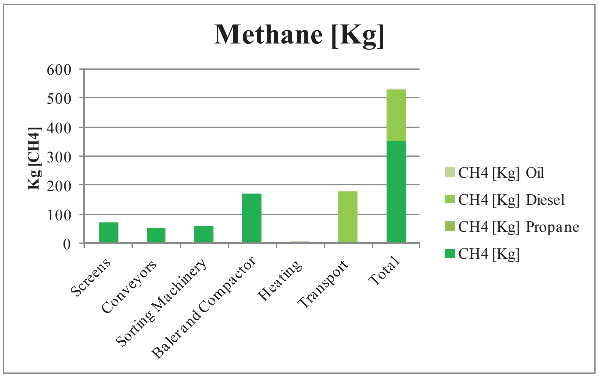


Figure 3.32: Methane emissions for processing aluminum waste in the MRF of the RIRRC within one year.

It becomes apparent that the diesel consumption within the transportation category is the main contributor to the total amount of methane emitted in this category (177.44 Kg), followed again by the baler and compactor category which form the second biggest contributor to the emission of methane (168.74 Kg) through its electricity consumption. The categories, screens and sorting machinery, do not really differ in the amount of methane they release, with individual contributions of 72.31 Kg and 59.82 Kg. The smallest amount to the total emission constitutes again the category of the conveyors with 52.41 Kg.

The last GHG regarded in the assessment is the nitrous oxide. Its result are displayed in the Figure 3.33 below.

Conveyors	N2O [kg]			
	Eletricity	Propane	Diesel	Oil
Screens	0.58	0.00	0.00	0.00
Conveyors	0.42	0.00	0.00	0.00
Sorting Machinery	0.48	0.00	0.00	0.00
Baler and Compactor	1.36	0.00	0.00	0.00
Heating	0.00	0.00	0.00	0.00
Transport	0.00	0.00	1.39	0.00
Total of each category	2.84	0.00	1.39	0.00
Total	4.23			

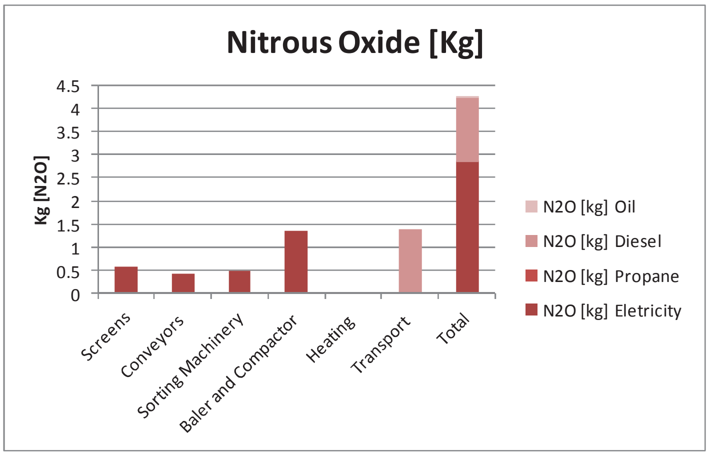


Figure 3.33: Carbon dioxide emissions for processing aluminum waste in the MRF of the RIRRC within one year.

The emissions of nitrous oxide concerning the whole process are very small compared to the other emissions (4.23 Kg). Nonetheless, this GHG is never negligible due to its enormous aggressiveness. The biggest contributors to this type of emission are the categories of transportation (1.39 kg), including the consumption of diesel and the balers and compactors (1.36 Kg) with their large consumption of electricity. The other three categories, screens, sorting machinery and conveyors, form only a very small share of this whole emission.

In the final step, the results for the impact categories are presented considering the total process. For further explanations concerning the impact categories see Chapter 0. The results are presented below in Figure 3.34.

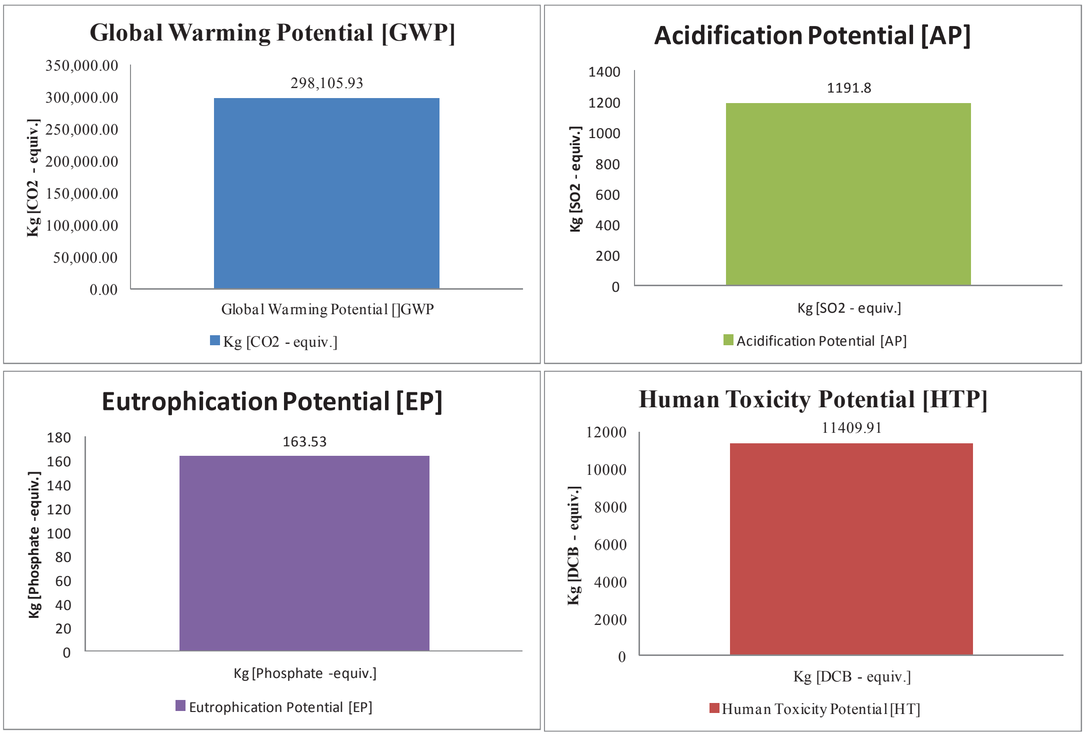


Figure 3.34: Impact categories for processing aluminum waste at the MRF of the RIRRC within one year.

Conclusion and Interpretation

This study provides the RIRRC with an up-to-date LCI and LCIA of a primary process of a particular recyclable waste at the MRF. The results are thereby referred to as the amount of aluminum waste processed at the MRF within one year but can be transferred to other commodity types that are processed at the MRF through minor changes.

Furthermore, the carbon footprint of this representative process was assessed providing the audience with an overview of the total performance of it in the context of environmental impacts and, in particular, GHG releases. This assessment can also be simply transferred onto every other similar process. While in the carbon footprint assessment of the entire MRF, the process was examined concerning its major inputs, such as energy and fuels. This assessment inspected processes within the whole process chain, disclosing the main contributors to GHG emissions. Thus, it can be stated that the main goal of this study has been reached.

Considering the results in particular and in the context of the carbon footprint assessment, it becomes apparent that, similar to the assessment for the entire MRF, the transportation is the greatest contributor to GHG emissions in this process, closely followed by the balers and compactors that consume large amounts of electricity, which leads to high releases for this particular process.

Analogous to the previous chapter, these results also have to be examined critically. Although mainly primary data is used for the modeling, some approximations were required to close data gap.

However, the obtained results in this study are consistent and reliable. Their accuracy, for the carbon footprint assessment, has been crosschecked both with the GaBi 6 sustainability software and the GHG equivalency calculator of the EPA (*Greenhouse Gas Equivalencies Calculator*, 2014). Moreover, as a last check, the assessment tool for GHG emissions provided by the German Federal Environment Agency (Umweltbundesamt, 2014) was used.

In conclusion, this study was performed to illustrate a general process that a particular recyclable waste runs through at the MRF of the RIRRC. The results, therefore, provide data and information for each process step of the entire process chain, concerning its environmental impacts such as the emissions of GHGs. All results are related to the total amount of aluminum waste processed within one year at the RIRRC. For a comparison with other recyclable waste materials it would be required to break down the results into a reference value, such as 1 ton of the particular recyclable waste that is processed in the MRF. Since no comparison with a different recyclable waste is made, it is not necessary at this point, but it could be interesting for a future research.

3.3 Carbon Footprint Comparison

In this chapter, two further WMS, a waste-to-energy plant and a land-fill, are examined considering their carbon footprint. Their results are subsequently compared with the results of the MRF that was previously examined. While primary data for the MRF was provided by the RIRRC, the access to primary data for the waste-to-energy plant and for the landfill proved to be difficult. However, for a realistic comparison this data is needed and specific requirements must be met. Therefore, most of the data used in this comparison originates from data that is readily available from previous LCI studies and life cycle databases within the GaBi 6 sustainability software. In cases where data is absence, approximations are used to close these data gaps.

The first requirement in this comparison is that the amount of waste, which is either incinerated in a waste-to-energy plant or dumped in a landfill, needs to be similar to the one processed in the MRF. Furthermore, the materials, as well, as their quantity within this waste need to be the same. To meet that requirement, all data concerning the recyclable waste provided by the RIRRC is also used for the other two WMS. This includes essentially both the time frame and geographical aspect of the data, meaning that the waste regarded for the two WMS, is the amount collected per year in the municipality of Rhode Island, which was estimated previously with an amount of 118,476.19 tons.

In addition to that, and to meet another requirement, it is assumed that the two viewed WMS are also located in Johnston, Rhode Island, so that the transportation of the waste after the curbside collection to the particular WMS is similar.

The two WMS are also modeled in the GaBi 6 sustainability software, ensuring that the same parameters are used for the assessment of their carbon footprints. However, it needs to be clarified, at this point, that only those stages of an LCA are performed that are necessary for the determination of the carbon footprint of both the waste-to-energy plant and the landfill. A full LCA of each WMS would go beyond the scope of this thesis.

3.3.1 Carbon Footprint Waste-to-Energy Plant

The first WMS to look at in this comparison is the waste-to-energy plant. As previously mentioned, primary data for this WMS originates mainly from the GaBi 6 sustainability software. A problem occurring in this context of modeling is that the educational version of this sustainability software is limited in certain areas of its databases. Regarding the modeling of this WMS, the software only represents a data set for an average European waste-to-energy plant. However, using this type of plant in the model should not have a significant influence on the results of the carbon footprint in the end. Global regulations and legal requirements that need to be met by this type of WMS have no significant differences between an average European waste-to-energy plants and an American one and therefore, become negligible.

The system boundaries for this type of waste-to-energy plant are determined by the GaBi sustainability software and its data set that are illustrated in Figure 3.35 below:

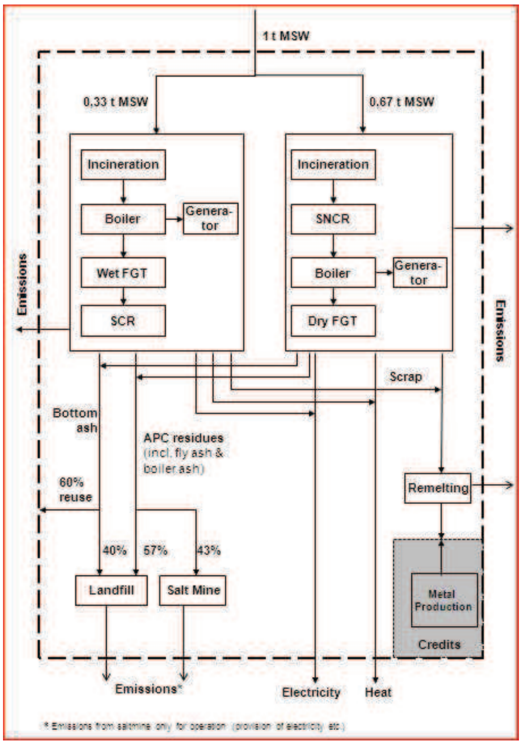


Figure 3.35: System boundaries for standard waste-to-energy plant (GaBi 6 sustainability software)

The regarded system includes a mix of two different incineration models, one with a wet flue gas treatment (FGT) and one with a dry FGT and different NO_x removal technologies to represent the application of the different FGT systems used in general. Thereby, two thirds of the MSW is treated within a plant operating with a dry FGT and the other one third is treated within a plant operating with wet FGT.

The plant consists of an incineration line fitted with a grate and a steam generator, whereby the average efficiency of the steam production is about 81.9 percent. The produced steam is then either used to generate electricity or is exported as heat to industry or households (PE International, 2013b).

Viewing this model provided by the GaBi 6 sustainability software and comparing it with the standard waste-to-energy plant previously described in detail in Chapter

2.4.3, it becomes apparent that all utilities, the operation of the underground deposit, the landfill for bottom ash and air pollution control (APC) residues as well as the meltdown processes for the recovered metals,[7] used in this waste incineration plant are included in the system boundaries. Only the curbside collection and the transport of the waste to the waste-to-energy plant are not included, but this has been modeled before in the GaBi 6 sustainability software for the MRF and can be thus easily added to the model (PE International, 2013b).

The inventory of the system is mainly based on industry data and is completed, when necessary, by secondary data. Furthermore, the data is based on an annual average, which fits the time requirements for the comparison and is necessary considering the fact that the combusted waste input, is also assumed to be the total amount collected within a year in the municipality of Rhode Island. This waste consists of the following commodity types Figure 3.36 and totals to 118,476.19 tons per year.

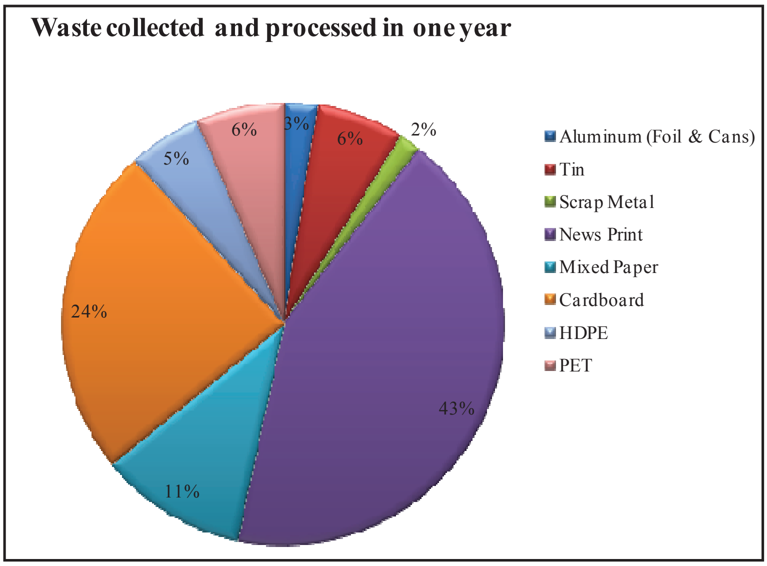


Figure 3.36: Waste collected at the municipality of Rhode Island and processed at a standard WTE plant

[7] For more information considering this waste-to-energy processes see (PE International (2013b))

The data set of this model includes the average emissions and resource consumption for the thermal treatment of this waste, so that after the modeling phase the GaBi sustainability software can be used to assess the carbon footprint of this waste-to-energy plant. However, it has to be considered that this data set is only an approximation to reality. It is a model of an average waste-to-energy plant; thus, a variance in data is to be expected if data from a specific waste-to-energy plant is used.

Nonetheless, before the carbon footprint is assessed, the conceptual model from the GaBi 6 sustainability software for the assumed waste-to-energy plant in this study and comparison is shown below in Figure 3.37.

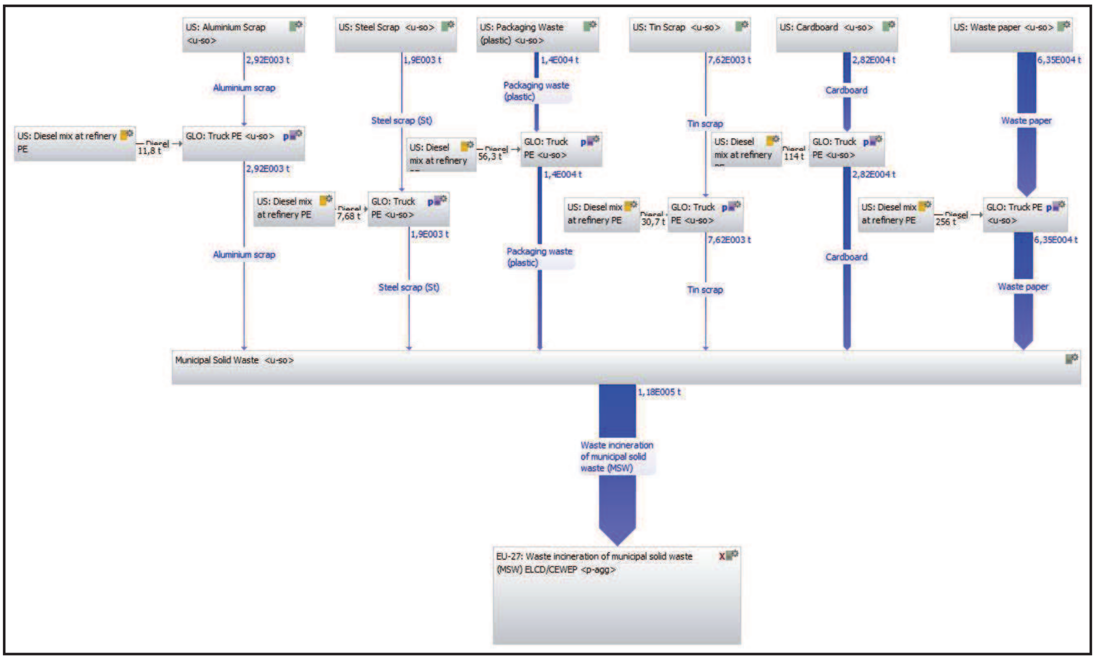
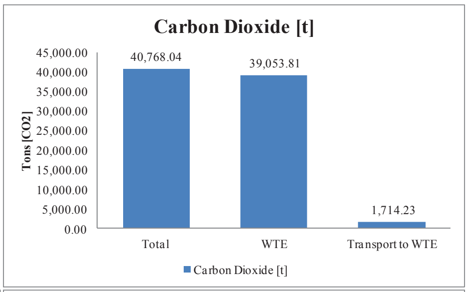


Figure 3.37: Model for the WTE plant in GaBi 6 sustainability software (GaBi 6 sustainability software)

For the carbon footprint assessment, the same GHGs as before are considered, which are carbon dioxide, methane and nitrous oxide. In contrary to the previous assessment for the MRF, the assessment is not broken down into particular amounts of releases for each commodity type, but only into the total amounts of emissions for the two processes, the transportation to the plant (which is similar to the MRF) and the combustion of the waste at the waste-to-energy plant. The results can be seen in the following Figure 3.38.

Process	Carbon Dioxide [t]	Methane [t]	Nitrous oxide [kg]
Transport to WTE	1,714.23	2.34	21.35
WTE	39,053.81	14.22	140
Total	40,768.04	16.56	161.35



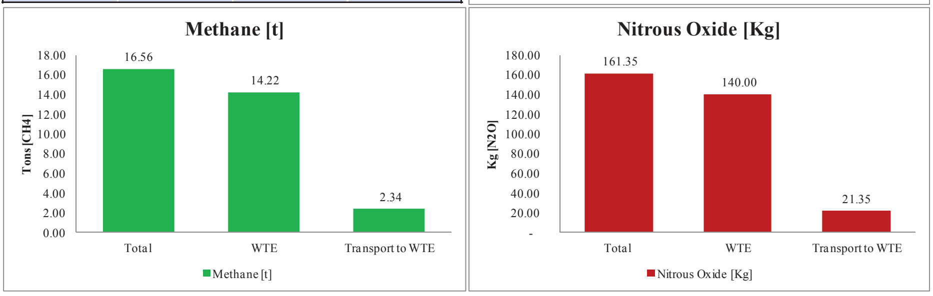


Figure 3.38: Carbon footprint of the WTE plant assessed for one year (GaBi 6 sustainability software)

Regarding Figure 3.38 it becomes apparent that the total amounts of the GHG releases are significantly higher than the previous assessed for the MRF. For the whole process from collecting of the recyclable waste to its combustion at the WTE plant a total of 40,768.04 tons of carbon dioxide is emitted. Considering the methane the releases account to 16.56 tons in total. The amount of nitrous oxide is 161.35 kg. To get a better impression of these relative large numbers, equivalency results for all three GHGs emitted per year are illustrated in the following Figure 3.39.

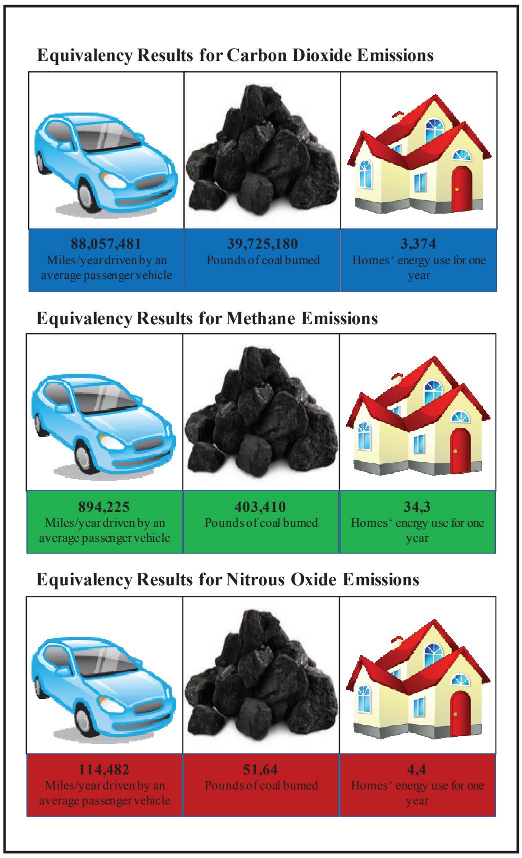


Figure 3.39: Equivalency results for the carbon dioxide, methane and nitrous oxide emissions assessed for the carbon footprint

3.3.2 Carbon Footprint Municipal Landfill

The last WMS that is viewed in this comparison is a standard landfill. Likewise the WTE plant, the landfill is supposed to be also modeled in the GaBi 6 sustainability software using its primary data. However, similarly as before when modeling the WTE plant, limitations in the educational version of this sustainability software required certain changes for modeling this landfill in order to fulfill the goal, the assessment of its carbon footprint. Origin for these required changes are based again on the fact that the educational databases mainly includes European data sets, meaning that there is no access to a data set of an American landfill, but only an average European one.

Nonetheless, as mentioned before, the global regulations today as well as the legal requirements in Europe considering environmental impacts of WMS are very similar to those in the United States, which allows using the European average landfill instead of an American for the modeling. The differences are therefore negligible.

Looking at the system boundaries of the landfill the process begins similarly to the other WMS regarded in this comparison with the curbside collection of the waste in the municipality of Rhode Island that is subsequently transported to the landfill, where it is deposited. The amount of waste considered thereby is the same as previously determined for the other two WMS.

The data set in the GaBi 6 sustainability software represents thereby a typical municipal waste landfill with surface and basic sealing meeting general limits for emissions. Furthermore, the site includes landfill gas treatment, leachate treatment, sludge treatment and deposition.

The landfill considers 100 years deposit and it measures a height of 30 meters and a landfill area of 40,000 square meters. This might seem to be small compared to other municipal landfills such as the landfill of the RIRRC, from which no primary data is provided except for its maximum height which is 76 meter from its base and its disposal footprint measuring 1,012,000 square meters (PE International, 2014). However, the chosen landfill in GaBi 6 is the greatest possible and its structure is comparable to the one previously described in detail in Chapter 2.4.4.

The effort for sealing materials like clay, mineral coating, PE film etc. and the diesel consumed by the compactors is included in the data set as well. Considering the distribution of the landfill gas, it is assumed that 22 percent is flare, 28 percent is used and 50 percent are released. This assumption of the usage of landfill gas represents industrial country standards (PE International, 2014).

The time frame for the assessment of the emissions is also one year, which is similar to the assessments for the other WMS and required for the subsequent comparison.

The data set for this landfill model in GaBi 6 is based on statistical and literature information collected by the PE International and the LCI modeling is fully consistent. Nonetheless, it is important to notify that this data set is also only an approximation to reality. Efficiencies, emission values, and elementary composition of waste used for this average municipal landfill model will distinguish from a specific landfill.

The conceptual model from the GaBi 6 sustainability software is displayed below in Figure 3.40.

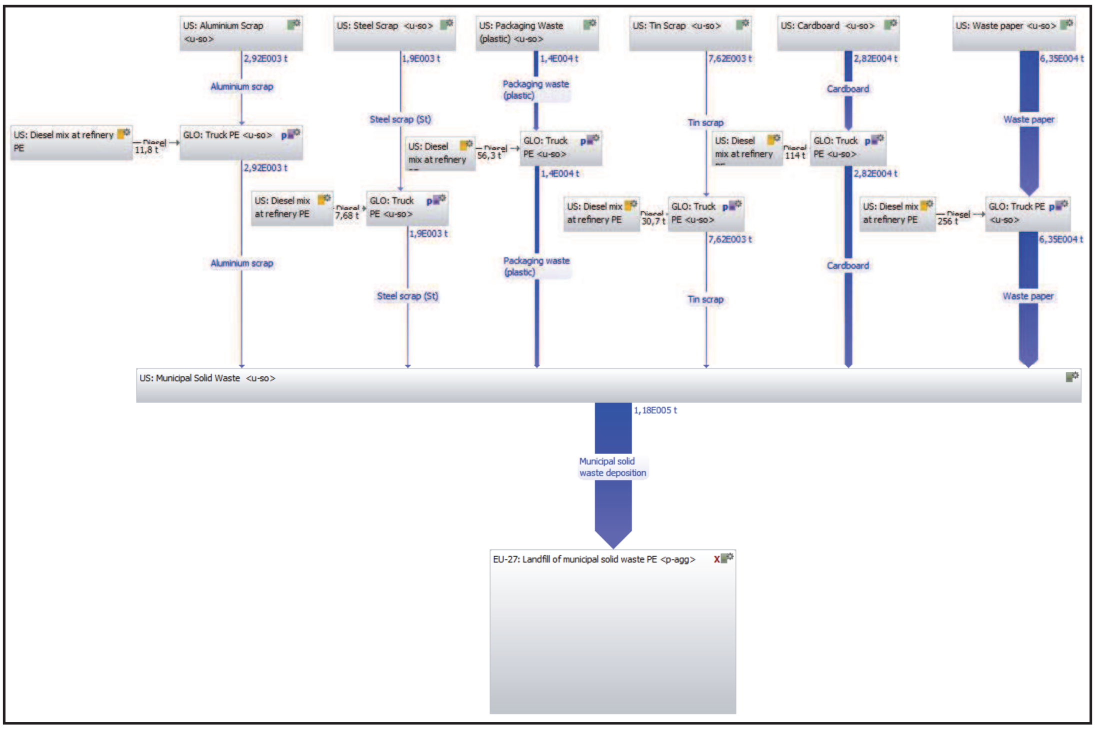
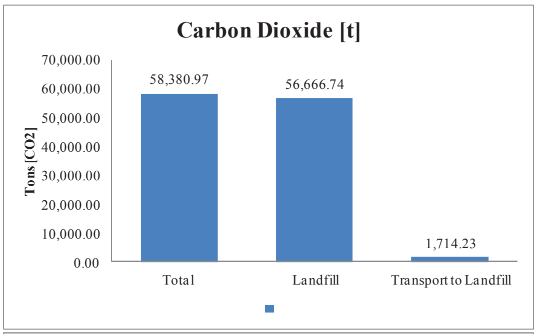


Figure 3.40: Model for the Municipal Landfill in GaBi 6 sustainability software (GaBi 6 sustainability software)

The carbon footprint assessment for this system is also done in GaBi 6. The results for the GHG emissions of this system including carbon dioxide, methane and nitrous oxide are illustrated in the following Figure 3.41. Similar to the presentation of the results for the WTE plant, the total amounts are only broken down into the two main processes, the deposition of the landfill and the transport to the landfill.

Process	Carbon Dioxide [t]	Methane [t]	Nitrous oxide [kg]
Transport to Landfill	1,714.23	2.34	21.35
Landfill	56,666.74	3,984.96	360
Total	58,380.97	3,987.30	381.35



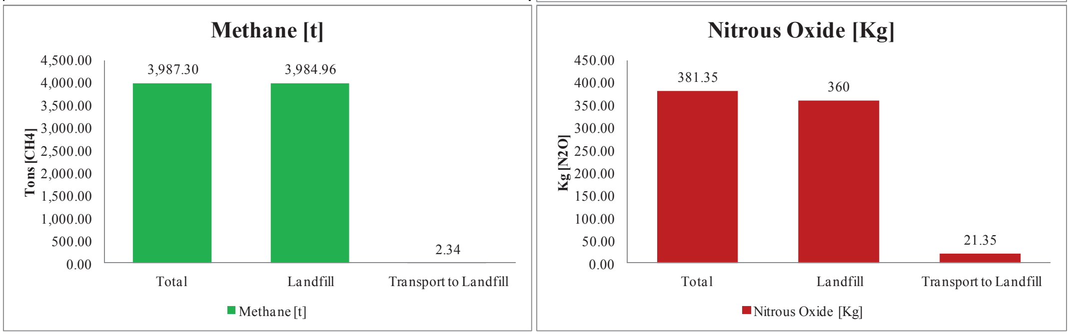


Figure 3.41: Carbon footprint of the WTE plant assessed for one year (GaBi 6 sustainability software)

Regarding the Pareto diagrams, which display the results of the three GHGs assessed for the carbon footprint, it is noticeable that the total amount of methane is relative high compared to the previous results for it. The reason for this lies in the earlier stated distribution of landfill gas. While 22 percent is flared at the plant, explaining also the high amount of carbon dioxide (58.380, 97 tons), 28 percent is only collected for generating energy and the residual 50 percent gas is released into the air, consisting mainly of methane. The total amount of methane accounts to 3,987.30 tons per year. The mass of nitrous oxide emitted from the entire process is 381.35 kg, whereby the landfill alone contributes with 360 kg the largest share to it.

To get a better understanding of these amounts emitted by the landfill process, Figure 3.42 shows equivalency results.

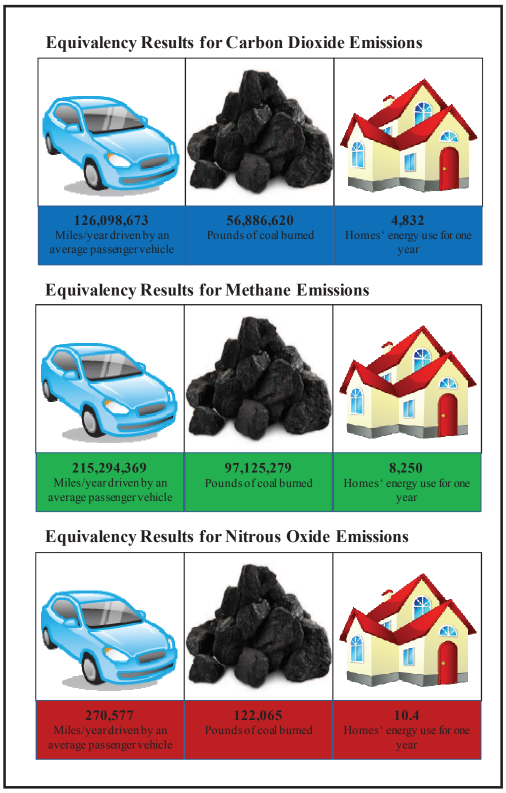


Figure 3.42: Equivalency results for the carbon dioxide, methane and nitrous oxide emissions assessed for the carbon footprint.

Regarding these equivalency results and especially comparing in this case the results of the carbon dioxide emission and the methane emission, it becomes apparent that for the first time the results for methane surpass the results of the carbon dioxide. The reason for that is on the one hand the tremendous amount of methane emitted from the landfill process per year and on the other hand that these equivalency results shown for methane and nitrous oxide are converted into carbon dioxide with their previously determined characterization factors. The environmental impact of methane is thereby 25 times bigger than the one of carbon dioxide, meaning that the amount of methane released per year was multiplied by 25 to obtain the equivalent amount of carbon dioxide emitted.

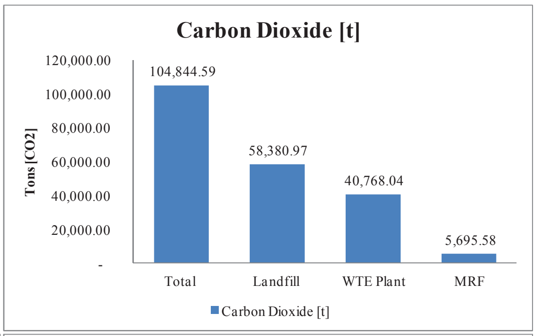
3.3.3 Comparison of the Waste Management Systems

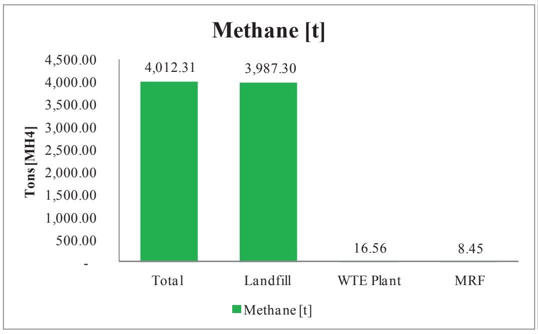
After all three WMS - MRF, WTE plant and municipal landfill - have been closer examined especially considering their emissions of the GHGs carbon dioxide, methane and nitrous oxide, the results of their carbon footprint assessments are compared in this Chapter.

The initial point for each of the three WMS was the curbside collection of waste in the municipality of Rhode Island within one year. All carbon footprints are therefore absolute values, which are referred to one year and the total amount of waste collected, which is 118,476.19 tons.

Within this comparison, only the total amounts of each GHG emission for the particular WMS are compared and displayed. Certain processes within the WMS or specific commodity types that are processed in them are not compared with each other nor are they shown in the results. The comparison is presented in Pareto diagrams in Figure 3.43, showing in a descending order the WMS with the largest releases to the air.

WMS	Carbon Dioxide [t]	Methane [t]	Nitrous oxide [kg]
MRF	5,695.58	8.45	65.81
WTE Plant	40,768.04	16.56	161.35
Landfill	58,380.97	3,987.30	381.35





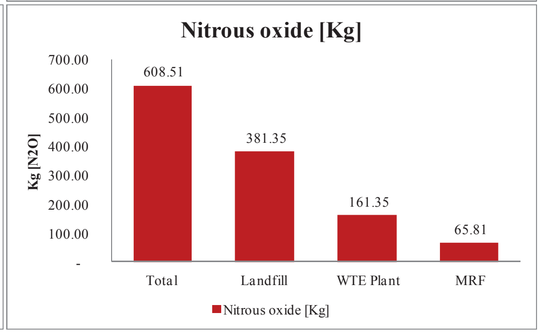


Figure 3.43: Comparison of the carbon footprints of the three WMS - MRF, WTE plant and Municipal Landfill (GaBi 6 sustainability software)

As expected, it becomes evident by viewing these Pareto diagrams that the landfill process is the largest contributor to each GHG emission. Beginning with the comparison of the carbon dioxide the entire landfill process emits within a year an amount of 58,380.97 tons, which is nearly 17,000 tons more than the WTE plant emits and nearly ten times more than the MRF emits (5,695.58 tons) for processing the same amount of waste. The same applies for the emission of methane per year, where the differences are even more significant. The landfill is the absolute top contributor concerning this GHG with an amount of 3,987.30 tons per year, the next biggest contributor that lag far behind is the entire process of the WTE plant with a methane release of 16.56 tons, which is still twice as much as the amount of methane emitted by the MRF.

Considering the last GHG that was regarded in the comparison, nitrous oxide, no changes in the order took place. The landfill process is still the main contributor, followed by the WTE plant and the MRF with the smallest share of emissions. However, the between the emissions of the particular WMS considering this GHG are not as big as before. While the landfill process emits 381.35 kg nitrous oxide per year, the WTE plant emits 161.35 kg and the MRF “only” 65.81 kg.

In conclusion, the examination of these WMS and their subsequent comparison showed their overall performance concerning their environmental impacts and especially considering their emissions of the three significant GHGs carbon dioxide, methane and nitrous oxide.

To complete this comparison all the previously shown equivalency results of the three WMS considering their emissions are summarized in an overview in Figure 3.44 below.

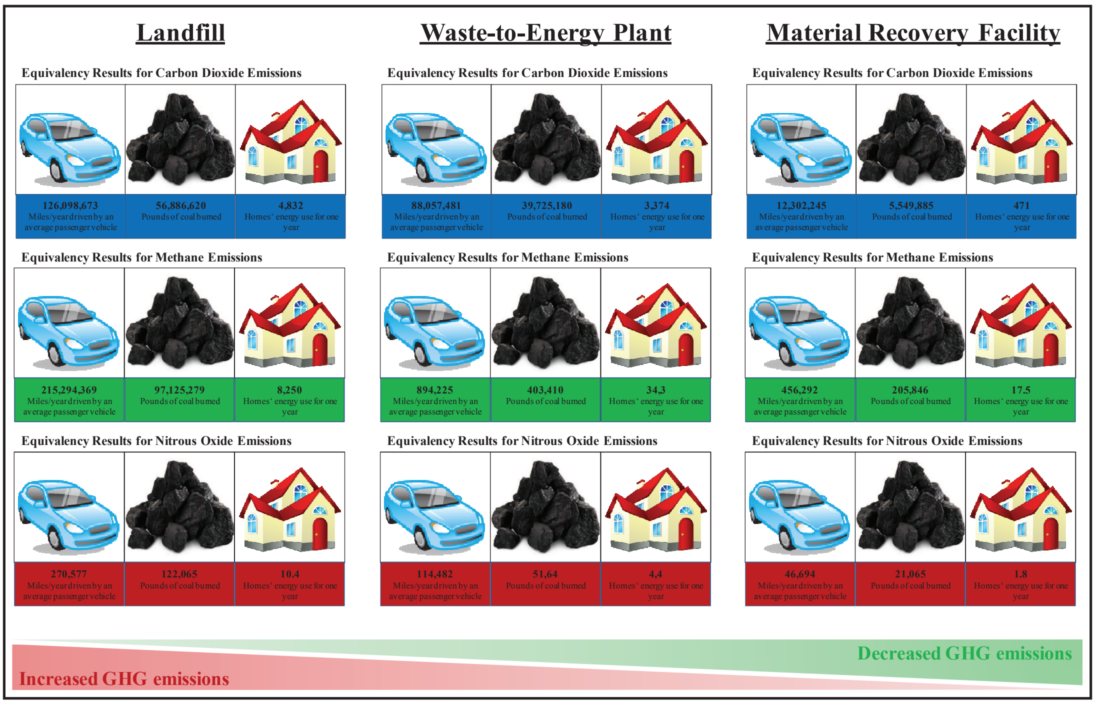


Figure 3.44: Comparison of the three WMS (Authors own graph)

4 Summary and Conlusion

The objective of this study was to evaluate the environmental impacts of the three different WMS, the MRF, WTE plant and landfill, and to compare their general performance in terms of their GHG releases. The focus, however, was essentially on the performance of the MRF, for which real data was provided by the MRF of the RIRRC.

The basis for this study can be found in the field of sustainability, with the ambition to find the WMS with the least environmental impacts. Therefore, the initial point of this study is the presentation of the basic concept of sustainability, as well as, the history of its development. In addition to that, a comprehensive literature review examines and categorizes different tools in the field of sustainability assessment.

With respect to the objective of this study, assessment tools considering the environmental aspects of sustainability are examined, determining the LCA to be the most suitable to achieve the defined goals. The LCA evaluates products, processes and services during each stage of their life cycle, integrating environmental aspects in its assessment.

Besides this assessment tool, another tool is taken into consideration, which is essentially used for measuring the emission of GHGs. This tool is the carbon footprint assessment, which is in some literatures assumed to be an integrated part of the LCA. While for the performance of a LCA guidelines exist that are defined in the international series of standards ISO 14040, guidelines do not exist for the measurement nor do appropriate definitions exist for the carbon footprint. Hence, it was required to first determine the carbon footprint in respect to the objective of this study.

The Kyoto Protocol, encloses six main GHGs, from which the three most common, carbon dioxide, methane and nitrous oxide, were chosen for the assessment and comparison of the carbon footprint in this study. Furthermore, those GHGs form the basis for the impact categories within the LCA.

An important decision that needed to be made was the choice of the sustainability software used in this study. It had to fulfill the requirements for modeling an LCA of a WMS and also had to be able to measure GHGs within the model. Therefore, several state-of-the-art sustainability softwares were compared with each other and their advantages and disadvantages pertaining to the objective were discussed. For this study, the GaBi 6 sustainability software was chosen, more precisely its educational version that was free available.

Before the WMS regarded in this study are described in detail, a general overview of the changes that took place within the waste management sector of the US during the last decades is provided, showing how through technological advancements the emissions of GHGs could be reduced. While, for example, in the 1970s landfilling without any gas collection was dominant in the field of waste management with a share of nearly 80 percent, today, its share decreased to 50 percent; however, the use of MRFs increased from 10 percent to nearly 35 percent. What type of WMS is used in certain geographical areas depends, however, on many different factors but the goal should always be to choose the WMS, which does not just fulfill the requirements but also, is the most efficient considering the environmental aspects of sustainability.

In this study, an existing MRF in the municipality of Rhode Island is examined and then afterwards compared to a standard municipal landfill and a WTE plant in terms of its carbon footprint. The examination of the MRF of the RIRRC was thereby done on two different levels. At the first level, a full LCA for the entire process of the MRF was performed, as well as a carbon footprint assessment. This level considered general inputs, such as the consumption of energy and fuel, and was the initial point for the comparison with the other two WMS.

At the second level, a particular recyclable waste that was chosen to illustrate different process stages of the whole process chain within the MRF. As well as for the entire MRF, an LCA was performed for this particular recyclable waste and its carbon footprint was assessed. Additionally, GHGs have been allocated to the certain process stages the recyclable waste runs through within the MRF, disclosing in the results the main contributors of GHG emissions in the entire process.

The performance of those two LCA and the assessment of the carbon footprint is mainly based on the primary data provided by the RIRRC; however, in cases of data gaps, approximations needed to be made. For assessing the carbon footprint of the municipality landfill and the WTE plant, the modeling was done in the GaBi 6 sustainability software, which provided as well as most of the data for these models.

Finally, for the comparison, it is assumed that each WMS processed the same amount of waste with the same composition. This amount was considered to be the amount of recyclable waste collected at the curbside of the municipality of Rhode Island within one year. Hence, the compared carbon footprints also include the total amount of GHGs emitted per year from each WMS.

As could have been expected, the results show that of the total performances for each WMS considering its environmental impacts the MRF of the RIRRC is by far the WMS with the lowest emissions per year. The next WMS in the order is the WTE plant. However, it has nearly an eight times higher emission of GHGs as the MRF. In last place in the comparison, the landfill has ten times higher amounts of emissions per year as the MRF.

However, these results have to be examined critically. Although a lot of the data used for modeling the process was provided by the RIRRC, approximations needed to be made to close certain data gaps. Alongside those approximations are uncertainties concerning the data used, which in turn influence the results presented in this study and might slightly alter the results compared to those in reality. An example for such an approximation is the recycling rate used for estimating the total waste produced within one year in Rhode Island. While for each recyclable material the same rate was assumed, variances may occur in reality. However, although the results may be only an approximation to reality, they are reliable and consistent in terms of this study and comparison. Furthermore, the result's accuracy was reviewed and cross-checked with several other assessment tools besides the GaBi 6 sustainability software, such as the GHG equivalency calculator of the EPA (*Greenhouse Gas Equivalencies Calculator*, 2014) and an assessment tool for GHG emissions provided by the German Federal Environment Agency (Umweltbundesamt, 2014).

In conclusion, this study provides the reader with an up-to-date LCI and LCIA of primary curbside collection and the transportation of recyclable waste in the municipality of Rhode Island in one year and the processing of this waste at the MRF of the RIRRC. Moreover, it provides an overview of the total performance of the MRF, a standard municipality landfill and a WTE plant in the context of environmental impacts and, in particular, GHG releases. However, it is important to note that the results are absolute values that are referred to the total amount of recyclable waste collected in one year in the municipality of Rhode Island.

5 Recommendations for Future Research

This study provides the basis for a general approach in performing an LCA on an existing WMS, precisely a MRF, and provides further an overview of the general performance of this MRF in terms of its environmental impacts. Additionally, the results of its environmental impacts are compared to those of a WTE plant and a Municipal Landfill. To increase the accuracy of the results, a next step would require a more professional data collection at both the MRF itself and the other two WMS. The data provided in this case for the MRF was two years old, while the data for the WTE plant and the Municipal Landfill was provided from the sustainability software GaBi 6 for standard systems.

Furthermore, the results were, as previously mentioned, referred to in the total amount of recyclable waste collected in one year at the curbside of the municipality of Rhode Island. For a comparison with other MRFs or a bench mark, it would be necessary to break down the results to a specific reference value such as 1 ton of recyclable waste processed. Additionally, it would be necessary that the compared systems have the same system boundaries.

Another interesting aspect for future research is the curbside collection and the transport to the MRF and leaving the MRF. In the results, it became apparent that especially the transport contributed to the GHG emissions. An optimization of the curbside collection routes could help to minimize the general diesel consumption and, therefore, lower the GHG releases.

Another future research aspect for minimizing the GHG emissions of the entire process of the MRF would be a closer examination of the process itself. While this study provided a first step in this direction, particular machineries and processes within the entire process chain that heavily contribute to the release of GHGs could be further examined.

Considering the comparison of the MRF with the municipality landfill and the WTE plant, the total amounts of GHG emissions have been compared in general with each other. However, although each WMS releases GHGs, it also saves some amount through either the generation of electricity or in the case of the MRF through the recovering process, which provides secondary raw materials for the production. In this case, an interesting aspect for future research could be to measure these savings and compare them with each other, to see which WMS has the lowest emissions considering the absolute results.

Appendices

A 1: Full comparison of the LCA software packages

Software name	GaBi 5 Software	openLCA	Sima Pro 8	Umberto NXT LCA
Supplier	PE International GmbH University of Stuttgart, LBP-GaBi	GreenDelta	PRé Consultants B.V.	ifu Hamburg GmbH
Language	English, German	English, German	Spanish, French, Italian, German, English	English, German
Main database	ecoinvent v3; GaBi Databank	openLCA Databank; on purchase: GaBi + ecoinvent v3 available	ecoinvent v3	ecoinvent v3; GaBi Databank optional
Supports full LCA	Yes	Yes	Yes	Yes
Carbon Footprinting	Yes	limited	Yes	Yes
Operating Systems	Windows	Windows, Mac, Linux	Windows	Windows
Sankey (Flow) Diagramms	Yes	Yes	Yes	Yes
Cost calculations with Sankeys for cost	Yes	No	Yes	No
Graphical impact assessment	Yes	Yes	Yes	Yes
Graphical inventory analysis	Yes	Yes	Yes	Yes
Auto sensitivity analysis	Yes	No	Yes	Yes
Export of results to Microsoft Excel	Yes	No	Extra reporting tool package needed	Yes
On line support	Yes	Yes	Yes	Yes
Restriction input / output	Depending on License	Yes	Depending on License	Depending on License
If commercial, free trials available?	30 days free trial + **free student version**	---	Demo Version	14 days free trial
Cost	Quote on Request	Free	Business Licenses: $8.000 - $16.000 Educational Licenses: $2.400 - $4.200	Quote on Request

Sources for **A 1**:

GaBi 5 Software: http://www.gabi-software.com/overview/product-sustainability-performance/

OpenLCA: http://www.openlca.org/features_overview

Sima Pro 8: http://www.pre-sustainability.com/all-about-simapro

Umberto: http://www.umberto.de/en/versions/

Ecoinvent: http://www.ecoinvent.org/database/resellers-lca-software-providers/

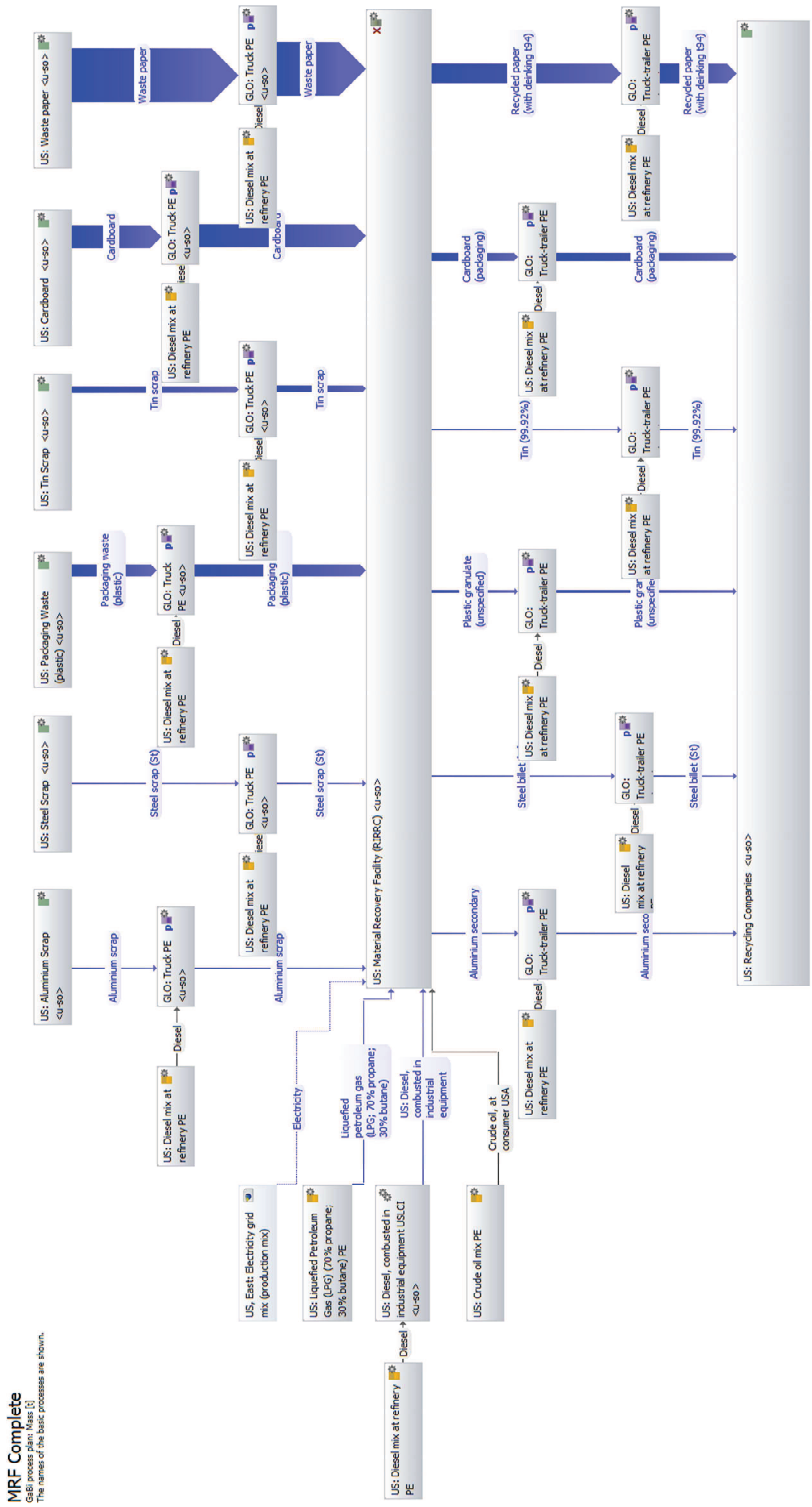
A 2: Cities in Rhode Island with a population over 15,000 people and distance to RIRRC.

Name	State	County	Population	Distance to RIRRC (miles)	Distance to RIRRC (km)
Barrington	Rhode Island	Bristol	16,310.00	18.70	30.09
Bristol	Rhode Island	Bristol	22,954.00	25.50	41.04
Burrillville	Rhode Island	Providence	15,955.00	18.80	30.26
Central Falls	Rhode Island	Providence	19,376.00	14.40	23.17
Coventry	Rhode Island	Kent	35,014.00	18.30	29.45
Cranston	Rhode Island	Providence	80,387.00	8.20	13.20
Cumberland	Rhode Island	Providence	33,506.00	14.90	23.98
East Providence	Rhode Island	Providence	47,037.00	11.60	18.67
Johnston	Rhode Island	Providence	28,769.00	0.00	0.00
Lincoln	Rhode Island	Providence	21,105.00	12.90	20.76
Middletown	Rhode Island	Newport	16,150.00	40.00	64.70
Narragansett	Rhode Island	Washington	15,868.00	31.70	51.02
Newport	Rhode Island	Newport	24,672.00	34.80	56.01
North Kingstown	Rhode Island	Washington	26,486.00	21.70	34.92
North Providence	Rhode Island	Providence	32,078.00	6.00	9.66
Pawtucket	Rhode Island	Providence	71,148.00	10.00	17.06
Portsmouth	Rhode Island	Newport	17,389.00	34.10	54.88
Providence	Rhode Island	Providence	178,042.00	6.50	10.46
Smithfield	Rhode Island	Providence	21,430.00	10.20	16.42
South Kingstown	Rhode Island	Washington	30,639.00	33.00	53.11
Tiverton	Rhode Island	Newport	15,780.00	30.70	49.41
Warwick	Rhode Island	Kent	82,672.00	14.80	23.82
West Warwick	Rhode Island	Kent	29,191.00	14.60	23.50
Westerly	Rhode Island	Washington	22,787.00	44.40	71.45
Woonsocket	Rhode Island	Providence	41,186.00	15.50	24.94
		Total	945,931.00	492.10	791.96
		Average		19.68	31.68

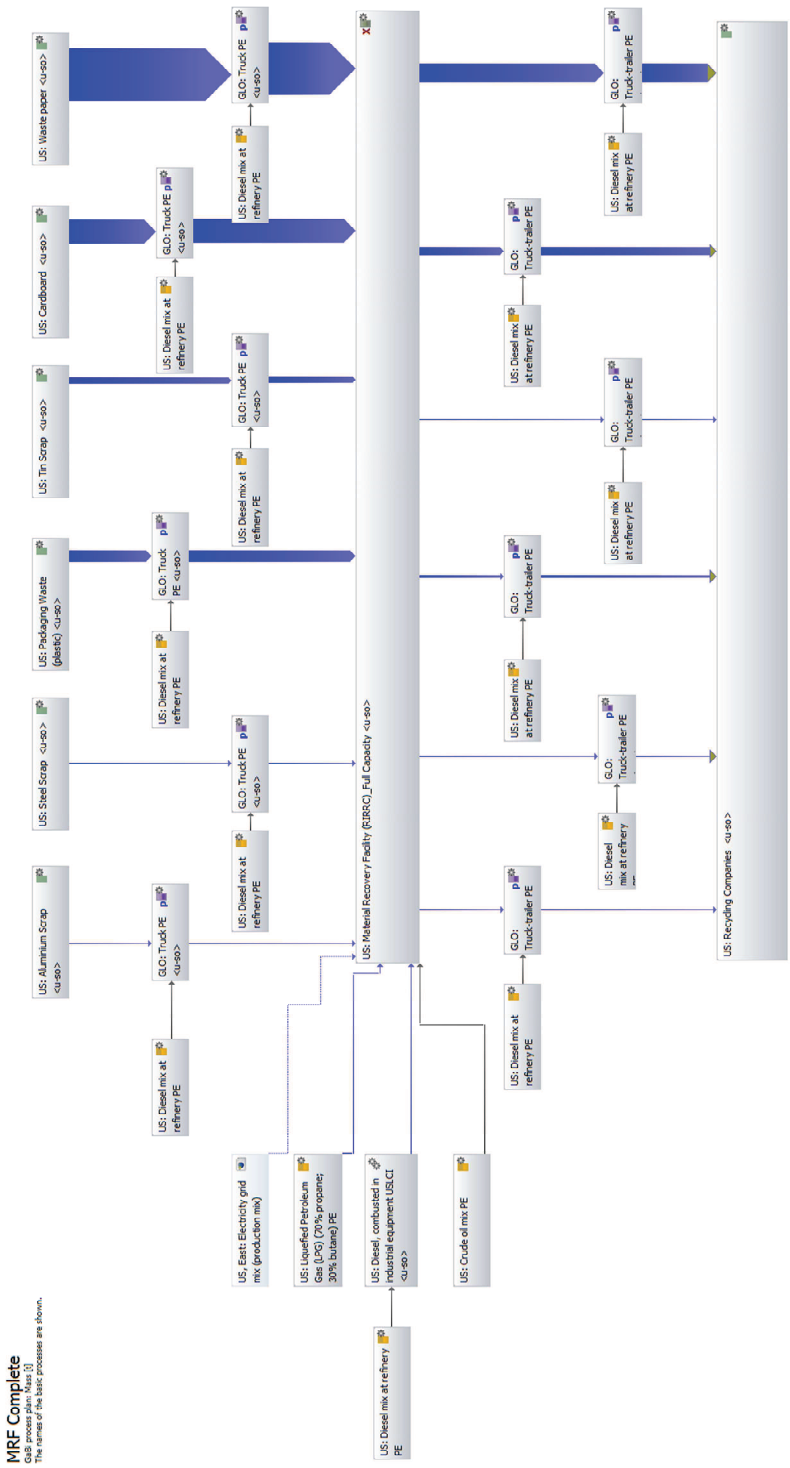
A3: Distances from RIRRC to every recycling company

#	Recycling Company	Location	Distance from RIRRC (miles)	Distance from RIRRC (km)
1	AMERICA CHUNG NAM	CA	2,949	4,745.94
2	ANHEUSER BUSCH	Ny	321	516.60
3	APEX GW TRADING	Brooklyn, NY	181	291.29
4	CANUSA HERSHMAN	VT	305	490.85
5	CLEAR PATH	NC	719	1,157.12
6	CONTI GROUP	Chatham, ON	658	1,058.95
7	ENTROPEX	ON, CA	655	1,054.12
8	ENVISION	NC	672	1,081.48
9	FULL CIRCLE	PA	328	527.86
10	GREEN LINE	VA	410	659.83
11	INTERNATIONAL FOREST PRODUCTS	CA	2,988	4,808.71
12	KW PLASTICS	AL	1,321	2,125.94
13	MID CITY	MA	32.5	52.30
14	MOHAWK	GA	1,048	1,686.59
15	OGO FIBERS INC.	Ontario, Canada	563	906.06
16	POTENTIAL INDUSTRIES	CA	2,981	4,797.44
17	RAND WHITNEY	RI	17	27.36
18	ROCKTENN PAPER	NY	319	513.38
19	TABB PACKAGING	MI	741	1,192.52
20	TUBE CITY	PA	537	864.22
21	WELLMAN	MS	1,467	2,360.90
		Total:	19,212.5	30,919.44
		Average:	914.88	1,472.35

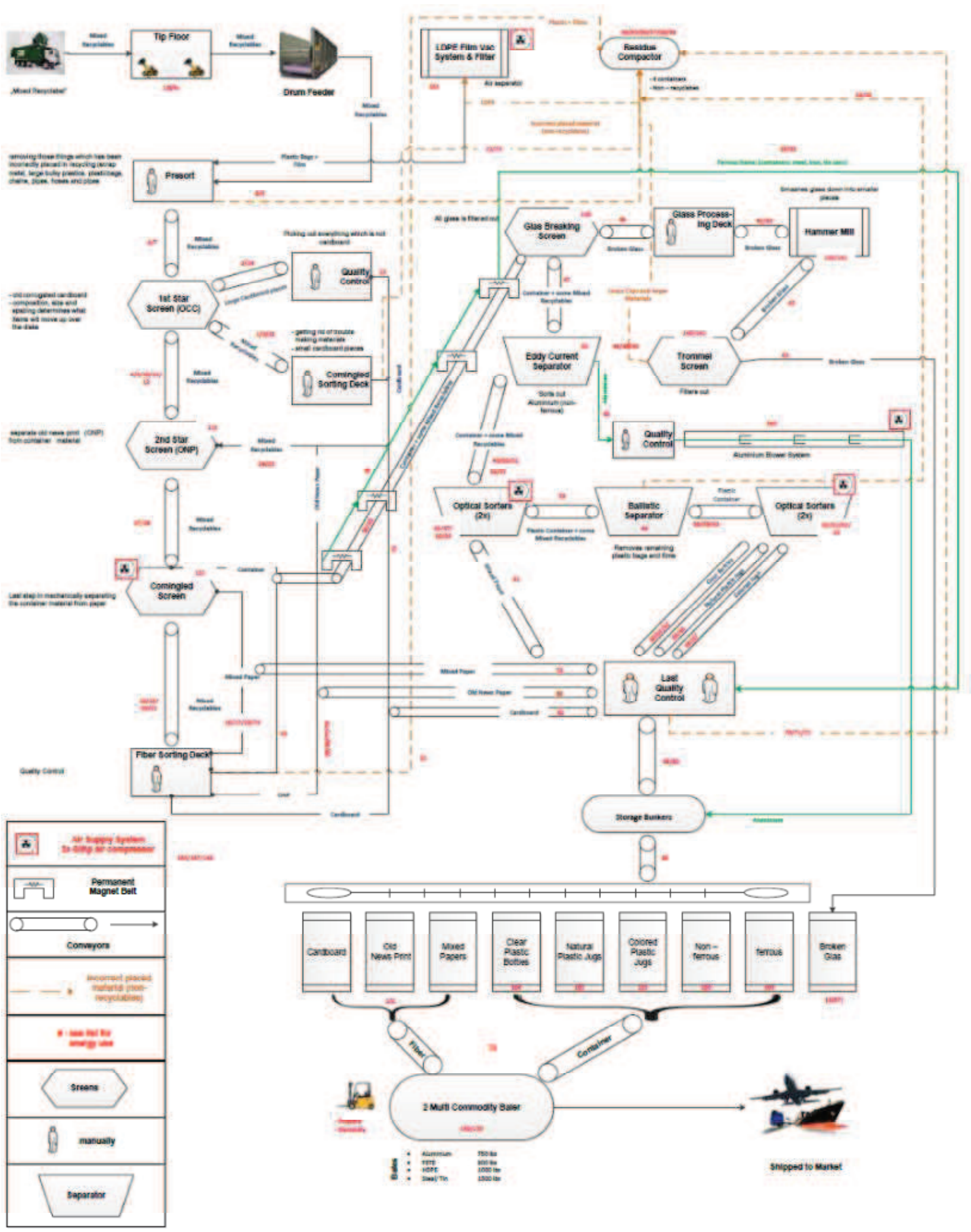
A4: Complete process of the MRF of the RIRRC modeled in GaBi 6 sustainability software



A5: Complete process of the MRF processing the largest possible amount of waste within one year (modeled in GaBi 6 sustainability software)



A6: Conceptual model of the whole process of the MRF



A7: Carbon footprint for each step of processing Aluminum waste at the MRF of the RIRRC

									Data provided by GaBi 6 Sustainability Software											
								Hrs per year	1 KWH mi:	per gallon	per gallon	per gallon	1 KWH mi:	per gallon	per gallon	per gallon	1 KWH mi:	per gallon	per gallon	per gallon
Recycling Process:								1920	0.00066	0.00157	0.0118	0.000739	0.00154	0.0111	0.0161	0.0132	1.24E-05	3.54E-05	3.97E-05	1.55E-05
									ton	ton	ton	ton	kg	kg	kg	kg	kg	kg	kg	kg
				Consumption per year					CO_2 [t]				CH_4 [Kg]				N_2O [kg]			
Commodity Type and Amount		Prozess #	Recycling Process Steps	Oil (gal/year)	Diesel (gal/year)	Propane (gal/year)	Electricity (kw)	Electricity Consumption (kw) per year	Eletricity	Propane	Diesel	Oil	Eletricity	Propane	Diesel	Oil	Eletricity	Propane	Diesel	Oil
Aluminum Waste including: Used Beverage Cans Aluminum Foil [2290 t / year]	Conveyor	1	Discharge conveyor OCC Screen				0.18	345.60	0.23	0.00	0.00	0.00	0.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		3	Discharge conveyor Non-OCC				0.18	345.60	0.23	0.00	0.00	0.00	0.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		4	Incline conveyor OCC unders				0.18	345.60	0.23	0.00	0.00	0.00	0.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		5	Incline conveyor OCC unders				0.90	1728.00	1.14	0.00	0.00	0.00	2.66	0.00	0.00	0.00	0.02	0.00	0.00	0.00
		6	Pre sort conveyor ONP				0.90	1728.00	1.14	0.00	0.00	0.00	2.66	0.00	0.00	0.00	0.02	0.00	0.00	0.00
		7	Pre sort conveyor ONP				0.90	1728.00	1.14	0.00	0.00	0.00	2.66	0.00	0.00	0.00	0.02	0.00	0.00	0.00
		10	Transfer conveyor OCC				0.90	1728.00	1.14	0.00	0.00	0.00	2.66	0.00	0.00	0.00	0.02	0.00	0.00	0.00
		11	Incline conveyor OCC				0.98	1881.60	1.24	0.00	0.00	0.00	2.90	0.00	0.00	0.00	0.02	0.00	0.00	0.00
		12	Transfer conveyor OCC				0.98	1881.60	1.24	0.00	0.00	0.00	2.90	0.00	0.00	0.00	0.02	0.00	0.00	0.00
		15	Transver conveyor top deck				1.50	2880.00	1.90	0.00	0.00	0.00	4.44	0.00	0.00	0.00	0.04	0.00	0.00	0.00
		16	Quality control conveyor ONP				1.50	2880.00	1.90	0.00	0.00	0.00	4.44	0.00	0.00	0.00	0.04	0.00	0.00	0.00
		17	Incline conveyor bottom deck				1.50	2880.00	1.90	0.00	0.00	0.00	4.44	0.00	0.00	0.00	0.04	0.00	0.00	0.00
		18	Incline conveyor bottom deck				1.50	2880.00	1.90	0.00	0.00	0.00	4.44	0.00	0.00	0.00	0.04	0.00	0.00	0.00
		19	Quality control conveyor ONP				1.50	2880.00	1.90	0.00	0.00	0.00	4.44	0.00	0.00	0.00	0.04	0.00	0.00	0.00
		20	Transfer conveyor bottom deck				1.50	2880.00	1.90	0.00	0.00	0.00	4.44	0.00	0.00	0.00	0.04	0.00	0.00	0.00
		21	Quality control conveyor ONP				1.50	2880.00	1.90	0.00	0.00	0.00	4.44	0.00	0.00	0.00	0.04	0.00	0.00	0.00
		24	Inclining conveyor unders				2.00	3840.00	2.53	0.00	0.00	0.00	5.91	0.00	0.00	0.00	0.05	0.00	0.00	0.00
		25	Inclining conveyor unders				2.00	3840.00	2.53	0.00	0.00	0.00	5.91	0.00	0.00	0.00	0.05	0.00	0.00	0.00
		36	Incline conveyor containers				3.70	7104.00	4.69	0.00	0.00	0.00	10.94	0.00	0.00	0.00	0.09	0.00	0.00	0.00
		47	Eddy Current Conveyor				5.50	10560.00	6.97	0.00	0.00	0.00	16.26	0.00	0.00	0.00	0.13	0.00	0.00	0.00
		48	Sort conveyor Aluminium				5.50	10560.00	6.97	0.00	0.00	0.00	16.26	0.00	0.00	0.00	0.13	0.00	0.00	0.00
		69	Sort conveyor 1-7				5.50	10560.00	6.97	0.00	0.00	0.00	16.26	0.00	0.00	0.00	0.13	0.00	0.00	0.00
		73	Transfer conveyor Rejects				7.50	14400.00	9.50	0.00	0.00	0.00	22.18	0.00	0.00	0.00	0.18	0.00	0.00	0.00
	Machinery MRF		Wheel Loader feeds recycables into it		223.71			0.00	0.00	0.00	2.64	0.00	0.00	0.00	3.60	0.00	0.00	0.00	0.01	0.00
			Drum Feeder					0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		113	1st star screen (OCC Screen)				7.34	14092.80	9.30	0.00	0.00	0.00	21.70	0.00	0.00	0.00	0.17	0.00	0.00	0.00
		120	2nd star screen (ONP Screen)				9.3	17856.00	11.78	0.00	0.00	0.00	27.50	0.00	0.00	0.00	0.22	0.00	0.00	0.00
		132	Comingled Screen (+ Air Blower)				28.8	55296.00	36.50	0.00	0.00	0.00	85.16	0.00	0.00	0.00	0.69	0.00	0.00	0.00
		138	Glas Breaking Screen				21.2	40704.00	26.86	0.00	0.00	0.00	62.68	0.00	0.00	0.00	0.50	0.00	0.00	0.00
		83	Eddy Current Separator				5.5	10560.00	6.97	0.00	0.00	0.00	16.26	0.00	0.00	0.00	0.13	0.00	0.00	0.00
		143	Aluminium Blower System (+ Air comp.)				49.63	95289.60	62.89	0.00	0.00	0.00	146.75	0.00	0.00	0.00	1.18	0.00	0.00	0.00
		100	Storage Bunkers				5.5	10560.00	6.97	0.00	0.00	0.00	16.26	0.00	0.00	0.00	0.13	0.00	0.00	0.00
		150	Commodity Baler (Container)				150	288000.00	190.08	0.00	0.00	0.00	443.52	0.00	0.00	0.00	3.57	0.00	0.00	0.00
	Heat		Heating within the MRF	115.47					0.00	0.00	0.00	0.09	0.00	0.00	0.00	1.52	0.00	0.00	0.00	0.00
	Trans-port		Curbside Collection		2217.888			0.00	0.00	0.00	41.21	0.00	0.00	0.00	57.13	0.00	0.00	0.00	0.53	0.00
			Power Forklifts for Balers			103.043		0.00	0.00	0.16	0.00	0.00	0.00	1.14	0.00	0.00	0.00	0.00	0.00	0.00
			Transport of virgin Material to Customer					0.00	0.00	0.00	82.79	0.00	0.00	0.00	116.29	0.00	0.00	0.00	0.85	0.00
			Total				325.57	625094.40	412.56	0.16	126.64	0.09	962.65	1.14	177.02	1.52	7.75	0.00	1.39	0.00
						Oper. rate i:	119.48419	229409.6448	151.41	0.06	126.64	0.03	353.29	0.42	177.02	0.56	2.84	0.00	1.39	0.00
							Total:		278.14				531.29				4.24			

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