Evaluation of a model used for environmental assessments of waste management systems

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Titel

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Sammandrag

I rapporten utvärderas the Waste Management Planning System (WAMPS), som är ett förenklat LCA-baserat verktyg för att jämföra avfallsscenarion utifrån miljömässiga aspekter. Syftet med studien var att hitta bristfälliga områden i modellen som behöver förbättras/uppdateras. Utvärderingen genomfördes genom att jämföra modellens struktur med liknande modeller samt genom att jämföra de resultat som beräknas i modellen med motsvarande värden från litteratur. Utvärderingen av beräkningarna inkluderade materialåtervinning av aluminium, stål, plast, glas, papper samt förbränning och kompostering. Klimatpåverkan var den enda påverkanskategori som undersöktes.

Jämförelserna visade att WAMPS stämmer överens med litteratur i de flesta avseenden. Utvärderingen av strukturen visade att de huvudsakliga avvikelserna i WAMPS är att det saknas en utförlig dokumentation över de beräkningar som görs i modellen, att det i beräkningarna av energi saknas en valmöjlighet för användaren att välja olika typ av energi som används i förgrundssystemet respektive vilken energi som ersätts i bakgrundssystemet, samt att det i grundversionen av WAMPS endast tas hänsyn till det rejekt som uppkommer vid förbehandling av materialåtervinning. Det senare går dock att ändra för användare med admin-tillgång.

Utvärderingen av beräkningarna påvisade avvikelser mellan WAMPS och värden från litteratur gällande materialåtervinning av stål, glas och kompostering. Jämförelsen visade också att fokus bör ligga på att kvalitetssäkra beräkningarna i de fraktioner som behandlar stora mängder avfall, då även små avvikelser i dessa kan ge stora effekter på resultatet. Den utförda jämförelsen innehåller dock flera osäkerheter. Dels jämfördes europeiska data med värden från WAMPS som är utvecklad i Sverige, och endast några aspekter av WAMPS utvärderades.

På grund av osäkerheterna i studien bör resultatet verifieras med en mer noggrann studie och på grund av den begränsade omfattningen av studien bör även en mer omfattande studie göras där fler fraktioner inkluderas, andra aspekter studeras och fler litteraturkällor används.

Nyckelord

WAMPS, utvärdering, avfallshantering, LCA, livscykelanalys

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Abstract

This report evaluates the model Waste Management Planning System (WAMPS), which is an LCA-based tool used to compare different waste management scenarios from an environmental perspective. The aim of the study was to find deficient areas in the model that needed to be updated or improved. The evaluation was conducted by comparing the structure of the model to the structure of similar models and by comparing the results calculated in WAMPS to corresponding values found in literature. The evaluation of the calculations considered the treatment systems: material recycling of aluminium, steel, plastic, glass, paper, incineration and composting. The only impact category that was assessed was Global Warming Potential.

The comparisons revealed that WAMPS agrees with literature on most aspects. The evaluation of the structure showed that the main deviations in WAMPS are that there is a lack of a detailed documentation of the calculations in the model, that it is not possible for the user to choose different types of energy that is used in the foreground system as opposed to the energy that is substituted in the background system, and that the model only accounts for the reject formed in the pre-treatment of material recycling. The latter aspect can however be altered by a user with admin access.

The evaluation of the calculations revealed deviations between WAMPS and literature regarding material recycling of steel, glass and composting. The comparison also showed that the calculations of the fractions that treated most of the waste should be quality assured, since a small deviation in these can render large impacts on the result. The conducted comparison however contains several uncertainties. European data was compared to values from WAMPS which is developed in Sweden, and only some aspects of WAMPS were considered for evaluation.

Due to the uncertainties in the result, the deviations found in this report should be further verified by a more detailed study. This study was also limited in its extensiveness which is why a more comprehensive study should be conducted where more fractions are included, other aspects studied, and additional literature sources are used.

Keywords
WAMPS, evaluation, waste management system, LCA, life cycle assessment

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Förord

Detta examensarbete är det avslutande momentet på civilingenjörsutbildningen Ekosystemteknik vid Lunds Tekniska Högskola. Arbetet har genomförts i samarbete med IVL Svenska Miljöinstitutet. Examinator har varit Pål Börjesson.

Jag vill tacka mina handledare på LTH, Per Svenningsson och Eva Leire, för mycket värdefull input och för intressanta diskussioner. Jag vill även tacka min handledare på IVL, Jurate Miliute-Plepiene, för att du lagt ner så mycket tid på att hjälpa mig i alla situationer och för att du haft ett så stort tålamod när jag har kört fast eller bara haft allmänna funderingar. Tack också till Åsa Stenmarck och Jan-Olov Sundqvist på IVL för värdefull input längs arbetets gång. Och tack till Pål Börjesson för att du hjälpt mig i mina funderingar om hur jag skulle strukturera arbetet.

Jag vill även rikta ett stort tack till alla på IVLs Malmökontor för fikastunder och trevliga samtal och för att ni gjort den här tiden så bra!

Lund 19 juni 2019

Jacob Magnusson

Table of contents

1 Introduction

1.1 Background

The overarching waste management regulations in the EU are defined in the waste directive (EU Directive 2008/98/EC). In the directive, a legally binding priority order is presented – the waste hierarchy – on how to achieve the best waste treatment, from an environmental perspective. The member states should initially strive to prevent the generation of waste, and subsequently prioritize the following waste treatment options in descending order: preparation for re-use, recycling, energy recovery and finally disposal (EU Directive 2008/98/EC). However, in addition to the waste hierarchy, member states are also required to:

> "…take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by *life-cycle thinking* on the overall impacts of the generation and management of such waste." (Article 4(2), (EU Directive 2008/98/EC)

The member states are thus not required to follow the hierarchy uncritically, but rather to use the hierarchy as a general principle and to seek the overall best environmental option. A growing practice has been to complement the waste hierarchy with the method of Life Cycle Assessment (LCA) (Laurent et al., 2014). Several specialized tools have been developed with the solitary purpose of conducting LCAs on waste management systems. Most of these have however been developed independently from each other and hence render different results (Gentil et al., 2010). One of these tools is the Waste Management Planning System (WAMPS), developed by IVL in the early 2000s. It was also developed in relative isolation and is thus in need of a quality check relative to available data and other models.

1.2 Aim

The aim of the study is to test and to evaluate WAMPS. This will be done to detect limitations in the model, to find differences between WAMPS and similar models or literature on waste-LCAs, and to be able to give recommendations on future developments and improvements of WAMPS.

1.3 Research questions

- How does the structure of WAMPS compare to similar tools and to literature on waste-LCAs?
    - What are the major differences in structure?
    - Which of these differences in structure are important to integrate into WAMPS?
- How does the calculations and the result in WAMPS compare to the result found in literature?
    - Which are the most significant differences?
    - How do these differences impact the result?
- How can the tool be improved?
    - Which aspects of the tool are most necessary to develop further?

1.4 Method

The evaluation of WAMPS will be performed in two parts to answer the first two main research questions – how the structure of WAMPS compares to other models, and how the results calculated by WAMPS compares to similar results found in literature. When these questions are answered, it will be possible to answer the last research question – how WAMPS can be improved.

The first part will be an evaluation of the structure of WAMPS. This will be conducted by comparing the structure and the assumptions in WAMPS to other models and to descriptions of what an LCA of waste management should include. The second part will be an examination of the calculations in WAMPS. This will be conducted by comparing the results of the calculations in WAMPS to results found in literature and in databases with similar system boundaries. By doing this it will be possible to evaluate the reliability of the result from WAMPS and to pinpoint calculations that needs to be improved. The result from these evaluations will subsequently be summarized and sorted after which aspects that are most necessary to develop further.

1.5 Limitations

The first part of the evaluation will only assess the structure and the technical assumptions made in WAMPS. The more detailed aspects, such as the underlying calculations and the source of the data that is used in the calculations, are not possible to evaluate because the documentation of how WAMPS was developed is lacking. The relative importance of the input parameters is also excluded from this study as this has been examined in previous studies for similar tools (Laurent et al., 2015).

The second part of the evaluation will assess the calculations and the result in WAMPS. Only the calculation of climate impact will be assessed. This indicator was chosen as it has been given much attention recently and it was assumed that the data on this indicator is robust. Similar assumptions have been made by Eriksson et al. (2015). In WAMPS, it is possible to calculate the impact of several waste categories. However, only the treatment methods material recycling of aluminium, steel, glass, plastic and paper along with incineration and composting will be included in the study. These treatment methods were included based on the criteria that the treatment methods should be conventional, i.e. they should exist in several countries, and that each system should treat a relatively homogenous waste stream. It was assumed that the data from these treatment systems would be more reliable and representative than waste streams which differs significantly in composition and treatment methods.

2 Theory

Included in this chapter:

Before conducting the evaluation of WAMPS, it is necessary with some background information of the tool and the context in which it operates. This context will be given in this chapter. The chapter includes a detailed description of the waste hierarchy and how LCA can complement the hierarchy, definition and description of LCA, how LCA can be applied to waste management, description of the special tools developed for this very cause and a description of the tool assessed in this study – WAMPS.

2.1 The waste hierarchy

The legislation of waste management in EU member states is fundamentally defined by EU directives. The most central directive regarding waste management is the waste directive (EC/2008/98/EG). It includes, among other things, the vital waste hierarchy which presents an order of priority for waste prevention and waste treatment methods (Avfall Sverige, 2018). According to the hierarchy, member states should initially strive to prevent the generation of waste, and subsequently prioritize the following waste treatment options in descending order: preparing for re-use, recycling, energy recovery and finally, disposal (EU Directive 2008/98/EC). A representation of the hierarchy can be seen in Figure 1.

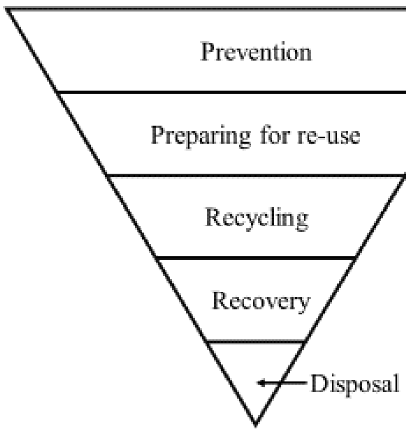

Figure 1. The waste hierarchy (European Commission, 2016).

Despite being legally binding, member states are still encouraged to evaluate the treatment options for different waste streams to make sure that the used treatment gives the best environmental outcome (EU Directive 2008/98/EC). Because, even if the waste hierarchy is a general guide for how to reach the best environmental outcome, it is not certain that the best treatment option can be located through the priority order of the hierarchy, as will be seen in the following section.

2.1.1 Examples of deviations from the waste hierarchy

What delivers the best waste treatment options from an environmental perspective is dependent on the treatment method and the waste composition. Prevention of waste is often the best option as resources are saved and environmental impacts from the waste treatment method do not arise. However, recycling could in some cases be compared to, or generate greater environmental impacts, than other options (for example landfilling or incineration) for certain waste fractions. The impact of the recycling is dependent on aspects such as the quality of the recycled products, what the recycled product can replace, the concentration of hazardous materials in the recycled product and the energy requirements for the recycling process. The environmental impacts from incineration are largely dependent on the energy content in the waste, how much of the energy that can be captured in the process and what the obtained energy replaces. Even landfill can in some cases render less emissions than other options. Take the case of inert material for example. The process of pre-treatment and recycling can have great impacts and the material it is able to replace may be of low quality (European Commission, 2009). These diversions from the waste hierarchy are also found in some cases in literature. In a review of 20 articles assessing the environmental impact of waste management systems, one article was found that did not recommend waste treatment according to the waste hierarchy (Cleary, 2009). Another study found that landfilling could become preferable to incineration if large transportation distances where needed to reach the incineration facility. The modelling of landfills was also found to be an important factor (Van Ewijk & Stegemann, 2016).

2.1.2 Life Cycle Thinking (LCT)

It is a complex process to find the best treatment option for waste from an environmental perspective. There are many variables to consider and there are many interconnections to consider that affect each other. One risk of assessing the environmental impact is to focus to narrowly and forgetting how the treatment options are connected and how they affect each other. One way of avoiding this, which is also encouraged by the waste directive EU Directive (2008/98/EC), is to utilize the conceptual approach of Life Cycle Thinking (LCT). LCT is a process in which one accounts for the impacts during a product system's whole life cycle – i.e. from the production phase until the disposal phase. In this way, it is possible to get a holistic perspective on the environmental impacts that the system not only causes during the usage phase, but also what impact it has caused in the production phase, and what impacts it will give rise to during the disposal phase. This gives a more truthful quantification and distribution of the environmental impacts between different systems. A risk of not using LCT when accounting for environmental impacts is to cause so-called "burden shifting", i.e. crediting environmental impact to other processes or systems (ISO 14040, 2006), (European Commission, 2009). LCT can be conducted in a structured way through the standardized method of Life Cycle Assessment (LCA). What LCA is and how it can be applied on waste management systems, will be elaborated in the following chapters.

2.2 Life Cycle Assessment (LCA) of a product

Life Cycle Assessment (LCA) is, as the name implies, a method of considering the environmental impact of the entire life cycle of a product[1]. The life cycle usually consists of the environmental impacts from the extraction of raw materials, refinement, production, usage, end of life treatment and finally disposal of the product. Usually, also secondary flows such as energy usage or transports are included. A common metaphorical description of this process is to analyze the impacts from the product, from "cradle" to "grave" (Dahlin, 2007). A simplified image of what an LCA generally includes can be seen in Figure 2. The impacts from the processes within the system boundary are assessed.

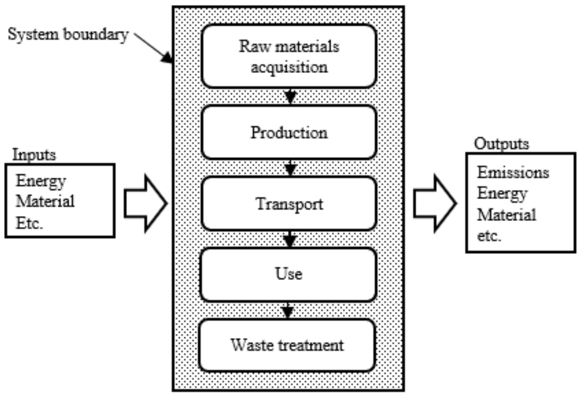

Figure 2. Example of what an LCA assesses. Based on ISO 14040 (2006).

2.2.1 LCA framework

The method of conducting an LCA has been standardized to regulate how the LCA should be conducted, communicated and interpreted. The standards can be found in the ISO standards ISO 14040 and 14044. ISO 14040 consists of the framework for LCA and ISO 14044 consists of requirements and guidelines in performing an LCA (ISO 14044, 2006), (ISO 14040, 2006). The ISO-standards however leaves the practitioner with several choices to be made which can jeopardize the quality and consistency of the LCA. To deal with this issue, The International Reference Life Cycle Data System (ILCD)-handbook was developed. The ILCD-handbook consists of a series of documents that provides guidance and support on how to conduct LCAs according to good practice (European Commision - Joint Research Centre, 2010), (ILCD Handbook, 2019). The guidelines in the handbook are scientifically based and it is considered sufficient to follow the handbook to conduct an LCA that satisfies the requirements of the ISO standards (Laurent et al., 2015).

2.2.2 Method of conducting an LCA

The procedure of conducting an LCA can be described in four main stages: Definition of goal and scope, inventory analysis, impact assessment and interpretation (ISO 14040, 2006), see Figure 3.

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[1] The term *product* is used regardless if the process generates a service, material or a complex product such as a facility (Erlandsson et al., 2014).

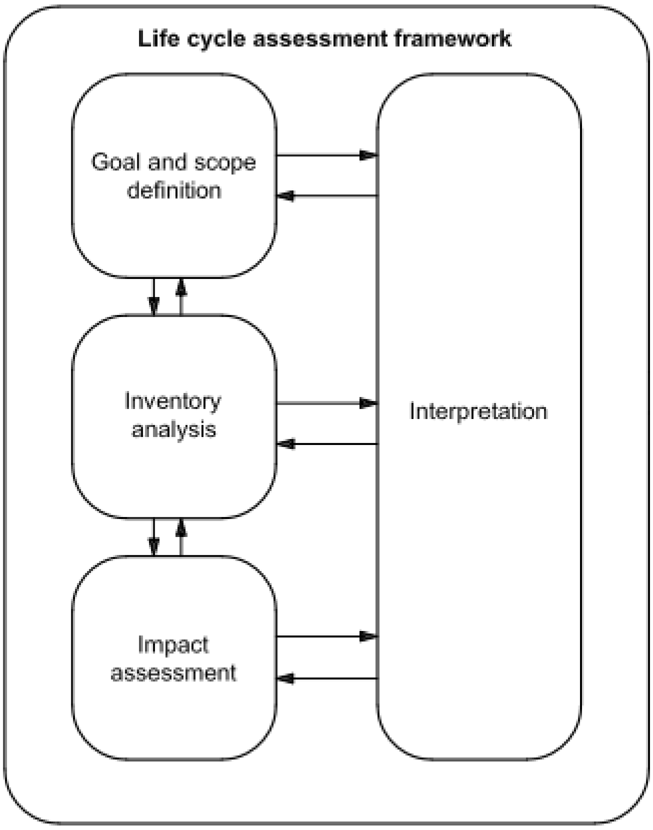


Figure 3. Stages of an LCA (ISO 14040, 2006).

A description of the stages along with important concepts are described in Table 1. The goal and the scope definitions are divided for clarity.

Table 1. Description of the stages in an LCA.

Stage	**Description**
Goal definition	The definition of the goal is the first process when conducting an LCA. It is important to have a clear goal both for the outcome of the study, but also to make sure that the result is not applied on areas outside the goal. The goal definition includes a definition of the intended usage, the limitations, the intended audience and if the LCA should be used for comparisons. Important aspects: • When defining the intended usage, the practitioner must define the *decision context*. That is, if the conducted LCA will form a basis for a decision, and if so, how much impact this decision will have. It could be that the decision effects a company, a region or the infrastructure of a whole country. The requirements on the study increases with the importance of the decision (European Commision - Joint Research Centre, 2010).

Scope definition	What to analyze and how to analyze it is defined in the scope. The scope sets the structure and the framework for the LCA. Important aspects: • There are two different modelling principles that handle the system perspective in different ways. *Attributional* modelling accounts for the direct impact from the life cycle. The other, broader, modelling principle is called *consequential* modelling, which considers the effects and possible changes that the analyzed system will have on other systems (Erlandsson, Ekvall, Lindfors, & Jelse, 2014). The modelling principle used in a study should be defined in the scope section. Which modelling principle to use is largely dependent on the *decision context*. If the assessed system will form the basis for a decision with large impacts/consequences for other systems, then the consequential modelling principle should be used, and vice versa (Laurent et al., 2015). • Definition of the *functional unit (FU)* - a quantification of the function that the analyzed system provides. A comparison between LCA studies should have the same FU in order to be comparable. • Definition of the *system boundary* – a boundary that defines which processes that should be included and assessed in the study. • Definition of *cut-off criteria* –Some processes that are deemed to not influence the result of the LCA significantly can be omitted from the study. How much of the environmental impact that is estimated to be excluded as a result of the cut-off is defined by the cut-off criteria. • Definition of *data requirements* – the sources and the type of data needed to meet the goal of the study should be defined. • Definition of the representativeness of the data – the data used to model the system should be representative regarding time, geography and technology. • Definition of *impact categories* – different emissions effect humans or the environment in different ways. What the study is assessing is defined by the impact categories. These can for example be climate change or acidification (European Commision - Joint Research Centre, 2010; European Commission, 2009).
Inventory analysis	The Inventory phase is usually where most of the work is done. Data is collected for all the emissions during the life cycle of the product and the product system including all the flows is modelled (European Commision - Joint Research Centre, 2010). Data is collected directly from the processes when it is possible to measure or find such data. In other cases, data from databases can be used (Hottenroth, Peters, Baumann, Viere, & Tietze, 2018).

	Important aspects: • One common issue when gathering data is *multifunctionality*, i.e. that one process can generate many products or services. Usually, the LCA is only focused on one of the products. It thus becomes an issue on how to distribute the impacts between the generated products. Practitioners are encouraged to solve this by either *system expansion* or *allocation* (European Commision - Joint Research Centre, 2010). How these methods are applied will be explained in the following chapter.
Impact assessment	The impact assessment phase is aimed at understanding and quantifying the environmental impact of the studied system (ISO 14040, 2006). First, the data from the inventory analysis is categorized under the impact categories that have been defined in the scope definition. This process is called *classification*. The inventory result is then multiplied with impact factors to assign a common unit to all the emissions within each impact category. This process is called *characterization*. For example, the common unit for the impact category climate change is usually CO_2-equivalents. All emissions related to climate change from the inventory analysis are thus calculated to CO_2-equivalents (Hottenroth et al., 2018; European Commision - Joint Research Centre, 2010).
Interpretation	The interpretation phase serves two purposes. During the performance of the study, the interpretation phase works in an iterative manner to improve the study and the inventory analysis in order to meet the stated goals of the study. When the study is finished and a result is acquired, the interpretation phase serves as the stage where the results are discussed, conclusions are obtained and where recommendations usually are given (European Commision - Joint Research Centre, 2010).

As stated in the interpretation stage, the process of conducting an LCA is an iterative process. This means that the stages are interlinked and can thus not be conducted completely independent from each other. The practitioner is recommended to move between the stages and complement calculations or re-define boundaries during the process (ISO 14040, 2006).

2.3 LCA applied to waste management systems

There are many connections between an LCA of a product and an LCA that assesses waste only. Waste is considered part of the life cycle of a product and should thus be included in the study of a product. Both the waste that is generated in the production phase, including the waste generated in the extraction of raw materials and during the refinement-phase, and the waste that is generated during the end-of-life treatment, after the product has been disposed or recycled, should be included in an LCA of a product (European Commision - Joint Research Centre, 2010). Assessing the environmental impact of waste solely however requires a range of adaptations (Laurent et al., 2015). Some critical aspects to consider are the difference in the life-cycle perspective (i.e. defining the life cycle of waste), how to account for secondary functions such as heat or electricity generation (J. Sundqvist, 2009) and how to assess emissions that occur over long periods of time (Laurent et al., 2015). These aspects will be further examined in the following sections.

LCA-methodology can be applied to waste management systems for various reasons. For example, to calculate the environmental benefits of better source separation or to quantify the environmental impacts of new policies. One common reason is to compare different waste management options and to help decision makers implement waste management systems with low environmental impact (Moora, Stenmarck, & Sundqvist, 2009).

2.3.1 System boundary of waste management

A product is generally regarded as waste when it is disposed of. The waste does hence not have a production phase in the common sense. Instead, when conducting an LCA on waste, the cradle becomes the point when the waste is generated. It is common in the context of waste-LCAs to use a “zero burden”-approach, i.e. to not include any environmental impacts from the product’s lifecycle until it becomes waste. The system boundary for when to no longer include the environmental impacts from waste, i.e. the “grave” of the studied system however varies between studies. Some studies trace the impacts of the waste until it is recycled and included in a new product, some studies define the system boundary right after the treatment of the waste is finished. Common activities that are included in most Life Cycle Assessments of waste are: collection, transport, pre-treatment, treatment, and landfilling of the treatment residue (Gentil et al., 2010). See Figure 4 for an example of what can be included in an LCA on waste management. The generation of waste is excluded from the system boundary.

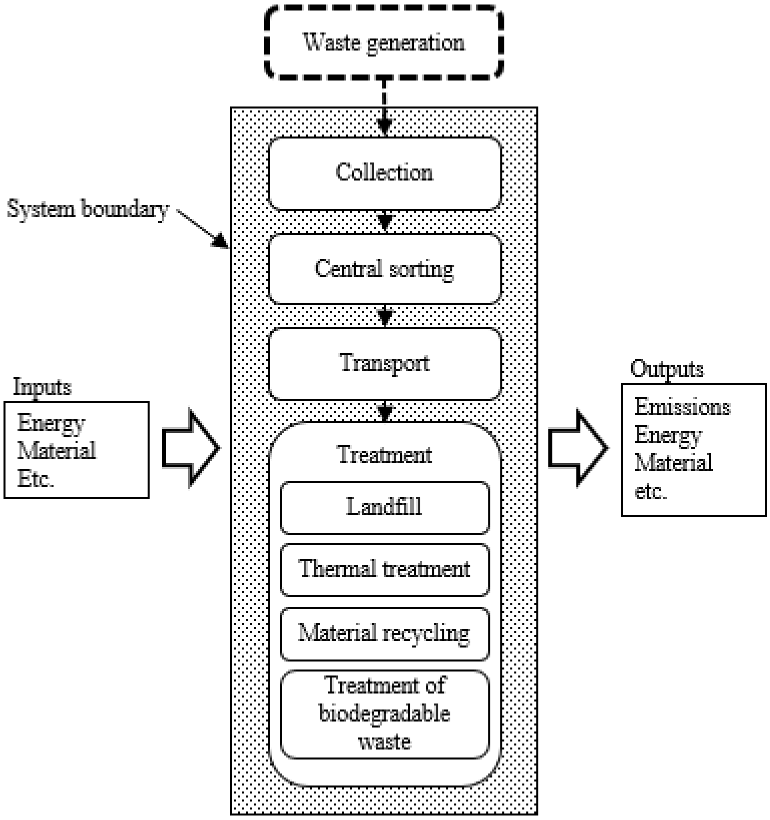


Figure 4. Example of what an LCA on waste assesses. Based on ISO 14040 (2006) and Gentil et al. (2010).

2.3.2 Alternatives for accounting for co-products

Another issue with the assessment of waste is how to account for the environmental impacts when the studied system generates useful services or materials. For example, the primary function of a waste management system is to provide treatment of waste. In the process, there are however other co-products generated, such as material or energy. These co-products can totally, or in part, substitute material or energy produced in other systems (e.g. virgin production). How to treat these co-products in an LCA is largely dependent on the *decision context* which decides the modeling principles, either *attributional* or *consequential* modelling can be used, depending on if the interactions with other systems should be included or excluded from the study. Purely *attributional* modelling does not include interactions with other systems. In this case, how the generated co-products impact other systems are not assessed. Purely *consequential* modelling however accounts for interactions and impacts on other systems (Erlandsson et al., 2014). In some LCAs, a combination of the modelling principles can be used (European Commission, 2009). See Figure 5 for an explanation of the differences between the modelling aspects. Even if the consequential modeling aspect should consider impacts on other systems it can depend from LCA to LCA which impacts on other systems that are included (Erlandsson et al., 2014).

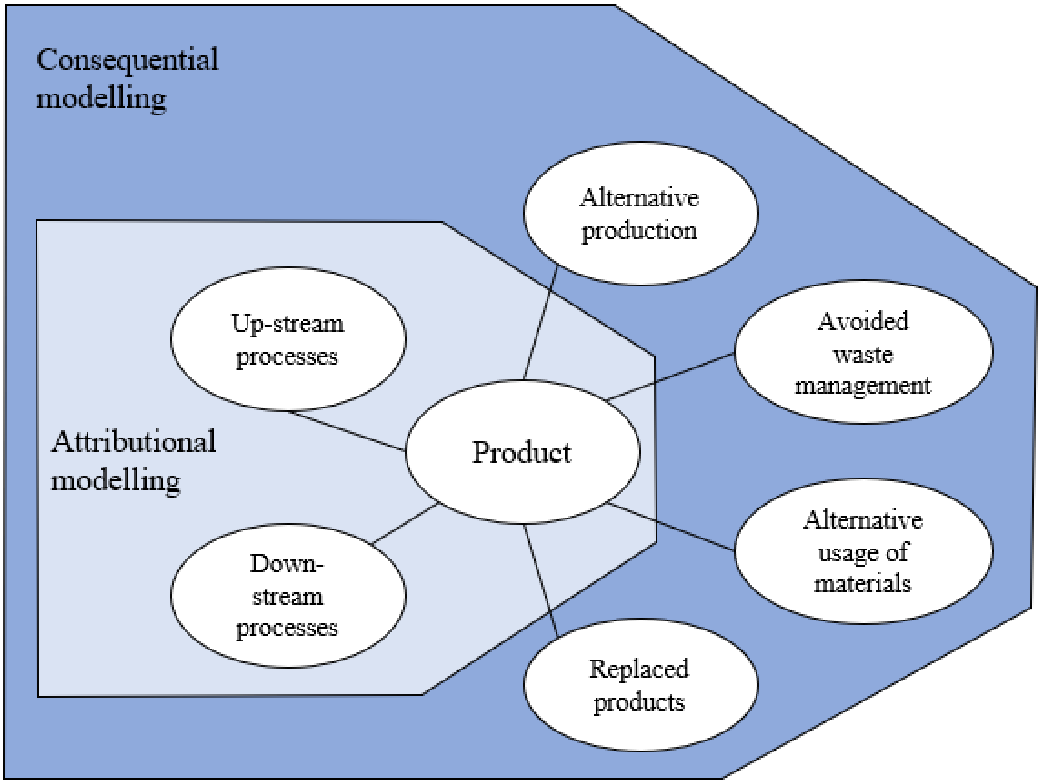


Figure 5. Simplified description of the different modelling approaches. Based on Bisaillon (2017).

If impacts on other systems are excluded (attributional modeling), then the impacts from the co-products can be accounted for by *allocation*. If impacts from other systems are included (consequential modeling), then impacts from co-products can be accounted for by *system expansion*. By *system expansion*, the system boundary is expanded to include also the co-functions/products that are produced by the system. In the case of waste management, this could mean to include also the electricity and heat produced in the incineration within the system boundary. The environmental impact of alternative means of production are then subtracted from the expanded system. This could for example be the generation of electricity from coal or wind power. By subtracting the alternative production from the studied system, it is possible to account for the avoided impacts caused by the co-products, and to acquire a quantification of the environmental impact of the primary function of the system (European Commision - Joint Research Centre, 2010). See Figure 6 for a visual explanation of the process of system expansion by substitution.

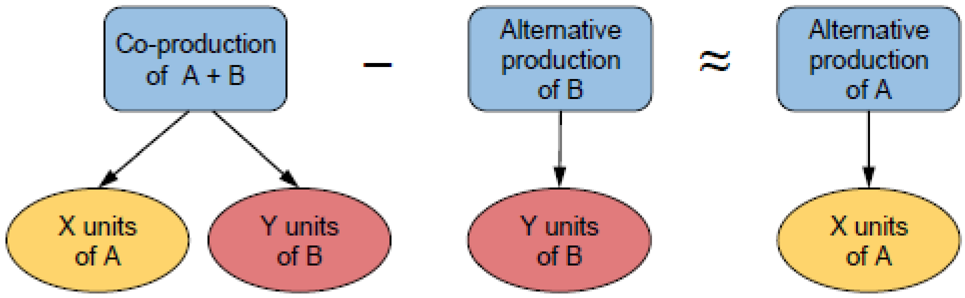


Figure 6. A visual depiction of how multifunctionality of a process is solved by system expansion by substitution (European Commision - Joint Research Centre, 2010).

Allocation, the second alternative, is a method of dividing and attributing the environmental impacts from the studied system to the co-products. This is done by some allocation criteria – often a physical relationship between the products. For example, splitting the environmental impact based on mass or energy content of the co-products (European Commision - Joint Research Centre, 2010).

2.3.3 How system expansion is used in waste-LCA

In the case of waste management, the co-products generated from the waste management system can replace products from other systems (such as heat, electricity or materials). The co-products can thus result in avoided emissions in other systems, which should be attributed to the waste management system. Most LCAs on waste management include this attribution and account for co-products through the method of system expansion (Laurent et al., 2015). In the case of waste management, system expansion can be conducted by dividing the system into a *foreground* and a *background* system where products produced in the foreground system can substitute products of similar function in the background system (European Commission, 2009). The concept of a foreground and a background system can be seen in Figure 7.

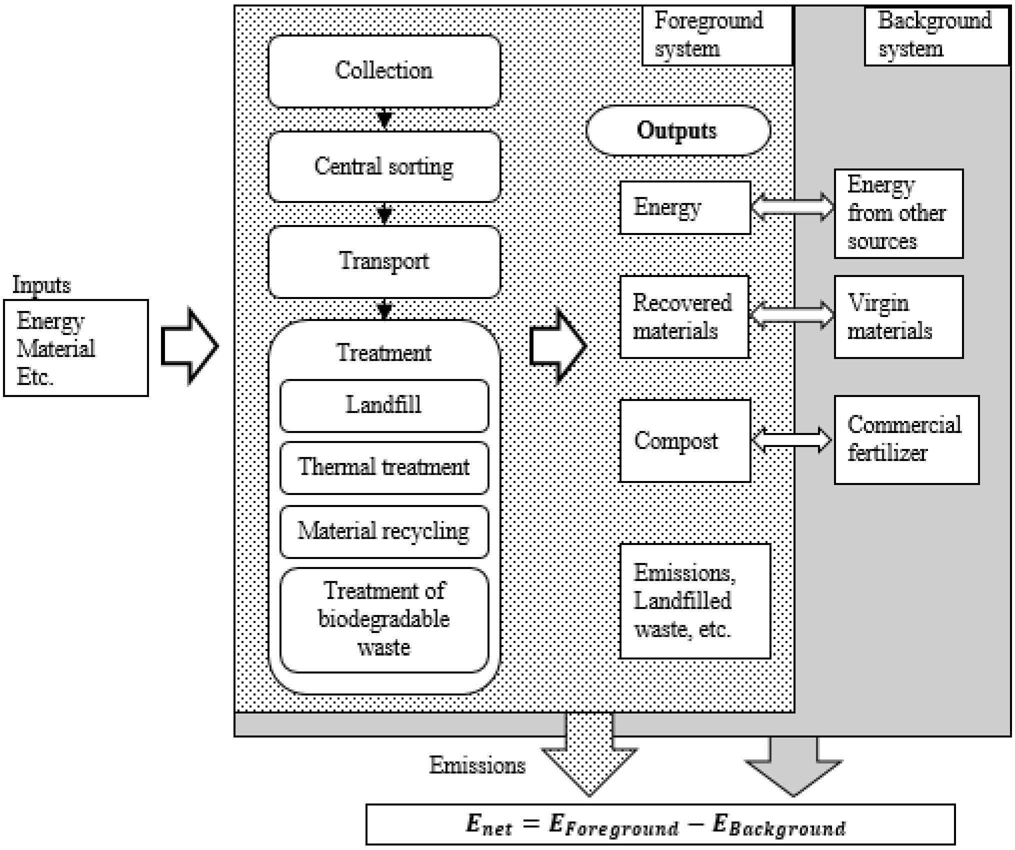


Figure 7. System expansion of a waste management system where a background system has been introduced. Based on Miliute J. & Staniškis J.K. (2010).

The foreground system is composed by the processes and the outputs from the waste management system. In the background system, products with similar functions are produced. By using system expansion to account for the saved emissions (due to substitution), the net emissions from the waste management system can be calculated as:

$$E_{net} = E_{foreground} - E_{background} \tag{1}$$

Where E_{net} are the emissions from the waste management system (including avoided emissions), $E_{foreground}$ emissions from the foreground system (the waste management system) and $E_{background}$ the emissions from the background system (production of equivalent products outside the waste management system).

A negative E_{net} means that the recycling/treatment of waste will generate lower emissions than the corresponding production in the background system, i.e. a net saving of emissions. For example, if aluminium is recycled, it is assumed that the recycled aluminium can substitute, and thus avoid, virgin production of aluminium. The recycling activity should thus be credited with the avoided production. If the emissions from the virgin production are greater than the emissions caused by the recycling, then the net emissions (E_{net}) will be negative, i.e. the recycling activity caused a net saving of emissions. The emissions are later *classified* into the appropriate impact categories and *characterized* to assign a common unit to all the emissions within each impact category.

2.3.4 What to substitute in the background system

It is assumed that the products from the foreground system substitute the production of some of the products in the background system. The products to substitute needs to be of equal quality and have similar functions, compared to the products in the foreground system (European Commission, 2009). It is however not always clear what products in the background system to substitute. These aspects will be further elaborated for some different treatment methods in this section.

Recovered material – open- or closed-loop recycling

Several questions arise when accounting for recycled materials, such as which materials that are substituted (and avoided) in the background system, how much material that is saved and how the product in the background system is produced. These aspects are accounted for in different ways in different LCAs. A key concept that influences the choice of material to substitute is the modeling of the recycling system, i.e. if the recycling can be regarded as *closed-* or *open-loop recycling*. Closed loop is the simplest way of recycling. The secondary material is recycled back into the same system and directly substitute material in the primary production (European Commission, 2009). For example, when a clean stream of scrap from an aluminium extrusion process is recirculated back into the production process. European Commision - Joint Research Centre (2010) states that closed-loop recycling can also be recycling where the recycled material is used in another system, as long as the functional unit is the same. An aluminium can that is recycled and produced in another system to a new aluminium can, can thus be regarded as a closed-loop recycling. In the case of closed-loop recycling, the recycled material is assumed to substitute a product of the same quality and with the same function in the background system. Figure 8 gives a visual representation of closed-loop recycling.

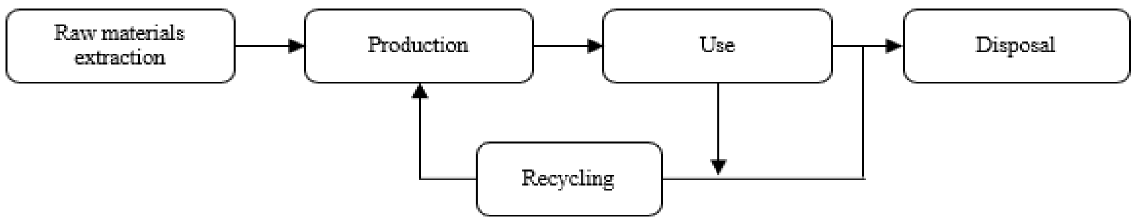


Figure 8. Closed-loop recycling. The recycled material is recycled back into the same process, or to another system where the product will have the same function. Based on European Commision - Joint Research Centre (2010).

Open-loop recycling on the other hand is the more complex option, but which is used in most waste management systems (European Commission, 2009). What defines if it is an open-loop recycling or not is whether the recycled product has the same function as the product prior to recycling (European Commision - Joint Research Centre, 2010). In some cases of open-loop recycling, the recycled material delivers a completely different function than prior to recycling. Plastic containers can for example be recycled into furniture that substitute furniture produced by wood. The case is similar for composting and anaerobic digestion where organic waste is transformed into compost and digestate which can replace fertilizers. It is therefore important to examine the function of the recycled material and choose a material or product in the background system which delivers the same function (European Commission, 2009). Figure 9 gives a visual representation of open-loop recycling.

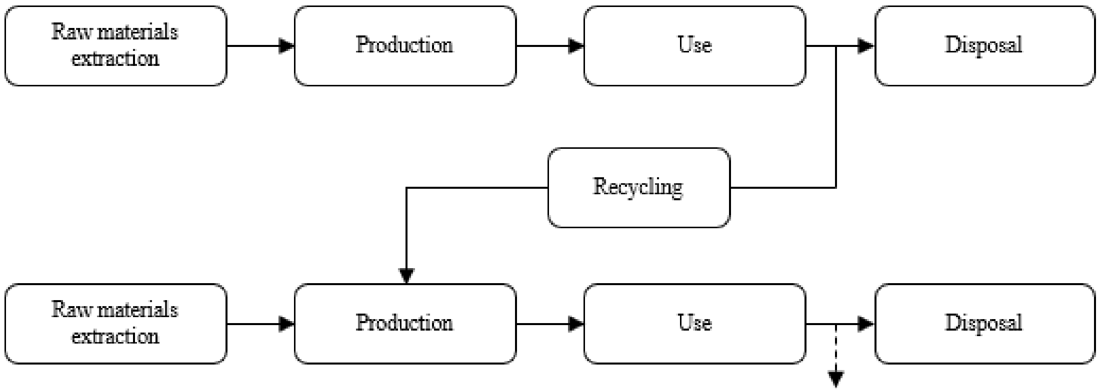


Figure 9. Open-loop recycling. The recycled material is used in another system that produces a product with a different function than the product of the first system. Based on European Commision - Joint Research Centre (2010).

Important aspects to consider when accounting for the substitution are how much of the incoming waste that is actually recycled material and how much of the recycled material that is able to substitute avoided material. In some cases, it is also necessary to check market availability to see if there is a demand for the recycled material. Without a market demand it is not possible to assume substitution (European Commision - Joint Research Centre, 2010).

Recovered energy – average or marginal production

The waste management system can produce different kinds of energy such as electricity and heat from the thermal treatment and fuel, heat or electricity from biogas. The choice of which type of energy (and specifically electricity) to substitute in the background system is of importance (Gentil et al., 2010). Another important aspect to consider is the production method of the substituted energy. There are generally two alternatives, either to substitute average production, or to substitute marginal production. The choice of marginal or average production is dependent on the decision context of the study. If there are large consequences from the decision to be taken from the LCA, then it is not sure that the market (i.e. the background system) can absorb the changes. If this is not the case, then marginal production must be used. Marginal production is the production that is assumed to be affected by a small change in production volume (Erlandsson et al., 2014). This modelling can be used for all kinds of produced goods or energy, but it is usually applied to energy production as the marginal production can render large consequences. For example, the average electricity mix in Sweden is produced by hydropower and nuclear power which have relatively low environmental impacts. The marginal production is however the production that cannot be absorbed by the market. In this case, electricity has to be imported or produced by other means. The marginal electricity production in Sweden could previously be assumed to be coal power from Denmark that had to be imported (Erlandsson et al., 2014). Whether marginal or average energy mix is chosen will thus have a big impact on the result.

2.3.5 Time aspects of landfilling

Another aspect that is special for LCAs on waste management compared to LCAs on products is how to model landfills. Most emissions from waste treatment are immediate. Leachate and other emissions from landfills will however continue for a very long time – hundreds of thousands of years or even millions of years in the future. One important issue is how to handle these emissions in the case of LCA studies. Studies on waste management have handled this issue in different ways. Some consider emissions in the foreseeable future (e.g. 100-years) while some account for the emissions that will occur in a near-infinite time period. The emissions from each of these time intervals will be integrated to get the total emissions during that time. A key difference is that emissions from metals will be low during the foreseeable future, but high during the near-infinite time period (J. Sundqvist, 2009). A lack of consensus on how to assess the landfill emissions have led to various combinations of the two alternatives in LCAs on waste management (Laurent et al., 2015). Modelling of landfill is concluded to be one of the aspects that influence comparability between LCAs on waste (Gentil et al., 2010).

2.3.6 LCA-tools and waste management systems

Several LCAs conducted on waste management utilizes LCA-tools to facilitate and structure the calculations (Blengini, 2008; Marques, Ferreira, Simões, Cabral, & da Cruz, 2014; Merrild, Damgaard, & Christensen, 2008). Two general types of LCA-tools exist:

- *Generic* LCA softwares which can be applied to different areas, but which requires the practitioner to adapt the software and to create the system which to analyze for each case. These tools can be used to conduct detailed LCAs, but they often require a comprehensive understanding of LCA-methodology. Some examples are SimaPro, GaBi and Umberto (Kulczycka, Lelek, Lewandowska, & Zarebska, 2015).
- *Specialized* LCA softwares are developed to assess the environmental impacts in a specific sector and they usually only require the practitioner to enter a limited amount of data. Specialized tools are often easier to use and usually do not require LCA expertise. Another advantage is that a specialized tool can provide better tracking of the flows, the materials and the emissions from and within the studied system (Laurent et al., 2015). The tradeoff of the simplicity is however less customizable options in the tool. Some examples of specialized LCA tools on waste management are EASETECH, MSW-DST, LCA-IWM, ORWARE and WAMPS (Gentil et al., 2010).

The option to use specialized LCA-tools are often dependent on the decision context of the LCA. Specialized tools can often be used to conduct simplified LCAs, that include the most important parts of an LCA, but that does not fully comply with the ISO-standards (Hochschorner & Finnveden, 2003). A simplified LCA is sufficient if the decision connected to an LCA is *not* linked to "high costs, high political relevance, need for infrastructures, create fixing technologies for a long time" (European Commission, 2009), i.e. when the decision context is not linked to decisions of great impact. A simpler LCA can in some cases be advantageous compared to a detailed LCA with regards to the amount of time and resources it requires to conduct the study. The following chapters will elaborate on one of these specialized tools that will later be evaluated – the Waste Management Planning System (WAMPS).

2.4 Waste Management Planning System (WAMPS)

The Waste Management Planning System (WAMPS) is an excel-based LCA-tool specifically developed to support planning and decision-making in the context of waste management (IVL Swedish Environmental Research, n.d.). The tool was developed from ORWARE, which is also an LCA-based tool to assess waste management. In the beginning of the 2000s, ORWARE was complicated to use, and the calculations were not deemed accurate. WAMPS was developed to improve the calculations and to make the interface easier to use (J. Sundqvist et al., 2002). From the time of development, WAMPS has been used to assess the waste management in Chile, the Baltic States and in Norway (J. Sundqvist, 2007).

WAMPS is simpler to use compared to many other specialized tools. Several parameters have been weighted together and data is used from conventional technologies, which requires less input from the user. The tradeoff is however that WAMPS becomes less flexible. In ORWARE for example, more input is needed which gives the user the possibility to customize scenarios and flows to a greater extent (J. Sundqvist, 2007). Other, more flexible tools are for example EASETECH and IWM (Miliute & Kazimieras Staniškis, 2010). WAMPS is however customizable to some extent. In the base case, WAMPS only considers Municipal Solid Waste but it is possible to extend the tool to also include other waste categories (Sundqvist, Palm, & Ekvall, 2010). It is also possible to enter specific data if some of the generic data is too general (Sundqvist, 2007). The intention of WAMPS is however not to reflect the exact environmental impact of one special case, but rather to be a “simple and reliable screening tool for local decision-makers” (Miliute & Kazimieras Staniškis, 2010), which reduces the need to be highly customizable.

2.4.1 Structure of WAMPS

WAMPS is primarily used to compare different waste management options and to help decision makers implement waste management systems with low environmental impact (Moora et al., 2009). When comparing different waste treatment scenarios usually one scenario is considered a base case. The base case could be the current situation, or a reference scenario. Additional scenarios that are being assessed are described and included in the model. By comparing the scenarios, it is possible to find which of the scenarios that gives the least environmental impact, and to make sure that the environmental impact does not succeed the base scenario (IVL Swedish Environmental Research, n.d.). Each scenario has the possibility to include the impacts from the collection, transport and treatment of the waste. The included waste treatment options are material recycling, composting, anaerobic digestion, incineration and landfilling. A more thorough description of the structure of WAMPS will be given in this chapter.

WAMPS is composed by six main steps which have their own tab in excel. In each stage, data is entered, or results are presented. The six stages are:

1. Total waste composition
2. Source separation
3. Configuration of treatment systems
4. Collection
5. Transports
6. Results

There are also other, hidden tabs where the calculations are conducted. These tabs can be accessed and altered with a password. The following section of the chapter will give a description of the main tabs in WAMPS.

1. Total waste composition

The first step is to enter the total waste composition. This refers to the total waste, not the sorted parts. The *actual* composition (in percent) should be entered based on waste composition studies or estimations. The total amount (tons) of waste generated in the region is also entered.

2. Source separation

The second step is to enter how much of each fraction is separated from the waste. The fractions are limited to the fractions that are, or could be, separated for recycling or composting/anaerobic digestion. For example – If 10% of the total waste is paper packaging and if 70% of the paper is sorted out for recycling, then 70% should be entered in this step (10% should be entered in the previous step). The waste that is not sorted out is assumed to be residual waste. The residual waste is either incinerated or landfilled. The figure below gives a visual representation of step 1 and 2.

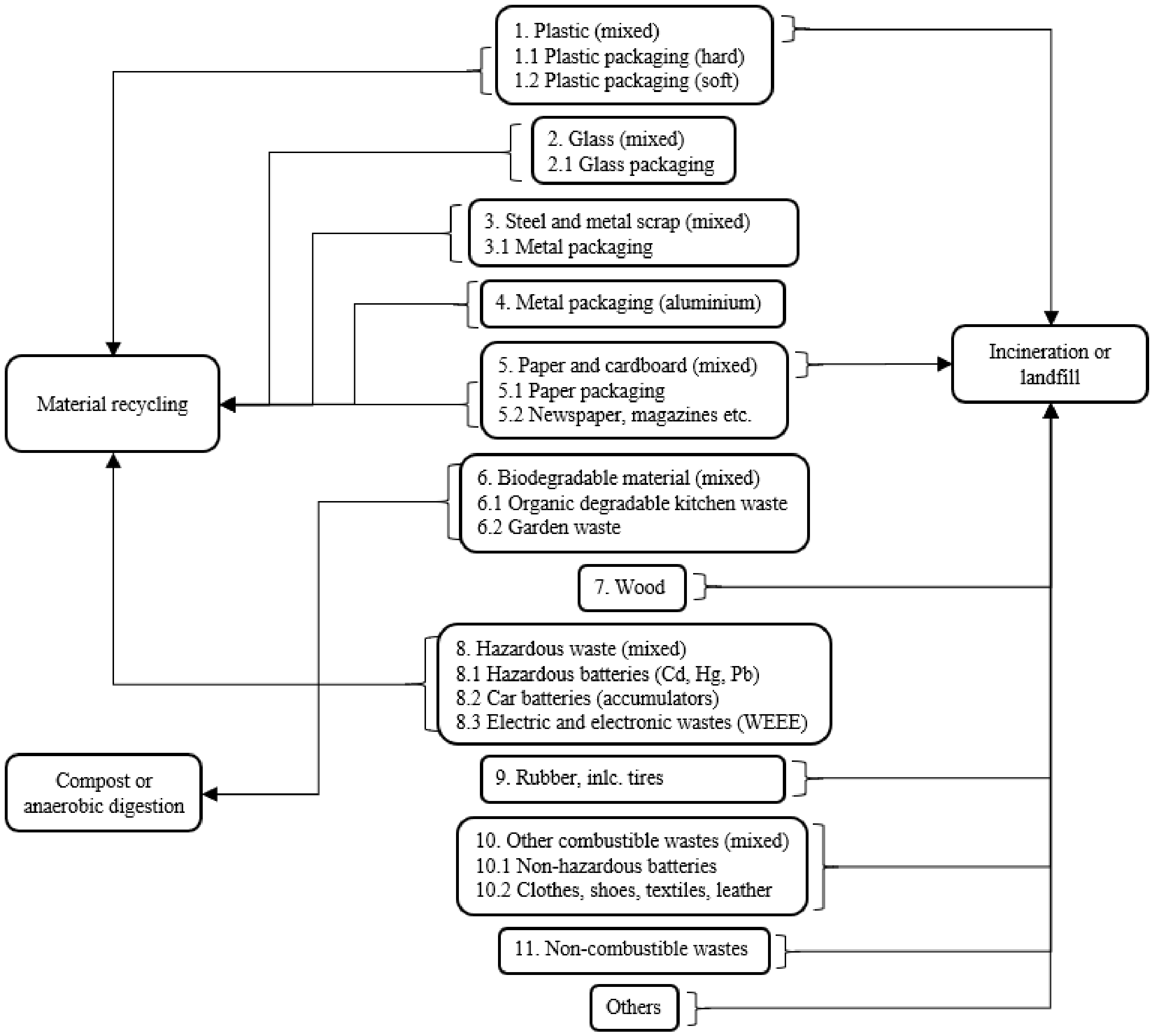


Figure 10. In WAMPS it is possible to divide the waste in the fractions showed in the image. The related treatment method is also shown.

Figure 10 depicts the waste fractions included in the model. Each of the waste fractions is calculated in a separate module. The difference between the categories for each section (1., 1.1, 1.2…) is that different categories can be used depending on the "resolution" of the waste composition studies. For example – if the composition between hard and soft plastic packaging (1.1 and 1.2) is known from the composition studies, then these categories should be used. If the waste composition studies do not include a differentiation between soft and hard packages, then the more general category, Plastic (mixed) (1.), should be used. The last fraction, Others, balance the composition so that the total amount always adds up to 100%. All the waste that is not separated for specific treatment, i.e. material recycling or composting/anaerobic digestion, is assumed to be landfilled or incinerated.

3. Configuration of treatment system

The third step is to determine the share of the waste that is being treated by compost/anaerobic digestion and by incineration/landfill respectively. This step is also where the treatment methods are configured to resemble the real, analyzed case.

Composting/anaerobic digestion

The treatment of degradable waste is divided into either treatment through composting or anaerobic digestion. The user can determine the share of the degradable waste that will be treated with either method. The composting model gives four composting alternatives which are described in the table below.

Table 2. Description of the included composting methods in WAMPS.

Composting method	**Description**
Home composting	Composting that is done at home in gardens and is operated by hand.
Windrow composting	Composting in windrows that is stirred and mixed weekly or bi-weekly.
Closed composting	There are several concepts for closed composting. The common denominator is that the composting process occurs in a closed volume and that off-gases are collected and cleaned.
Reactor composting	A form of closed composting where the compost is continually stirred. This speed up the process. Off-gases are collected.

The anaerobic digestion model does not give any treatment options. The digestion includes production and use of biogas and production of digestate. The usage of the biogas is entered – either for heat/energy production or upgraded and used as vehicle fuel. It is assumed that the produced compost and digestate substitute mineral fertilizer in the background system (more specifically, Nitrogen- and Phosphorus-fertilizer).

Landfill/incineration

The treatment/disposal of residual waste is either landfilled or incinerated. The user can determine the share of the residual waste that will be treated with either method. The landfill-model gives three alternatives of landfilling which are described in the table below.

Table 3. Description of the included landfilling methods in WAMPS.

Landfilling method	**Description**
(Sanitary) landfilling	A landfill that includes collection of landfill gas.
Biocell	Landfill is conducted in biocells and the gas recovery exceeds that of the sanitary landfill.
Dumping	The model does not include any gas collection or leachate treatment.

It is assumed that the collected gas from the sanitary landfill and the biocell can be used for district heating or for electricity production. The user is given the choice to determine how much of the landfill gas that is recovered, and how much of the gas that is used for district heating and for electricity production respectively. The model accounts for the emissions to air and water from the landfill over a 100-year period. It is assumed that energy is recovered in the incineration process and that heat and electricity is generated and distributed. The user is given the option determine how much of the recovered energy that is produced to heat and electricity respectively. And how much of the energy in the waste that is lost in the incineration process. The model accounts for landfilling of the fly and the bottom ash and for the energy used internally in the incineration process.

It is assumed in the model that the energy in the from the treatment processes will substitute energy in a background system. The user is given the option to choose how the replaced energy has been produced. For replaced electricity, the user can choose to substitute electricity generated from biofuels, hydropower, wind power, nuclear power, oil, natural gas, coal or oil shale. It is also possible to choose electricity that is a country mix of the following countries: Estonia, Latvia, Lithuania, Sweden or Poland. For replaced district heating, the user can choose between heat generated from oil, biofuels or natural gas. It is not possible to choose which vehicle fuel that the upgraded biogas substitutes.

Material recycling

The modules for material recycling include separation of the waste, transport and preparation for recycling, recycling activities and processing of the recycled material into a usable product. WAMPS lacks thorough information on what is included in each module, it has therefore been difficult to know how much of the production phase of the recycled material that is included in the calculations. After contact with one of the developers of WAMPS[2] it has however been possible to acquire information on some of the fractions: Glass is recycled to a new glass container, paper is recycled to new paper, metals are recycled into billets or ingots that are subsequently processed into sheets or other shapes. Plastic is recycled into granulate. The modules for material recycling account for the energy consumed in the processes and for emissions released to air and water.

4 & 5. Collection and transports

The fourth and the fifth step contains information about how the waste is collected (collection from households) and transported (longer transports – for example to a recycling facility). In the collection model, the user defines the number of collection points, average distance between stops, average velocity during collection, average time per stop, number of collections (per household and year), distance to waste plant, average transport velocity, manning per truck, type of truck, average load, amount of waste during a year. The parameters can be varied for all the different fractions. The parameters can also be divided further into collection from apartment complexes, houses and rural areas. In the transport model, the user defines average

[2] Jan-Olov Sundqvist, IVL Swedish Environmental Research Institute.

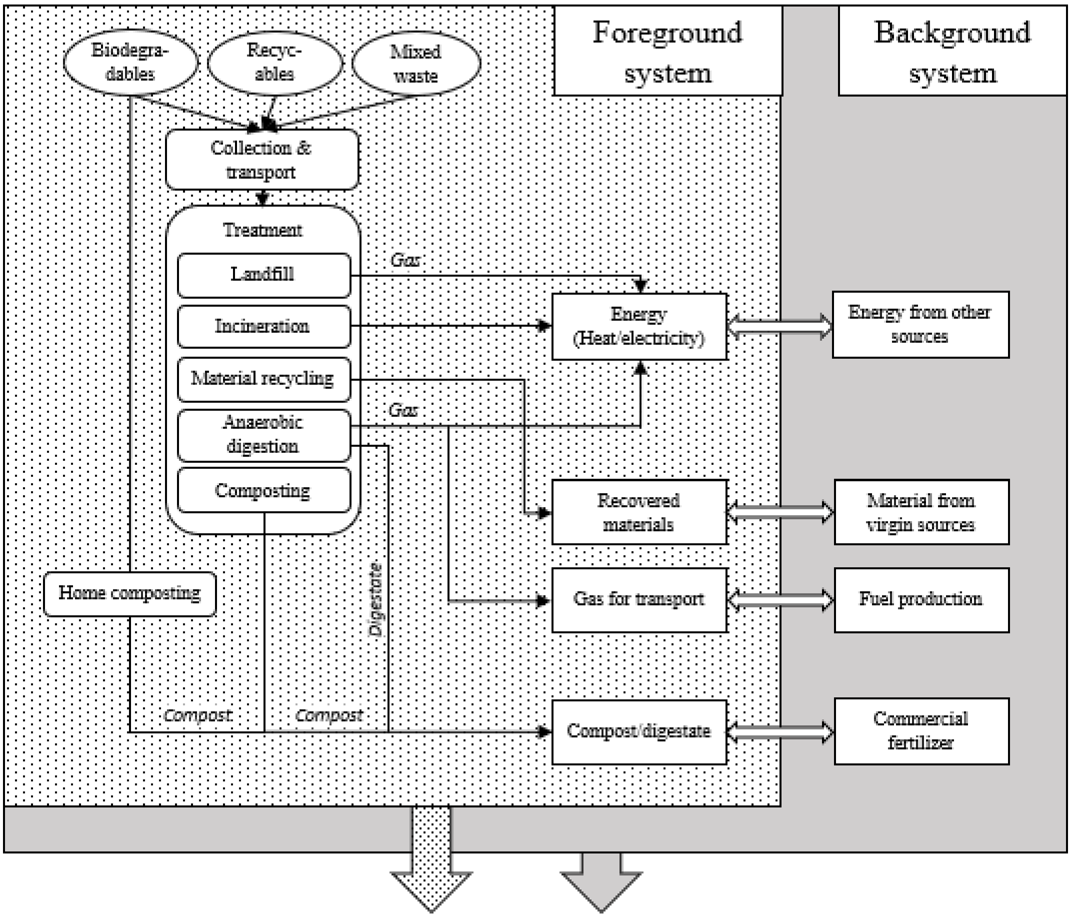
distance to treatment facility, average load, and if the vehicle returns full or empty. Both the collection and the transportation model are limited to diesel-driven vehicles.

6. Results

The sixth step presents the results from the calculations. The result is presented in charts where it is possible to see the total impact from each scenario. It is also possible to see more detailed information about the impact from each fraction/treatment method.

2.4.2 Calculations in WAMPS

WAMPS uses system expansion where a foreground and a background system have been introduced. A visual depiction of how WAMPS calculates net emissions, i.e. the emissions from the waste management system where the avoided emissions have been accounted for, can be seen in Figure 11.



$$E_{net} = E_{Foreground} - E_{Background}$$

Figure 11. System expansion of the waste management in WAMPS where the background system has been introduced. Based on Miliute J. & Staniškis J.K. (2010).

The foreground system is the waste management system modeled in WAMPS. From the foreground system, energy (heat and electricity), materials, biogas and compost and digestate are produced from the waste management system. In the background system, similar products are produced from other sources (which are defined by the user). The net emissions from the modeled system in WAMPS are calculated as:

$$E_{net} = E_{foreground} - E_{background} \tag{1}$$

Where E_{net} are the emissions from the waste management system (including avoided emissions), $E_{foreground}$ emissions from the foreground system (the waste management system) and $E_{background}$ the emissions from the background system (production of equivalent products outside the waste management system).

WAMPS first calculates the emissions from each activity/module. The emissions considered are for example, fossil CO_2, biogenic CO_2, HCl, NO_x, NH_3, BOD etc. Then, in the classification phase, the emissions impacting the same impact category are aggregated. The impact categories used in WAMPS are global warming, acidification, eutrophication, photo-oxidant formation. In the next phase, the characterization, the emissions in each impact category are calculated to a common unit through characterization factors. Global warming-emissions are calculated to carbon dioxide equivalents (the characterization method used is called IPCC 1998), the emissions contribution to acidification are calculated to sulfur dioxide equivalents, emissions contributing to eutrophication are calculated to oxygen gas equivalents and emissions linked to photo-oxidant formation are calculated to ethylene-equivalents. This gives a quantitative measurement of the studied environmental impact categories (J. Sundqvist, 2009, 2007).

2.4.3 Assumptions and limitations in WAMPS

WAMPS generally account for separation of the waste (in sorting facilities), transport and preparation for treatment and emissions connected to the treatment (and energy used in the treatment process). Also additional emissions are accounted for, depending on the treated waste, such as treatment of reject/residues. WAMPS however excludes impact from ancillary materials used in the treatment processes, infrastructure, maintenance and production of the machines used in the treatment process. WAMPS uses a zero-burden approach, i.e. no burdens are included from the upstream processes. WAMPS is developed in Sweden and the models and processes are built on data from actual waste treatment facilities in Sweden. The processes can be regarded as the average recycling system in Sweden[3] at the time of the development of WAMPS, i.e. in the beginning of the 2000s. And WAMPS only accounts for some emissions for each impact category. For global warming potential, WAMPS accounts for CO_2, CH_4 and N_2O-emissions.

[3] Jan-Olov Sundqvist, IVL Swedish Environmental Research Institute. Phone call - 8 May 2019.

3 Evaluation of WAMPS

Included in this chapter:
In this chapter, WAMPS will be evaluated. The evaluation will be conducted in two parts. The *first part* will be an evaluation of the structure of WAMPS. This will be done by comparing the structure and the assumptions in WAMPS with other models and to descriptions of what an LCA of waste management should include. The *second part* will be an evaluation of the calculations in WAMPS. This will be conducted by comparing the results of the calculations in WAMPS to results found in literature and in databases. The result from these evaluations will subsequently be summarized and sorted after which aspects that are most necessary to develop further.

Waste management LCA-tools like WAMPS have been developed to make it easier to calculate and compare different waste treatment options from an environmental perspective. It has however been found in literature that the reliability of similar tools is lacking. Winkler & Bilitewski (2007) compared waste-LCA models and found high variations between the models. Some of the models even contradicted each other regarding which treatment option that was the most beneficial. Kulczycka et al. (2015) concluded that even if the same data, similar assumptions, the same system boundaries and the same characterization factors where used, it was not certain that the models would generate similar results. Gentil et al. (2010) stated that a lack of conformity check with other tools and with documents describing the state of the art for waste management tools, it is possible that the tool produces results that do not give the overall best environmental alternative. WAMPS has not been included in any of these assessment and it is therefore necessary to conduct an evaluation of WAMPS. The evaluation will be conducted in two parts. The first part will be an evaluation of the methodology, modelling assumptions and the structure of WAMPS. The second part will be an evaluation of the calculations and the input parameters in WAMPS.

3.1 Evaluation of the structure of WAMPS

The first part of the evaluation will be conducted by comparing the structure of WAMPS to literature. The studies that are used for comparisons are reviews of waste-LCA models - Gentil et al. (2010), Winkler & Bilitewski (2007) and Kulczycka et al. (2015), reviews on waste LCAs - Laurent et al. (2015) and Cleary (2009) and literature describing how a waste-LCA should be conducted - European Commission (2009). The literature was found by combining the keywords “waste management systems”, “LCA”, “life cycle assessment” and “review” in Scopus, LUBsearch, Google scholar and Google. The literature for waste-LCA models used in this evaluation is the relevant literature found on the subject, the literature used for waste-LCAs is the literature that reviewed the most waste-LCAs and the literature describing how a waste-LCA should be conducted was used because of the reliable source (the European Commission).

The structure of the comparison is primarily based on Gentil et al. (2010) as this is the most comprehensive review of waste-LCA models. However, some aspects that are not included in Gentil et al. (2010) but that are stressed in the other studies are included in the evaluation as well. The evaluation is mainly focused on the methodology and the input parameters in WAMPS. The agreement between WAMPS and literature will be evaluated for each category. The agreement, or lack thereof, will be graded on a scale which includes three colors. An explanation of each color is given in Table 4.

Table 4. Description of the evaluation of the structure of WAMPS using colors to depict the level of agreement between WAMPS and literature on waste LCAs.

Color coding	How well does WAMPS agree with the literature
(green)	WAMPS agrees with/includes the aspects addressed in the category.
(yellow)	WAMPS includes most (more than half) of the aspects addressed in a category but lacks some aspects. The impact of the aspects is not stated, or it is unclear how the aspects could be implemented in similar models.
(red)	WAMPS is different than most or all models/waste-LCAs regarding a category. The aspects that are not included in WAMPS are stated in literature to be of great importance. Or, the aspects that are not included impact several waste fractions, which could have a great impact on the calculated result. It is clear how the aspects could be included/improved in WAMPS.

The comparison and the evaluation are presented in sub-sections, each starting with a header which briefly introduces the section. The leftmost column is a description of the category. The included categories are mainly the categories assessed in Gentil et al. (2010). The "literature review"-section contains the information found in literature on the aspect. The section called "WAMPS" includes a description of how the aspect is handled in WAMPS. In the case that there is a lack of agreement or inclusion of the aspect, a note is included on which aspect that should be improved. The column farthest to the right includes the color which depicts the level of agreement between WAMPS and literature. After the table, a summary of the most important aspects will be presented. The comparison of WAMPS with literature and the evaluation of the agreement can be seen in Table 5.

Table 5. Comparison and evaluation of the agreement of WAMPS and literature on waste LCAs.

Category	Literature review	WAMPS	Comparison
LCA methodology WAMPS has been developed to correspond to the ISO-standards on LCA, but with some simplifications[4]. This sub-section will include a comparison between WAMPS and some important LCA-aspects.			
Functional unit	The reviewed models use a functional unit according to all the waste generated and managed in a specific region, generally defined in tons/year. Some of the models have the possibility to change the functional unit to 1 ton (Gentil et al., 2010). Laurent et al. (2015) argues that the functional unit should be more defined than just 1 ton of municipal waste as this differs between regions.	The functional unit is defined as all the waste that is managed, in tons, in a specific region per year.	(green)
System boundaries – upstream and infrastructure	System boundaries are considered of importance since they could significantly change the results. All reviewed models have chosen a zero-burden assumption on the incoming waste, but otherwise, there is little coherence between the system boundaries (Gentil et al., 2010). When waste is processed, some additional material can be needed in the processes. For example, material to clean the flue gas from the incineration. Six of the reviewed models include the emissions associated with the production of such up-stream materials (Gentil et al., 2010). Another debated aspect is the inclusion of infrastructure. This is included in WISARD and WRATE. Laurent et al. (2015) states that infrastructure could give a big impact compared to the treatment processes and states that practitioners should examine carefully whether exclusion of this is regarded sufficient. Some models also include emissions from production of collection bins (Gentil et al., 2010). European Commission (2009) however states that the impact from infrastructure is small compared to the usage phase, and Sundqvist et al. (2002) did not see a need to include it in the early ORWARE-model.	A detailed comparison of the system boundaries can be found in appendix A – system boundaries. WAMPS includes the most important input processes. Infrastructure, water usage and additional materials used in the processes are not included. → *Consider including water usage, infrastructure and ancillary materials.*	(yellow)
System boundaries - downstream	The models also differ regarding "down-stream" system boundaries, i.e. how much of the recovery system that should be included. IWM2 only includes the impact from the separation of the recyclable materials and does not include reprocessing into secondary products. Other models include the separation, transportation, preparation, reprocessing and also the saved emissions from the substitution/offset of primary materials or energy (Gentil et al., 2010). Reviewed waste-LCAs are also lacking in reporting and being consistent in choice of system boundaries. Most of them do not state exactly what is included (Cleary, 2009). Laurent et al. (2015) stresses the importance of being transparent with system boundaries and further states that how the secondary product is valuated can have a major impact on the outcome. Winkler & Bilitewski (2007) adds to this and states that the models differ significantly with regards to accounting for secondary energy and material. The models must be more coherent in downstream system boundaries and in the method in which they account for avoided production.	A detailed comparison of the system boundaries can be found in appendix A – system boundaries. WAMPS includes the same processes as most of the other models. One difference is how the secondary products are accounted for. WAMPS generally includes the reprocessing until a new product is created. The difference is plastic where the data only includes reprocessing to plastic granules. → *Consider checking the consistency of how secondary products are valuated, compared to other tools.*	(yellow)

[4] Jan-Olov Sundqvist, IVL Swedish Environmental Research Institute. Phone call – 28 May 2019.

Cut-off criteria	Cut-off criteria are not well defined in the reviewed models. Usually cut-off criteria are imbedded in the calculations but not communicated. Generally, it can be stated that the more complicated models usually include emissions from more processes, which render higher environmental emissions (Gentil et al., 2010).	Cut-off criteria are not defined in WAMPS → *Consider including cut-off criteria.*
Solving multifunctionality	Most of the waste LCA-models and 75% of the reviewed waste LCAs use system expansion to account for the avoided impacts caused by the recycling process. It is also the most common to assume that the recycled material/energy replace virgin production (Gentil et al., 2010; Laurent et al., 2015). This approach is also encouraged by European Commission (2009).	System expansion is used to account for the avoided production of materials/energy.
Impact categories	The impact categories used in the models have not been assessed by Gentil et al. (2010). However, Laurent et al. (2014) states that a major part of reviewed LCA-studies only assesses climate change impact. Cleary (2009) states that most reviewed waste LCAs only assess four impact categories. Laurent et al. (2014) further states that to include too few impact categories is contradictory to ISO14044, which states that all relevant impact categories should be assessed. The risk with two few impact categories is to make the wrong conclusions. Laurent et al. (2015) states that toxicity is an important impact category. They also state that exclusion of toxicity impact may have been valid in the beginning of the 2000s but that there has been a lot of research and that robust methods have been developed to assess toxicity recently.	Four impact categories are included. WAMPS include some toxic compounds such as dioxins and heavy metals. They are however not used in any impact category but only there to give the user the option to check hazardous substances. → *Consider including an impact category for toxicity.*
Data requirements	The quality of the data is to a large degree a dictating factor for the representativeness of the study (Laurent et al., 2015). The data and what is included in the data varies between the models and which datasets that have been used (Gentil et al., 2010). European Commission (2009) states that software tools used to asses waste managements must use quality checked data. They further state that the data used should follow the data quality regulations in ISO 14044 which means that the data should be "consistent, independently externally reviewed, and have a minimum declared quality". Winkler & Bilitewski (2007) adds to that and states that the validity of the used data must be improved. Laurent et al. (2015) however also states that it is difficult to find up to date and site-specific data that matches the analyzed system. Winkler & Bilitewski (2007) also states that it is important to report what is included in the used data.	WAMPS uses data from environmental reports from Swedish treatment facilities. → *The documentation of the data should be improved.*

Waste composition

The waste composition is both a question about the *fractions* of waste (such as garden waste or plastic) and of the *elemental composition* of each fraction (such as amount of carbon or nitrogen in a specific waste fraction). The *fraction* composition of the waste is an input to the model and is thus defined by the user. It is however important that the tool has enough fractions to choose between so that it can model the real case. The *elemental* composition is however often integrated in the model and defined for each fraction. The elemental composition is often used when modeling the emissions from combustion processes and the emissions from landfill (Gentil et al., 2010). Thus, to give a fair picture of the emissions from these processes it is important to have correct elemental compositions. It is also important to include enough elements in the composition to give a fair picture of the impacts – for example, if the elemental composition does not include the amount of carbon in the waste, then it is difficult to calculate the CO_2-emissions from incineration for different waste compositions. A comparison between WAMPS and the reviewed models can be seen in appendix A-waste composition and properties. Overall, WAMPS is coherent with the models regarding waste composition. Some of the important aspects of waste composition are assessed in this section.

Number of waste fractions	The most advanced models, EASEWASTE, MSW-DST and WRATE include 48, 48 and 67 waste fractions respectively. The simpler models such as EPIC/CSR, IWM2 and LCA-IWM include 7, 9 and 11 fractions respectively. All models include merged waste categories such as metal or paper. The difference however lies in the inclusion of the composition of the fractions. For example, the fraction paper includes the sub-fractions graphic paper and cardboard, which is not included in all the models (Gentil et al., 2010).	WAMPS include 24 fractions.
Elemental composition	The reviewed models include elemental composition of the waste, but different chemicals/elements are assessed. The difference in elemental composition is stated to be a one cause of differences between the results of the models and it is stated that the data for waste composition needs to be harmonized and standardized for all the models (Gentil et al., 2010).	WAMPS include elemental composition for all the waste fractions. The composition should however be harmonized. → *Update the elemental composition in WAMPS if a standard is developed.*

Elemental composition - CO_2 from biological sources	One aspect of the elemental composition which is handled differently in the reviewed models is CO_2 from biological sources. Treatment of biomass, such as incineration of biomass or composting, releases, among other substances, CO_2. CO_2 from these sources is called biogenic CO_2. The difference between biogenic and fossil CO_2 is that emitted fossil CO_2 release CO_2 that has been stored in the ground for a long time and can thus be said to increase the total amount of atmospheric carbon. Biomass is however included in the "biogenic carbon cycle" (IEA Bioenergy, n.d.) and is thus not respected as a net emission. In LCAs, release of biogenic carbon should be accounted for, but the global warming factor should be set to zero (Gentil et al., 2010). The reviewed models treat biogenic carbon in different ways. IWM2 does not differentiate between fossil and biogenic carbon and EPIC/CSR does not include the emissions from biological processes (Gentil et al., 2010). Laurent et al. (2015) found in the reviewed LCAs that biogenic carbon was managed in different ways they stated that biogenic carbon is a source of uncertainty in the results.	WAMPS accounts for biogenic carbon by setting the global warming factor to zero.	

Energy aspects

Energy is used in the treatment systems (such as electricity in material recycling) and energy can be produced in the treatment systems which offsets energy in the background system (such as heat from the incineration that can offset district heating). How the energy is modeled, and which assumptions are used of great importance for the outcome (Laurent et al., 2015). Some assumptions include the generation efficiency and transmission losses during the distribution (Gentil et al., 2010). These assumptions are however not documented in WAMPS. Therefore, only the modeling aspects and the possibility for the user to choose different options are assessed.

Options for heat and electricity.	In reality, both heat and electricity will be used and/or offset. It is therefore important that the models are able to make the distinction between heat and electricity. This distinction is possible in EASEWASTE, ORWARE, WISARD and WRATE (Gentil et al., 2010).	WAMPS allow the user to choose between heat and electricity.	
Single energy carriers and energy mixes.	One essential part of the energy modeling is for the user to have the option to choose between energy mixes, such as a national electricity mix, and energy produced from single energy carriers, such as electricity from coal or oil (Laurent et al., 2015**.** Energy mixes can be used when average data is needed and energy from single energy carriers can be used when marginal data is needed. Gentil et al. (2010) emphasizes that it is necessary for the user to be able to modify the energy mixes. All reviewed models except one allows the user to choose between an energy mix and single energy carriers (LCA–IWM only allows energy mixes) (Gentil et al., 2010).	WAMPS includes the possibility to choose between mixes or single electricity carriers. It is however not possible to choose a mix for the heat. It is possible to modify the energy mix, but the possibilities are limited since some energy carriers are not represented, such as solar power. → *Include more variation in the choices of single energy carriers. Consider including heat mixes.*	
Different energy used in the treatment as the energy offset from the production.	Most models allow the practitioner to choose different energy compositions to use in the treatment process as the energy composition that is being offset. For example – a national electricity mix can be used for a process and the produced energy in the system can be modeled to offset European electricity mix. The tools however differ regarding their customizability of this aspect. In MSW-DST, WISARD and WRATE, a simple approach is used. The user is only able to choose different energy mixes to be used and to be offset. In EASEWASTE and ORWARE a more complex approach is used. In these models it is possible to define the specific energy composition to use in each treatment process and to specify what type of energy composition that is being offset for each treatment process (Gentil et al., 2010). For example – wind power can be used in one process, solar power in another and it can be defined that the energy produced will replace coal power.	In WAMPS, it is not possible to differentiate between the energy that is used in the recycling process and the energy that is being offset in the background system. → *It should be possible to choose different energy in the foreground and in the background system.*	

Waste Management processes

The calculation of the waste treatment is the central part of the tools. In this section – the different modules will separately be compared with literature.

Included processes	The reviewed models generally include “collection, transportation, intermediate facilities, recycling, thermal treatment, biological treatment and landfill” (Gentil et al., 2010). Waste management systems have however been developed during the past decades to encompass a wide variety of treatment options – such as gasification, production of bioethanol and pyrolysis. Both Gentil et al. (2010) and Winkler & Bilitewski (2007) stress the necessity of waste-LCA models to be able to model these more complex systems.	WAMPS models the necessary activities but lack options to include more complex treatment methods. → *Consider including more treatment options.*	
Collection, transport & intermediate facilities.	All reviewed models include some account of the impacts from the collection and transport of waste. Collection and transport are distinguished as the transport from households to the intermediate facility (collection), and the transportation between the intermediate facility and the waste management facility (transport). Some reviewed models allow a large number of user inputs while others calculate average emissions based on a small amount of inputs (Gentil et al., 2010). Some reviewed waste LCAs excluded the impact from the collection and transport (Laurent et al., 2015). In most cases it has been found that collection and transport contribute insignificantly to the overall impact compared to the treatment of the waste (Winkler & Bilitewski, 2007). Intermediate facilities are facilities where the waste is sorted and prepared for recycling. These facilities are included in different ways in the models. Some tools model the intermediate facilities in separate calculation modules, while other models (such as ORWARE) account for the emissions from the facilities in the data (Gentil et al., 2010).	WAMPS include several user inputs for the modeling of collection and transport and WAMPS include emissions from intermediate facilities in the data.	
Reject	The different models account for the reject from the processes in different ways. Some models account for the reject from the intermediate facilities, i.e. from the sorting process. Some models account for the reject formed for the treatment processes within the data (Gentil et al., 2010). A detailed comparison of the reject from the processes can be found in appendix A – reject.	WAMPS accounts for the reject from the sorting process, but not for the reject formed at all the recycling processes. This can however be altered by users with a password. → *WAMPS should either account for the reject generated in the recycling process or clearly indicate to the user that this must be altered in each case.*	
Material recycling	All reviewed tools account for the recycled material through system expansion, i.e. where it is assumed that recycled material replace material in the background system. One tool however, IWM2, does not include any emissions from the recycling process. What is substituted in the background system depends on if open- or closed-loop recycling is assumed, i.e. if the waste is recycled to products with the same function or to a product with another function. No information of open- or closed loop recycling has however been found in the reviews of the tools. Another aspect to consider is the production method in the background system, i.e. if the product in the background system includes some recycled material. For example – in reality, production of glass containers often includes some recycled glass cullet (Svensk Glasåtervinning, n.d.). All the reviewed models and the reviewed LCAs have however assumed that virgin products are replaced, i.e. products produced without recycled material (Gentil et al., 2010; Laurent et al., 2015).	WAMPS uses system expansion to account for avoided replaced products. The use of closed- or open-loop recycling varies depending on waste fraction. For some materials, closed loop-recycling is assumed (e.g. paper and glass). For some materials, open loop-recycling is assumed (e.g. steel). It is assumed that virgin products are replaced.	
Material recycling – substitution ratio	Some recycled products are not of the same quality as the replaced products in the background system. This leads to that more recycled material might be needed to replace a virgin product in the background system. To account for this, a substitution ratio is introduced. The substitution ratio defines how much of the recycled material that can substitute virgin material. A substitution ratio of 1:0.95 means that 1 kg of recycled material is used to replace 0.95 kg of virgin material. This ratio depends on the production technique and on the material at question. The substitution ratio is essential to the results, but it is handled different in different models. Two models assume a substitution ratio of 1:1 for all materials, the other models have various substitution ratios depending on the material. Some of the reviewed models even allow the user to define the ratios (Gentil et al., 2010). Most reviewed waste LCAs assume a substitution ratio of 1:1. The substitution ratio is considered to be of high importance for the result and it is advised that the substitution ratio is included in a sensitivity analysis (Laurent et al., 2015)**.**	WAMPS have defined substitution ratios which can be seen in appendix A – substitution ratio. There, also a comparison is made with literature even though the literature on substitution ratios is scarce. (Gaudreault, 2012) states that it is difficult to identify distinct substitution ratios. The substitution ratios used in WAMPS lies within the variation found in literature.	

Thermal treatment	A detailed comparison of the thermal treatment module between WAMPS and the assessed models can be found in appendix A – thermal treatment. Some important aspects will be included in the rows below.	WAMPS concur with the models on most aspects regarding thermal treatment (see appendix A). 8/9 models however include the impact of ancillary materials which WAMPS does not include. Ancillary materials have however already been considered in the "system boundaries"-category above.	
Incineration – Calorific content	To quantify and model the potential energy that can be extracted by incineration of waste, it is necessary with a measure of the potential energy in the waste. This is achieved in the models by calculating the calorific value, which is defined as the heat that is generated as combustion. Some models calculate the Lower Heating Value (LHV), which is an alternative method of calculating the energy content in the waste (CNG Europe, n.d.). The calorific value is an important variable in the incineration equations (Gentil et al., 2010). It is however calculated in different ways in the different models. Some models calculate the calorific value from the elemental and fractional composition of the waste, some models base the calorific values on literature.	WAMPS calculate the calorific values based on the elemental composition of each fraction. No information was however available on the method used to calculate the value.	
Incineration – recovery efficiency	The next aspect to consider is how much of the potential energy in the waste that can be recovered. Most of the models include/consider the recovery efficiency of electricity (see appendix A – thermal treatment). About half of the models include the recovery efficiency of steam and about half of the models lets the user define the recovery efficiency. A higher recovery efficiency means that more energy can be offset in the background system and more impacts can be avoided (Gentil et al., 2010).	WAMPS allows the user to define how much of the energy content in the waste that is recovered to heat and electricity respectively and how much of the energy that is lost as excessive heat.	
Incineration – abatement efficiency	Incineration of waste causes emissions of H_2O and CO_2 but also of other emissions, for example dioxins. How these other emissions are modeled in the tools is assessed last in this section since it relates to all the treatment methods, not only incineration. To remove these emissions, also called flue gases, an incineration plant will include a flue gas treatment which removes some of the emissions (Laurent et al., 2015; J. Sundqvist, 1999). In the models it is important to account for this removal of emissions, also expressed as "abatement efficiency" (Gentil et al., 2010), prior to release to the atmosphere.	WAMPS account for the cleaning of the flue gases.	
Incineration - ash	Incineration of waste will leave some rest product, called ashes. The models should account for transport and disposal of the ashes. The modeling of these rest products is important for the overall environmental performance of the incineration. The models should account for the quantity the composition and the emissions from the disposal method of the bottom and fly ash (Gentil et al., 2010). The fly ash is a lighter ash which enters the exhaust gas, bottom ash is the heavier ash that remains in the combustion chamber after incineration.	WAMPS models the disposal of ashes. The quantity and the composition are based on waste composition. WAMPS also includes both bottom, and fly ash.	
Biological treatment - compost	There are several different composting techniques. This complexity should be reflected in the models. Also, transport and spreading of the compost can be of importance and should be included in the modeling (European Commission, 2009).	WAMPS includes four composting options and includes transport and spreading of the compost.	
Biological treatment – anaerobic digestion	The reviewed models include anaerobic digestion, except MSW-DST. The modeling of the digestion is based on the elemental composition and the degradability of the included elements (Gentil et al., 2010)	WAMPS includes anaerobic digestion and models it based on different degradability of the included carbon.	
Biological treatment - substitution	Most of the models includes substitution of the produced compost/digestate with NPK-fertilizers and/or other materials such as peat or wood. Some models do not account for the avoided production of fertilizers because the compost/digestate is not considered of sufficient quality to substitute fertilizer. The system boundaries for how much to include of the produced	WAMPS assumes that compost and digestate substitute N and P fertilizer.	

	compost/digestate varies (Gentil et al., 2010). European Commission (2009) states that there are additional benefits with compost such as soil fertility and improved water retention which should be included in the modeling.	→ *Consider including substitution of K-fertilizer, and maybe also other materials.*	
Biological treatment - energy	Which energy that is used in the biological treatment process and which energy that is replaced in the model is stated to be of importance but how this is done in the models and what energies/fuels that are substituted are not elaborated other than stating that ORWARE includes the upgrading of the biogas into various qualities which can substitute different energy/fuels (Gentil et al., 2010).	WAMPS accounts for the production and the substitution of biogas from anaerobic digestion. The user can determine the percentage of biogas that substitutes vehicle fuel and district heating respectively.	
Biological treatment – retention time	The biotreated waste will require different duration of processing depending on the composition. The retention time is the duration of the processing. The reviewed model accounts for the retention time in different ways. The solutions vary between introducing a carbon degradation coefficient, to allowing the user to determine the degradation of the biologically treated waste.	WAMPS accounts for the retention time by including carbon of different degradability in the elemental composition.	
Landfill – time aspects	The aspect of time is important in the modelling of landfills. There are two emissions that are of specific importance – leachate and landfill gas. For leachate, the models vary greatly on the time that is considered. Two models have chosen a 100-year period for landfill leachates. Other models give the option to choose between 50, 100 and 500 years. Two models consider the impacts over 500 and 20 000 years respectively. Leachate time horizons is concluded to be one of the aspects that could make comparisons difficult. Landfill gas is mostly modeled to be emitted for 100 years. Other models have chosen to account for the landfill gas as a volume emitted per ton of waste that is landfilled (Gentil et al., 2010). European Commission (2009) states that emissions and modelling of landfills is important for the results and that it is not sufficient to rely on literature data to estimate the emissions from landfill. Laurent et al. (2015) states that there is no consensus on how to model the emissions from landfill. The collection of landfill gas must also be modeled (Laurent et al., 2015).	WAMPS include emissions of landfill gas and leachate for a 100-year period	
Landfill - gas	The more advanced models calculate the landfill gas from the waste composition. The composition of the landfill gas is estimated from literature. The user has the possibility to choose what the gas will substitute, or if it will be flared (Gentil et al., 2010)	WAMPS calculate the landfill gas based on the waste composition. No information is found on the composition of the gas.	
Landfill - Leachate	Some models calculate the quantity and composition of the leachate based on the waste fractions, other use typical values for the quantity and composition. Some models include the aspect of precipitation when calculating leachate, others dismiss the impact of precipitation because the modeled landfill is assumed to be capped. Most tools include some kind of treatment system. This is usually modeled as removal efficiencies. Some models use general removal efficiencies, other utilize specific removal efficiencies for specific compounds (Gentil et al., 2010).	WAMPS calculate composition and quantity based on the waste composition. Removal efficiencies are incorporated in the calculations. Precipitation is not considered.	
Other aspects			
Included emissions	Different models include the emission of different compounds/substances. For example, some models include emissions of N_2O and CH_4 from composting, while other models exclude these emissions. This difference could lead to significant difference between the models (Gentil et al., 2010). Winkler & Bilitewski (2007) however states that it is not certain that a model will give more accurate results just because of the numbers of emissions that are assessed, or the complexity of the calculations.	WAMPS include emissions of CO_2, N_2O and CH_4 when accounting for climate change.	
Uncertainty	Winkler & Bilitewski (2007) stresses the necessity of including or communicating the uncertainty in the calculations. (Laurent et al., 2015) states that uncertainties are important in the LCA-result but however also writes that few of the assessed LCAs included uncertainty.	WAMPS does not include uncertainty. → *Consider including uncertainty.*	

A summary of the categories where WAMPS disagrees with, or does not include the aspects considered in literature are presented in Table 6. Only the categories labeled with a red or yellow color are considered, since these are the categories where WAMPS deviate from literature.

Table 6. Summary of the aspects where there is a lack of agreement between WAMPS and literature.

Category	What could/should be implemented in WAMPS	Comparison
Data requirements	The documentation of the data should be improved.	
Different energy used in the treatment as the energy offset from the production.	It should be possible to choose different energy for the treatment process and the avoided production respectively.	
Reject	WAMPS should account for the reject generated in the material recycling process or indicate to the user that this parameter must be altered in each case.	
System boundaries – upstream and infrastructure	Consider including water usage, infrastructure and ancillary materials.	
System boundaries - downstream	Consider checking the consistency of how secondary products are valuated, compared to other tools.	
Cut-off criteria	Consider including cut-off criteria.	
Impact categories	Consider including an impact category for toxicity.	
Elemental composition	Update the elemental composition in WAMPS if a standard is developed.	
Single energy carriers and energy mixes.	Include more variation in the choices of single energy carriers, e.g. solar power. Consider including heat mixes.	
Included processes	Consider including more treatment options (such as pyrolysis and gasification)	
Biological treatment - substitution	Consider including substitution of K-fertilizer, and maybe also other materials.	
Uncertainty	Consider including uncertainty in the result.	

The table has been ordered to show the categories assumed to deviate the most from literature first (i.e. the red categories). Thereafter are the categories labeled with the yellow color presented. The evaluation of the structure showed that primarily three categories are deviating the most. These aspects are: the lack of data quality and documentation in WAMPS, the lack of options for the user to choose different energy in the foreground and in the background system and the lack of accounting for reject from the recycling processes.

3.2 *Evaluation of the calculations in WAMPS*

3.2.1 Method and limitations

A comparison and an evaluation of the calculations in WAMPS are needed to examine the accurateness and potential limitations in the calculations. As mentioned in chapter 2.4.2 - Calculations in WAMPS, the calculations in WAMPS are conducted by subtracting the avoided emissions from the substituted materials/energy (background system) from the treatment process (foreground system). To be able to trace potential deviations in the result, the calculations in the foreground- and the background system will be compared separately to other sources. There are however several options for which sources to use in the comparison. One possibility is to compare the calculations in WAMPS to results from other waste-LCA models. Previous studies have however found that the other waste-LCA models differ significantly in the calculated results (Winkler & Bilitewski, 2007), which makes them unsuitable for comparison. Instead, the calculated results from WAMPS will be compared to values from literature and databases. It was assumed that these sources would render more reliable results.

There are however many options for choice of literature data to compare with. After the initial data search it was found that several LCAs on waste management were conducted by either using database data, such as data from Ecoinvent (Paraskevas, Kellens, Van De Voorde, Dewulf, & Duflou, 2016; Raadal & Modahl, 2010) or by using data from waste-LCA models similar to WAMPS (Bigum, Brogaard, & Christensen, 2012; Merrild et al., 2008). Since it was decided to not compare WAMPS to other tools, and to avoid double counting, it was decided to primarily use data directly from the Ecoinvent database. Additional data was used from trade associations such as European Aluminium and Plastics Europe as these presented transparent data from recent years (European Aluminium, 2018; PlasticsEurope, 2017). There was however a lack of data for some fractions – such as glass and plastics. In this case, the data sources Prognos (2008a) and Frischenschlager et al. (2010) were used as they also have been used in other, similar assessments previously (Eriksson, Hillman, Fluck, Jonsson, & Damgaard, 2015). Some additional data with presumably worse quality (or at least less documentation explaining the calculations) was also used in the presentation of the result, such as APEAL (2015) and European Commission (2014). These were found by searching Google and LUBsearch for LCAs on the different waste fractions. Data from these sources was included to demonstrate the potential variation in result found in literature but it was not included in the calculations.

The data from the literature mostly represented European averages. One of the key contributors to the impact is, according to Brogaard, Damgaard, Jensen, Barlaz, & Christensen (2014), the electricity modeling. To make WAMPS comparable to European data, a new module for electricity was developed to represent the average electricity produced in Europe. According to IEA (2018), the average production of electricity caused emissions of 296 g CO_2/kWh in the year 2016. Another adjustment of WAMPS prior to the evaluation was to update the LCIA-method for the global warming impact category, i.e. the characterization factors that are used to calculate all the data within a specific impact category to a common unit. WAMPS included the characterization method from IPCC 1998, which was updated to the latest version – IPCC 2013 (Myhre et al., 2013).

Due to time limitations, only the impact of climate change was assessed in the comparison. This indicator was chosen as it has been given much attention recently. Also due to time limitations, it was not possible to assess all the fractions included in WAMPS (see chapter 2.4.1 - Structure of WAMPS). Instead, conventional fractions and treatment methods were chosen. The chosen treatment methods were: material recycling of aluminium, steel, glass, plastic, paper and also incineration and composting. The term conventional in this context means that the treatment system of the waste fractions exists in many countries. The assumption was made that the data from these fractions would be of good quality and represent average treatment methods. The treatment methods for assessment were also chosen based on the criteria that they should treat most of the municipal solid waste in an average municipality. The share of treatment methods for municipal solid waste in Sweden in 2017 can be seen in Figure 12, which also shows that the chosen treatment methods make up about 70% of the treatment system. The category "other treatment" include additional treatment methods such as anaerobic digestion and landfilling. The average distribution was chosen from Sweden since WAMPS was developed in Sweden.

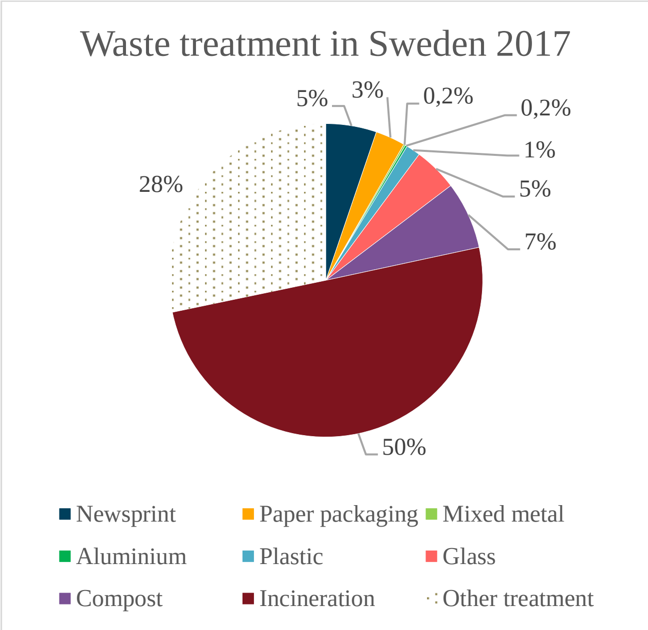


Figure 12. Distribution of the average waste fractions and treatment methods for municipal solid waste in Sweden in 2017. Based on Avfall Sverige (2018a).

There are several assumptions made in the following sections. The assumptions are based on communication with one of the developers of WAMPS[5] who gave recommendations on which datasets and which assumptions to consider in the calculations. Landfill was excluded since it was assumed that the impact of climate change would be minor since it is forbidden to dispose organic waste in landfills in Sweden (SFS, 2001:512). Anaerobic digestion was excluded due to uncertainties on how WAMPS accounted for biogas.

3.2.2 How the results are presented

The results of the comparison of the calculations are presented in the sections below. As described above, the comparison was made by comparing the foreground and the background system separately. Data has been collected from the sources described above, and the values for the processes were calculated in WAMPS. The result is presented in charts. An example of a chart can be seen in the figure below.

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[5] Jan-Olov Sundqvist, IVL Swedish Environmental Research Institute.

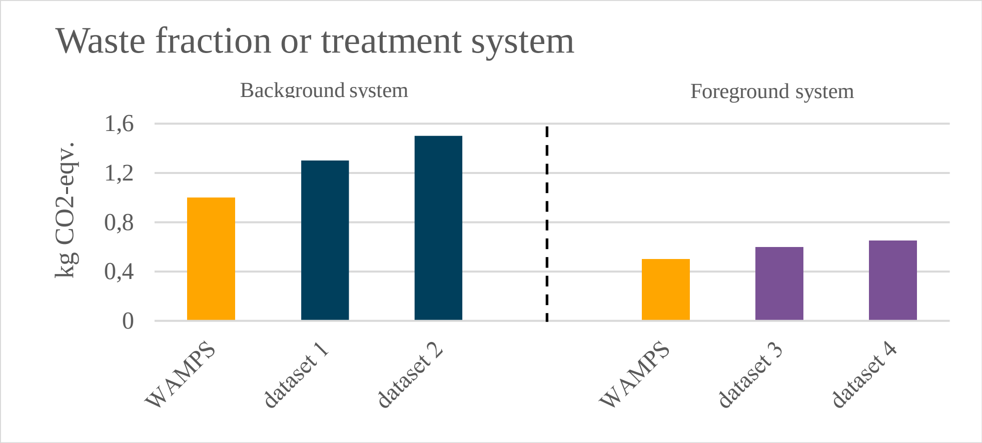

Figure 13. Example of how the datasets are presented.

The dividing line separates the presentation of the background – and the foreground system. The values for the foreground system (emissions from treatment of waste) are shown to the right and the emissions from the background system are shown to the left of the separator. The y-axis represents the emissions, in kg CO_2-eqvivalents, that are released by the process per kg treated waste. In the case of energy, the emissions are instead related to the energy produced, i.e. kg CO_2-eqv./MJ. Each dataset is labeled with the name of the dataset, i.e. what it represents, the region which is represents, the year(s) which it is representative for and an id of the dataset. The id of a dataset can be used to locate a specific dataset in appendix B, where a more thorough presentation of the datasets and what they represent is given.

Prior to presenting the result, each waste fraction is described, i.e. how it is treated, what it substitutes and how the substituted material/energy is produced. After the results section, an average value is calculated for the datasets in the background- and in the foreground system respectively. This is done to enable a clearer comparison, and to only include the data that is most reliable in the comparison.

3.2.3 Aluminium

Primary production

The main processes required in the production of primary aluminium are mining of bauxite, production of alumina, electrolysis and casting. Bauxite is the base for primary production of aluminium and it must be mined. Bauxite contains one or several forms of aluminium hydroxide compounds in its unrefined state. The Bauxite is crushed and ground, and a small amount of water is added to the mixture. The mixture is then heated to remove impurities and treated with lime-caustic soda. Eventually this allows pure alumina to settle at the bottom. The alumina is further processed through electrolytic reduction to aluminium. This is done in at high temperature in big smelters and it results in liquid aluminium that is further mixed with other metals and alloyed according to the requirements of the consumer. The liquid aluminium is usually cast into ingots which subsequently can be processed to either aluminium sheets, -foils or -profiles (European Aluminium, 2018; Aluminium Production, n.d.). Aluminium is produced in many regions of the world. Bauxite is primarily found in regions close to the equator, alumina is produced in Europe but also in other countries, e.g. Brazil and Jamaica. Aluminium is produced from alumina in Europe, but it is also produced in, e.g. Russia and the Middle East. More than half of the world's aluminum is produced in China (Brown et al., 2018). About half of the Aluminium used in Europe is imported (European Aluminium, 2018).

Recycling

There are several processes for the recycling of aluminium and they vary from plant to plant (Cusano et al., 2017). In general however, the recycling process can be categorized into two alternatives – *remelting* or *refining* of aluminium scrap (European Aluminium, 2018). The choice of either treatment method is primarily based on the pureness of the incoming scrap. During the remelting process it is not possible to separate alloying elements, i.e. other metals, from the aluminium. The alloys will therefore accumulate in recycled aluminium which limits the application of the recycled metal, or which requires that virgin aluminium is added to dilute the alloys (Biganzoli, Falbo, Forte, Grosso, & Rigamonti, 2015). The purity of the aluminium waste stream is therefore important.

Aluminium scrap that includes a small number of alloying elements and where the incoming material is of known quality, such as process scrap from primary production or beverage cans which have been collected in specified systems, can be processed in remelters. Remelters utilize reverberatory furnaces to recycle the aluminium and the product from the process is wrought alloy, which have low percentages of alloying elements. The wrought alloy can be further processed into sheets or be extruded. The high purity makes the wrought alloys suitable to re-use in packaging material or in cars. Remelters generally include few pre-treatment steps. Usually de-coating is included before the treatment in Remelters. In this process, coatings such as plastics or paints are burned off the collected aluminium scrap.

The other option of aluminium scrap treatment is refining. This treatment can be used for incoming aluminium of unknown origin and quality. The process uses a mix of reverberatory and rotary furnaces and the output from the process are casting alloys that have a higher percentage of alloys and that can be used in in for example the vehicle industry as engine blocks (European Aluminium, 2018). Refining of aluminium scrap requires more pre-treatment such as magnetic separators and sink- and float processes in order to separate unwanted materials, such as iron or labels from the aluminium (Damgaard, Larsen, & Christensen, 2009). Recycling of aluminium saves a lot of energy and emissions. In the industry, it is often stated that recycling of aluminium only requires 5% of the energy required to produce primary aluminium. It is however not clear where this number has originated from (Frisk, 2013).

Common by-products or wastes arising from the recycling process are: skimmings, i.e. a mixture of aluminium, gas and aluminium oxides that is removed from the molten aluminium – often called "dross", and salt slag, a salt mixture used to cover the molten aluminium to prevent the metal from oxidation. Salt slag is also used to increase the yield of the process, clean the aluminium from impurities and to increase the thermal efficiency of the process (International Aluminium Institute, 2009). Some aluminium recycling facilities recover and recycle some or all of the generated salt slag (Cusano et al., 2017).

Results

The results, from WAMPS and from the collected datasets, for virgin production and recycling of aluminium can be seen in Figure 14.

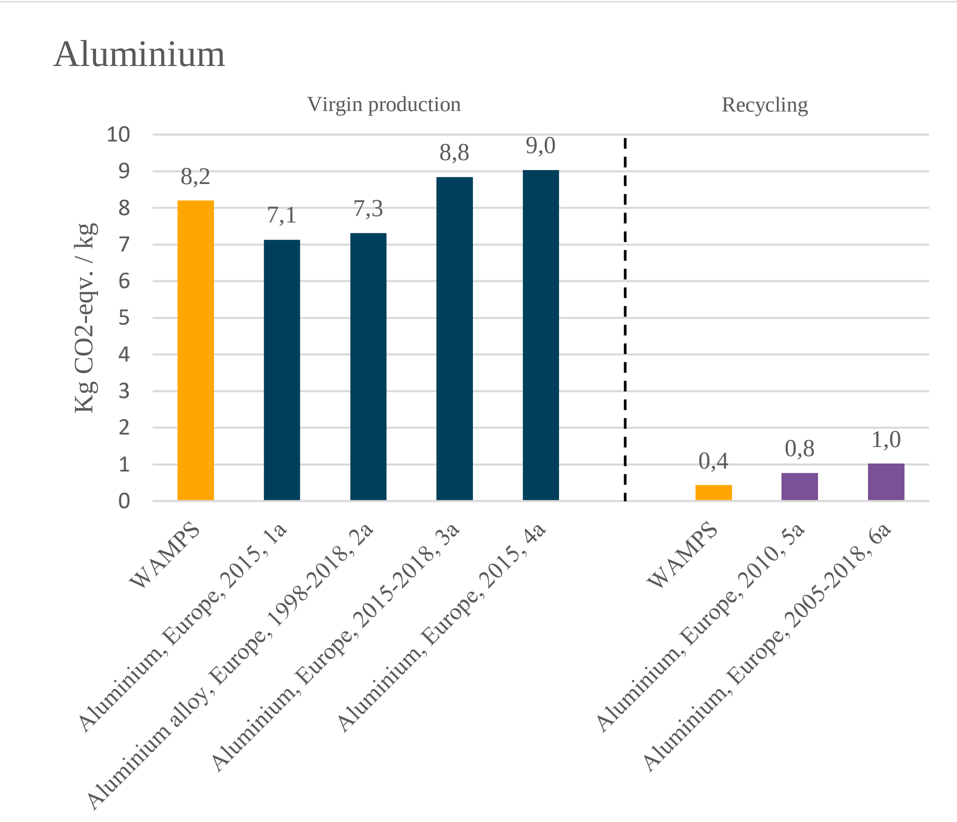

Figure 14. Presentation of the CO_2-equivaents for aluminium production and recycling calculated by WAMPS and identified in literature/databases.

The figure shows that the calculated CO_2-equivalents for production of 1 kg of virgin aluminium in WAMPS are within the distribution of the datasets. The CO_2-equivalents for recycling, as calculated by WAMPS, are however lower than the corresponding datasets. The datasets for virgin production include the process from bauxite mining, to ingot production and production of aluminium sheets. The data for recycling of aluminium includes remelting of aluminium scrap and processing to aluminium sheets. The datasets 1a and 3a represents production of aluminium in Europe while the datasets 2a and 4a represents the aluminium that is used in Europe. The datasets for the recycling represent treatment in Europe.

Comparison

It was assumed that the production of aluminium used in Europe would be substituted by recycled aluminium. The average value from literature for virgin production was therefore calculated as the average of the two datasets that represents virgin aluminium in Europe, dataset 2a and 4a. Both datasets that represent the recycling of aluminium have the same system boundaries and both represent recycling of Aluminium in Europe. The average value from literature for recycling of aluminium was therefore calculated as the average of the datasets 5a and 6a. The average values and the values calculated by WAMPS can be seen in Figure 15.

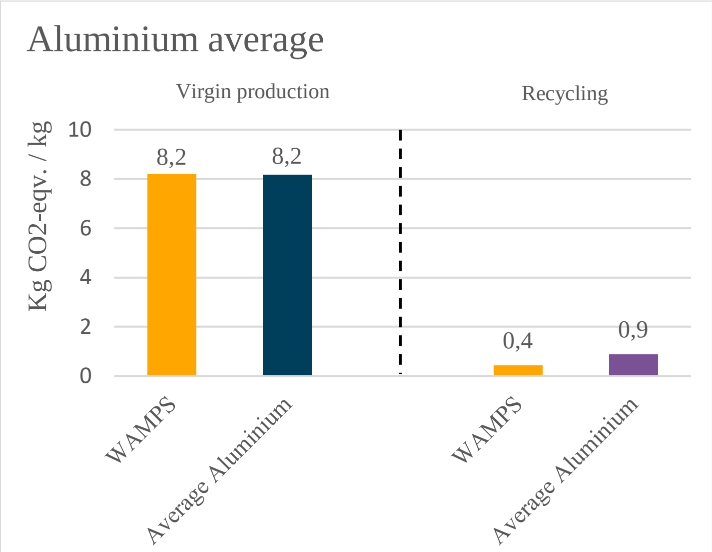

Figure 15. Comparison of the values calculated in WAMPS and the average values from literature/databases for the production and recycling of aluminium.

The figure shows that the literature and WAMPS agrees on the CO_2-equivalents for production of virgin aluminium. The calculated CO_2-equivalents by WAMPS for recycling was lower than the average literature value.

3.2.4 Steel

WAMPS incorporates, in addition to the treatment of aluminium, two options for treatment of metals: “Steel and metal scrap (mixed)” and “Metal packaging”, which can be seen in Figure 10. These general metal categories are however treated in the same module in WAMPS. Scrap metals is composed of many kinds of metals with different alloying compositions. The most common metal for packaging is however steel (Cederberg et al., 2015). The simplification will be made in this chapter that the mixed metals stream only contains steel, as this simplification also has been made previously in similar studies (J.-O. Sundqvist et al., 2010), (Frischenschlager et al., 2010). WAMPS is also using data for steel production and recycling.

Production

Steel is an alloy which is mostly consisting of iron and a small amount of carbon. When iron is mined it consists of iron oxides which must be reduced to create iron. The most common reducing agent is coke, which is generated from coaking coal (World Steel Association, 2019). The most common route for producing virgin steel is called the *integrated* route (European Commission, 2014). In this route, iron ore and coke are sent to a blast furnace where it is melted. Other compounds, such as slagging agents, are also added in this process to remove impurities from the iron. In blast furnace, coke reduces the iron oxides in the ore to iron. The iron is extracted from the furnace and residues and impurities are removed from the iron. The molten iron is subsequently transported to a basic oxygen furnace where oxygen is added to oxidize the iron. When the melted mass has reached a desired temperature, deoxidizing agents and alloying elements are added and the produced steel is cast (Damgaard et al., 2009). The furnaces are sometimes also called converters. The cast steel is subsequently further processed, depending on the application of the steel, by for example by hot- and cold rolling by surface coating (Jernkontoret, 2018). Cast steel generally contains mostly iron and 2% of carbon (World Steel Association, 2019). The main residues from the production are slags and sludges from the melting process (World Steel Association, 2018). Iron ore is common in the earth’s crust and it is mined several countries. Most of the iron ore comes from Brazil, Australia, China, India, the US and Russia (World Steel Association, 2019). EU is the region that produces second most steel products in the world with countries such as Germany, Italy, France, Spain and Poland being the main producers (European Commission, 2014).

The steel can have different properties depending on the amount and the composition of the alloyed elements added. Stainless steel, which is usually used in packaging material, is one type of steel with special alloys. What differentiates it from other steel variations is that stainless steel usually contains chromium which protects the surface from corrosion. There are however many variants of stainless steels which have different compositions of alloys such as nickel or copper (Cederberg et al., 2015). The emissions from the production of steel are usually tied to the complexity of the steel, i.e. how much processing that is needed after production of the steel and the number and amounts of alloying elements. More complex steels will generate more emissions, but it will generally also give steel with a longer lifetime and with other application possibilities than general carbon steel (Jernkontoret, 2018).

Recycling

Steel is theoretically 100% recyclable (World Steel Association, 2019) but in practice impurities, losses and contaminants makes this theoretical cycle impossible (Haupt, Vadenbo, Zeltner, & Hellweg, 2017). Steel is recycled through a route called the *electric arc furnace* route. The main inputs are scrap steel and electricity (World Steel Association, 2018). The materials are fed to the electric arc furnace where the steel is re-melted (World Steel Association, 2019). The biggest difference between making steel from iron ore and from metal scrap is that in the virgin production process the iron ore must go through a reduction process in order to produce steel. This process is not needed when utilizing steel scrap (Jernkontoret, 2018). Before the metal can be recycled it has to be sorted. The scrap metal is sorted in magnets which separate the magnetic fractions. Another separator, called an eddy current separator, separates aluminium from the metal scrap stream (Damgaard et al., 2009). When the steel has been recycled it is cast into billets and further processed according to the application of the steel

(Jernkontoret, 2018). The main co-products and wastes in the recycling process are slags, dust and sludges (World Steel Association, 2018).

Recycling of steel is, just as recycling of aluminium, sensitive to alloying elements in the incoming fraction. Alloying elements that are more noble than iron are not volatile and will remain in the metal when it is re-melted. This results in that the recycled steel loses quality and application possibilities. It is therefore important to have a good material separation of the metals. The Electric arc furnace uses primarily electricity as energy source and the electricity consumption of the process will vary with the composition of the incoming material (Haupt, Vadenbo, et al., 2017).

Results

The results, from WAMPS and from the collected datasets, for virgin production and recycling of steel can be seen in Figure 16.

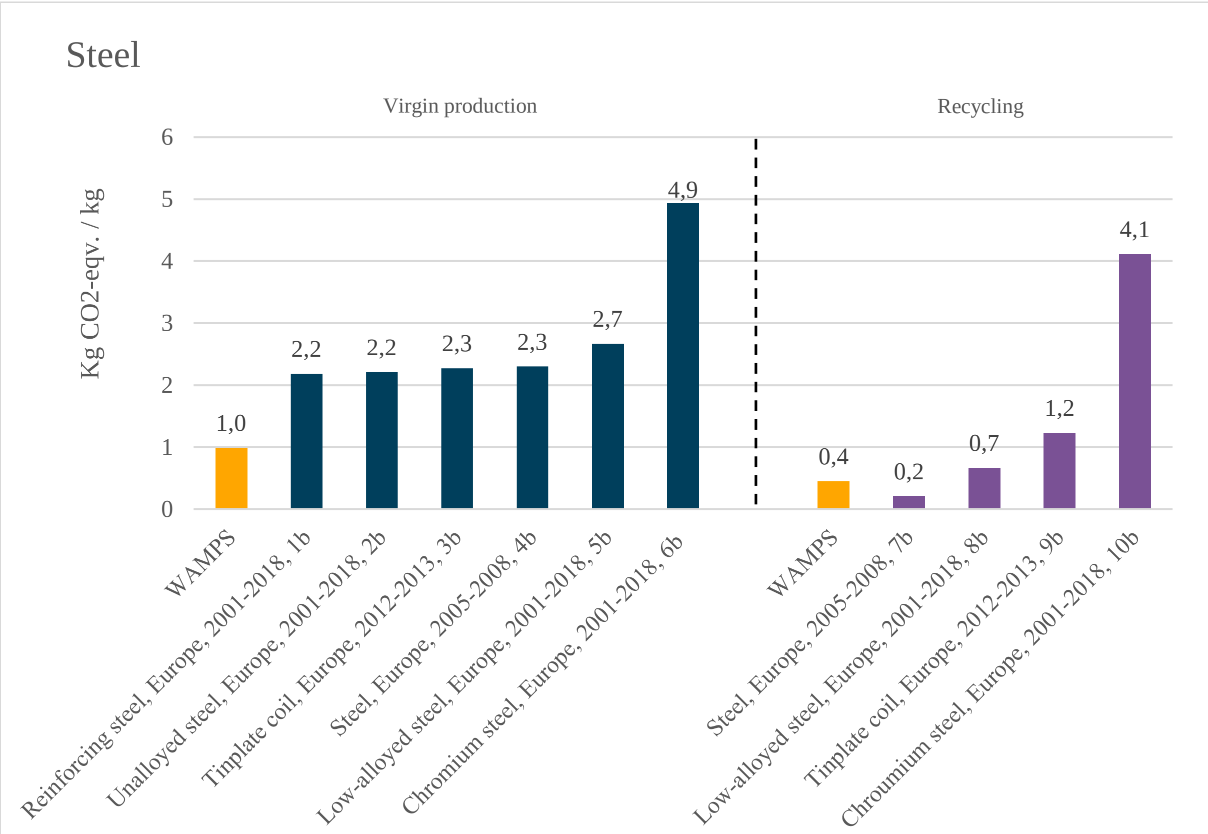

Figure 16. Presentation of the CO_2-equivalnets for steel production and recycling calculated by WAMPS and identified in literature/databases.

The figure shows that the calculated CO_2-equivalents for production of 1 kg of virgin steel in WAMPS are lower than the datasets. The CO_2-equivalents for recycling, as calculated by WAMPS, are however within the values of corresponding datasets. The datasets for virgin production include the process from mining to production of steel, including hot rolling. Dataset 3b includes the processes until a tinplate coil is produced. The datasets for recycling of steel includes recycling of steel, including hot rolling. Dataset 9b includes the processes until a tinplate coil is produced from the recycled steel. The difference between the datasets can be explained by the difference in alloying elements. Datasets, such as 2b and 5b, includes non or small amounts of alloying elements while the datasets 6b and 10b include additional alloying elements. Alloying elements can be a significant contributor to total emissions for metals (Jernkontoret, 2018).

Comparison

It was assumed that the recycled steel would substitute steel with low or no alloys that have been hot rolled. The calculation for average virgin production of steel was calculated as the average emissions from 1b, 2b, 4b and 5b. The average for recycling was calculated as the average emissions from 7b and 8b. The result of the calculated average values can be seen in Figure 17.

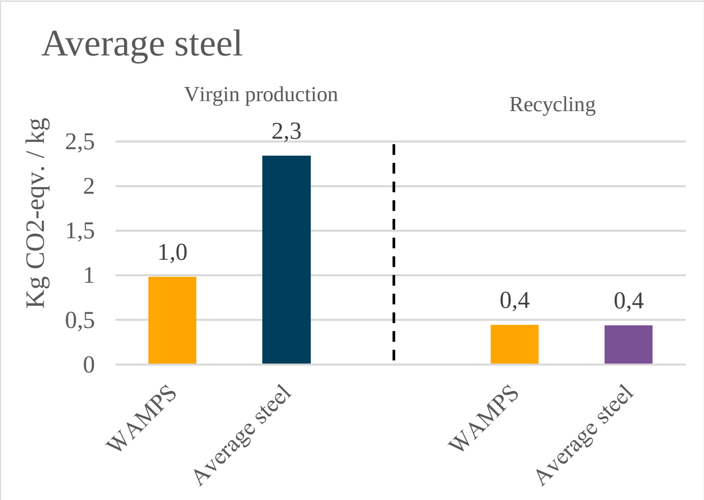

Figure 17. Comparison of the values calculated in WAMPS and the average values from literature/databases for the production and recycling of aluminium.

The figure shows that the calculated CO_2-equivalents for virgin production of steel are lower for WAMPS than for the average literature value. The calculated CO_2-equivalents by WAMPS for recycling agrees with the corresponding average literature value.

3.2.5 Glass

Production

There are several production processes for glass depending on the usage of the final product. The most common glass for containers is called sodium glass. The necessary input materials are limestone, soda ash and silica sand. Usually, also 20-50% glass cullet, i.e. recycled crushed glass, is added (Owens-Illinois, n.d.). Frischenschlager (2010) on the other hand states that there is no glass packaging production that does not include glass cullet and that the average glass production in Europe include 50% glass cullet. Common for the techniques are that these materials need to be melted in a furnace to about 1500 °C. The glass is subsequently removed from the furnace, formed and cooled. It is possible to further process the glass afterwards to get certain properties of the glass, (Glass Alliance Europe, n.d.).

Recycling

After collection, the glass is sent to a sorting facility. The glass is manually and mechanically sorted to remove materials such as metals, ceramics and gravel. The metals are detected by a magnetic field and the ceramics and the gravel are detected by x-ray cameras. The unwanted material is removed by air jets. Additional material such as labels or smaller particles are removed by a cyclone process. Green, brown and transparent glass is then sorted in different fractions and crushed (Svensk Glasåtervinning, n.d.; ALLCOT Group, 2016). Some of the cullet is sent to glassworks where it is melted and recycled to new glass packaging. Some of the glass cullet is sent for production of glass fiber (Svensk Glasåtervinning, n.d.).

Results

The results, from WAMPS and from the collected datasets, for virgin production and recycling of glass can be seen in Figure 18.

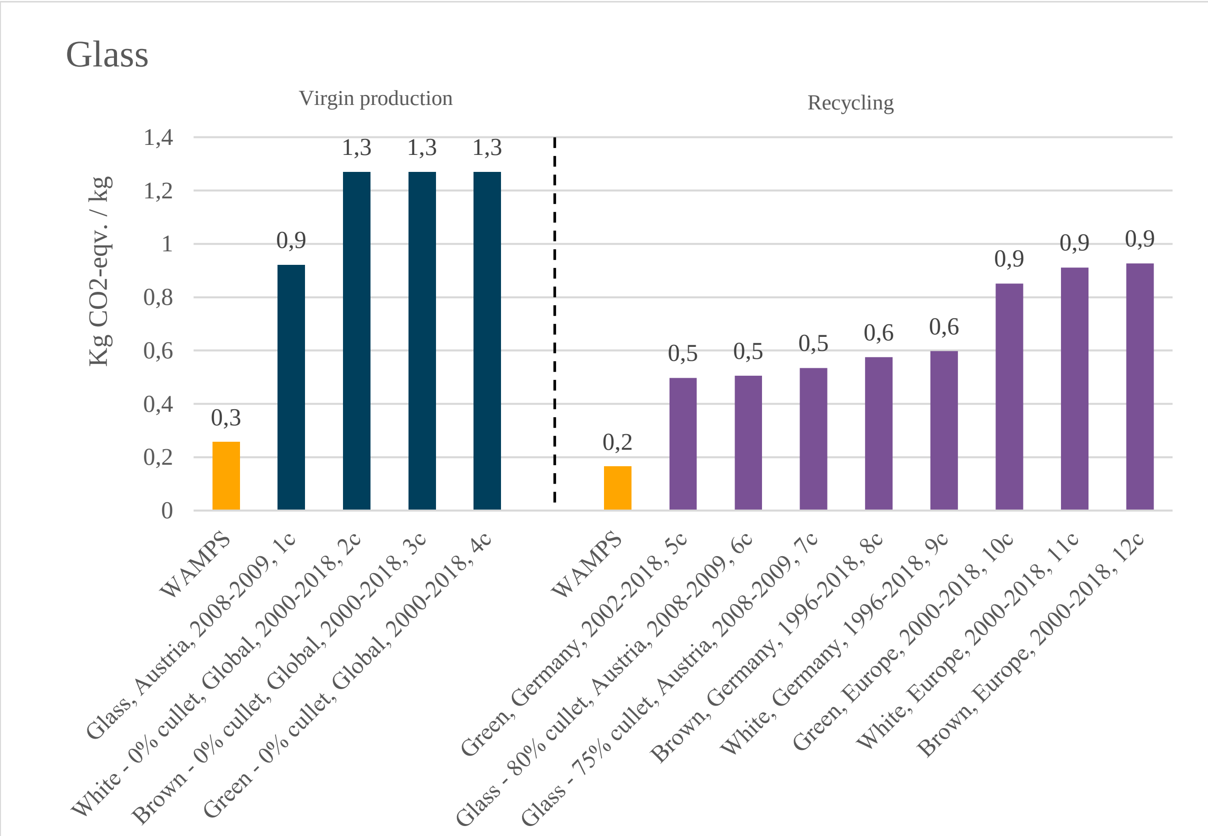

Figure 18. Presentation of the CO_2-equivaents for glass production and recycling calculated by WAMPS and identified in literature/databases.

As mentioned above, glass is a special material since such a large share of recycled glass is included in the primary production. It can thus make it difficult to distinguish between virgin and recycled glass. Two approaches have been found in literature on how to solve this issue. Frischenschlager (2010) and ALLCOT group (2016) have assumed unrealistic shares of cullet, i.e. non or a small amount of cullet included in the virgin production. The other option, conducted by Prognos (2008a), is to calculate the "virgin" production as a production with 20-

50% glass cullet included. In this study, it was assumed that recycled glass would replace glass with little or no cullet.

The figure shows that the calculated CO_2-equivalents for production and recycling of glass are lower than the corresponding datasets. The datasets include the process of producing glass packaging. Datasets 2c, 3c and 4c represents the virgin production globally. These were used in the calculations due to lack of more representative data. The other datasets, except 10c, 11c and 12c, represent processing in Germany or Austria.

Comparison

The average value for virgin production was calculated as the average of 1c-4c. This value is expected to be higher than the actual European value since global data is used. The recycling is calculated as the average of 5c-12c. It was assumed that datasets representing Germany and Austria could be included in the calculations to represent average European values, since the CO_2-emissions per generated kWh electricity is lower in Austria than in the EU, and higher in Germany than in the EU (Moro & Lonza, 2018). It was assumed that the combination of the values from the two countries could render a result representative for Europe. The comparison of the average values with WAMPS can be seen in Figure 19.

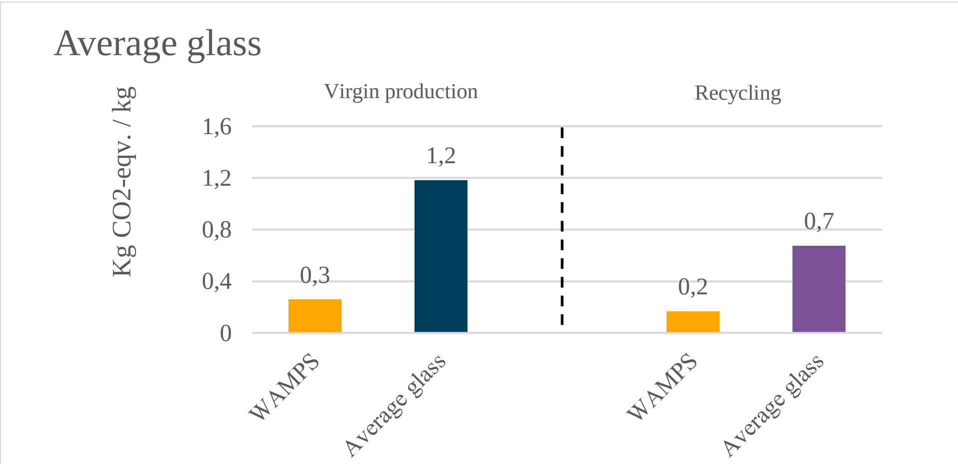

Figure 19. Comparison of the values calculated in WAMPS and the average values from literature/databases for the production and recycling of glass.

The figure shows that the calculated values in WAMPS are lower than the corresponding average values for glass production and recycling.

3.2.6 Plastic

Production

Plastics are constructed by polymers which in turn consists of monomers that have been polymerized into longer chains (Klar, Gunnarsson, Prevodnik, Hedfors, & Dahl, 2014). The monomers are primarily extracted from crude oil. The oil must be refined and cracked into smaller parts which can be used in polymerization. Additives are added to the polymers to acquire the desired properties of the plastic and molding or extrusion is used to get the desired shape of the plastic (Palm & Myrin, 2018).

There are two main types of plastics – thermosets and thermoplastics. Thermosets cannot be re-shaped by heat, thermoplastics on the other hand can be softened by heat and can be re-shaped. It is therefore much easier to recycle thermoplastics. The sensitivity to heat, oxygen and light, however makes thermoplastics less resistant and more additives must be incorporated in the production to make them resistant (Klar et al., 2014). Some thermoplastics are: Polyethylene Terephthalate (PET), Polypropylene (PP), Polystyrene (PS), Polyethylene (PE) and Polyvinyl-chloride (PVC) (Plastics Europe, 2018). The most common are polyethylene (PE) and polypropylene (PP) (Palm & Myrin, 2018).

Recycling

The incoming collected plastic is sorted manually and/or automatically. It is common that about 25-30% of the incoming material is waste that is not plastics and that cannot be recycled. This fraction is removed from the rest of the material. The plastics are subsequently sorted by for example Near Infrared Spectroscopy (NIR), air jets and separation by density. The NIR-cameras can differentiate between materials and plastic-types depending on their chemical structure. The plastic is illuminated by near infrared light and the NIR-cameras detect the reflecting light (Fråne, Andersson, & Lassesson, 2017). One sorting facility stated that the NIR-machine was able to detect PP, HDPE, LDPE and PET[6], the rest, about 20%, is sorted out as reject. The reject can also consist of the recyclable plastic flakes that are too small for the NIR to detect, or recyclable plastics that have been contaminated by liquids that have leaked out during the baling process. Liquids can prevent the NIR cameras from correctly determining the plastic type in the sorting process[6]. The plastic types sorted for recycling are washed and grinded and sorted into colored plastics and non-colored plastics (Palm & Myrin, 2018).

The prepared plastic flakes are then recycled through re-granulation of the plastic, which is often done for colored and non-colored plastics separately. One issue with re-granulation is additives that are mixed into the plastic. This can be coloring agents or additives that change the melting point of the plastic. These remain in the plastic when recycled and effect the recycled product. The colored plastic flakes are for example often mixed into a grey or black granulate and some of the additives limits the possible application of the recycled plastics (Palm & Myrin, 2018). Plastic products can be formed from granulate by for example melting or extrusion (Hestin et al., 2017). Common products made from recycled plastics are garbage disposal bags, trash cans, containers (Fråne, Stenmarck, Sörme, Carlsson, & Jensen, 2012) and flowerpots (Nacka kommun, 2014). Hestin et. al. (2017) states that more than 50% of recycled plastics in Europe are used in packaging materials.

[6] Anders Hjelm, Logistics, Swerec AB. E-mail 12 March 2019.

Results

The results, from WAMPS and from the collected datasets, for virgin production and recycling of plastic can be seen in Figure 20.

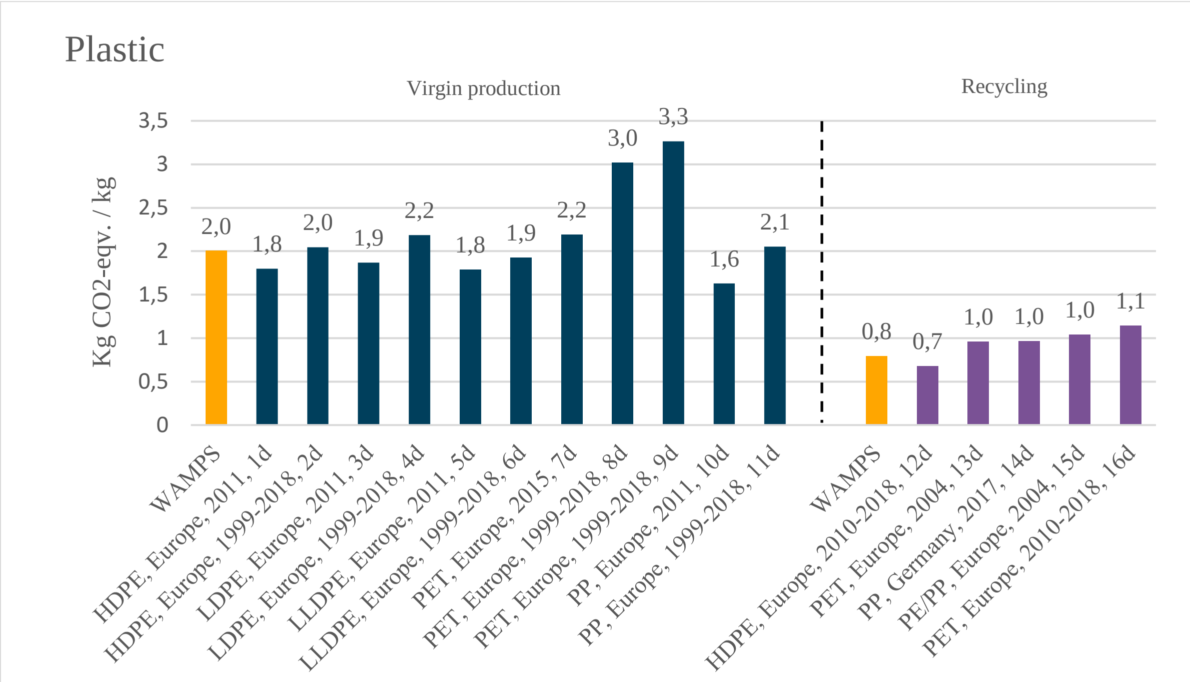

Figure 20. Presentation of the CO_2-equivaents for plastic production and recycling calculated by WAMPS and identified in literature/databases.

Most of the produced plastic packing consist of thermoplastics, i.e. plastics that can be reshaped by heat (Palm & Myrin, 2018). Only thermoplastics has therefore been included in the study. Some thermoplastics, such as PS and PVC have been excluded due to the decreasing usage of these plastics in packaging (Hestin et al., 2017). The plastics in the figure above are sorted by plastic type. All the datasets for virgin production of plastic include upstream activities and include emissions until production of plastic granulate. A big variance can be seen in the datasets for virgin PET production which is caused by the PET quality represented. Dataset 8d represents amorphous PET, i.e. transparent PET, and dataset 9d represents bottle-grade PET, i.e. PET with a certain viscosity that can be used for bottle production. The datasets representing the recycling differs regarding system boundaries. Dataset 13d and 15d does not include the granulation process, only the emissions until the production of plastic flakes are included. These datasets are however included due to lack of more representative data. Another differentiated dataset is 14b which represents the recycling process used by one company in Germany. The figure shows that the calculated values in WAMPS are within the values found in literature.

Comparison

WAMPS does not differentiate between different plastic types. A weighted average was therefore calculated to be able to compare the result in WAMPS to literature. First, average values were calculated for the different plastic types above represented in Figure 20. The weighted average was then calculated by accounting for the distribution of the different plastic types sent to recycling (which can be seen in Figure 21). Dataset 15d was included due to lack of data for recycling of PP, even if the dataset represented old data. The dataset from the same source, 13d, was however excluded due to more reliable data on PET than on PP. The other datasets were used in the calculations. The comparison of the weighted average values with WAMPS can be seen in Figure 22.

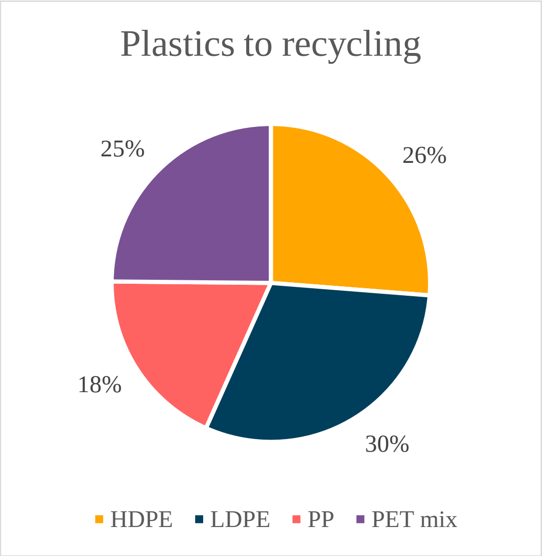

Figure 21. Plastic fractions sorted out for recycling in Europe 2014 according to Hestin (2017)

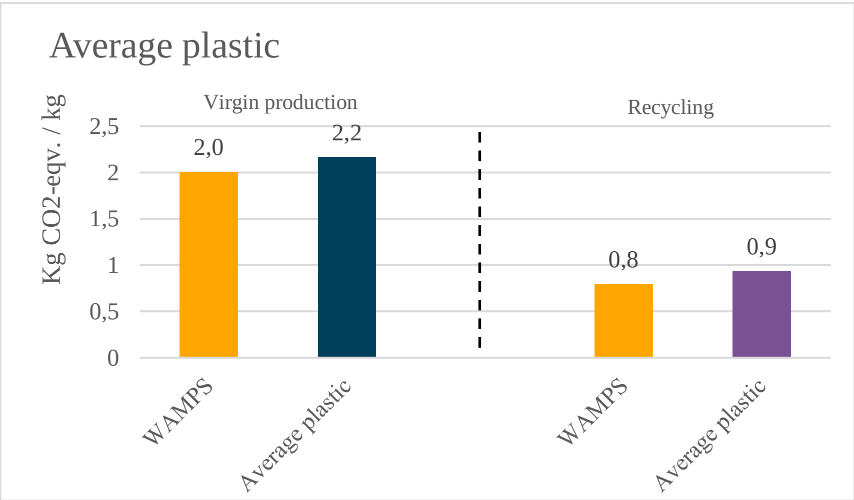

Figure 22. Comparison of the values calculated in WAMPS and the weighted average values from literature/databases for the production and recycling of plastic.

The figure shows that the calculated values in WAMPS are lower than the corresponding average values for plastic production and recycling. The difference between the values is however low.

3.2.7 Paper

Production

Most paper are made from wood which is shredded to wooden chips and further processed. It is however also common for paper production to include some share of recycled paper, depending on the application of the produced paper (SkogsSverige, 2016). The wooden chips are processed through pulping – a method of removing the binding material in wood (called lignin) from the fibers (which contain cellulose and hemicellulose that are the main components in paper) (Bajpai, 2016). Pulping can generally be conducted in one of two ways, through mechanical or chemical pulping (SkogsSverige, 2016).

Mechanical pulping is the older pulping process, but it is still used today. The wooden chips are ground to separate the fibers from each other. The process is energy intensive, but the yield is high (Bajpai, 2016). Mechanical pulping however leaves some impurities in the pulp which gives a lower grade paper that is less durable, and which becomes yellow over time. It is common that mechanical pulp is used for production of newspaper (SkogsSverige, 2016). The other major pulping method, chemical pulping, is a process in which the lignin is dissolved and removed from the fibers with the aid of chemicals (M'Hamdi, Kandri, Zerouale, Blumberga, & Gusca, 2017). The wooden chips are first steamed to prepare them for the pulping process. The chips are then mixed with chemicals and cooked under pressure to dissolve the binding material. The yield from chemical pulping is lower than the yield from mechanical pulping, but it renders a pulp with less impurities that can be used for higher quality paper (Bajpai, 2016). Chemical pulp is often used in the production of packaging paper or office paper (SkogsSverige, 2016).

The pulp is further processed depending on how it was produced. A common practice is to mix pulp produced by different methods to achieve the wanted properties and quality of the paper (Skogsindustrierna, n.d.). In the papermaking process, the pulp is first deposited on a moving belt. The water content of the pulp is high, so water must be removed - either by gravity or by sucking water from the pulp. The pulp is then transported on the belt through rollers which compresses the pulp and forms sheets of paper (Bajpai, 2016). The raw paper can be further processed depending on the desired properties. A common treatment is to coat the paper to protect the surface (Bajpai, 2016). The finished paper is subsequently cut into sheets of paper, or rolled, depending on the requests of the customer (Fiskeby Board, n.d.). There are several different qualities of paper that can be produced (Bajpai, 2016).

Recycling

Paper is collected, impurities are removed and the paper is baled before it is sent to paper mills where it is recycled (Swedish environmental protection agency, 2018). The paper is dumped into a tank where pulping is conducted. The tank contains either hot water or special chemicals that aid the fiber separation. The paper mass is mixed and additional impurities, such as plastic or glue, are removed by filtering of the pulp (Bajpai, 2016), When recycling newspaper or magazines, a pre-treatment step is added to remove the ink. The de-inking is however not conducted if the pulp is destined for corrugated packaging (Haupt, Hellweg, Kägi, Zschokke, & Stettler, 2017). The rejects from the pulping and sorting is usually incinerated. The produced pulp is incorporated in the production process described above and mixed with other pulp qualities to acquire the requested paper or paperboard quality (Fiskeby Board, n.d.). Recycled newspaper is often used in new newspaper. It can however also be recycled into paper towels or toilet paper (Swedish environmental protection agency, 2018).

It is possible to recycle paper 5-7 times before the fibers are too short. After the last recycling, the paper is sent to incineration (Swedish environmental protection agency, 2018). It has been demonstrated that there are clear environmental benefits with recycling papers (Kinsella, 2012). There are however very different usages of the recycled paper and certain paper qualities can be recycled several times more than others. Because of the shortening of the fiber, recycled paper is often mixed with virgin fibers to get the appropriate strength. Office papers are often collected in clean fractions which enables them to be recycled several times. The quality of newsprint is lower, and it can generally only be recycled three times. It is also possible to recycle mixed paper streams. Fibers from mixed streams can however not be used in certain products that require high quality of the fibers, such as office paper (Kinsella, 2012).

Results

WAMPS distinguishes the treated paper into paper packaging and newspaper and magazines. This separation will therefore also be made in the results. It is assumed that paper packaging consist of paperboard and that newspaper consists of paper destined for production of newspapers or magazines. No clear definition of paperboard was found, other than that the density should be higher than 150 g/m^2 and that paperboard contains several layers of paper (Skogsindustrierna, n.d.; Fiskeby Board, n.d.). The results of the literature review can be seen in the two figures below. The results, from WAMPS and from the collected datasets, for virgin production and recycling of newspaper and magazines can be seen in Figure 23.

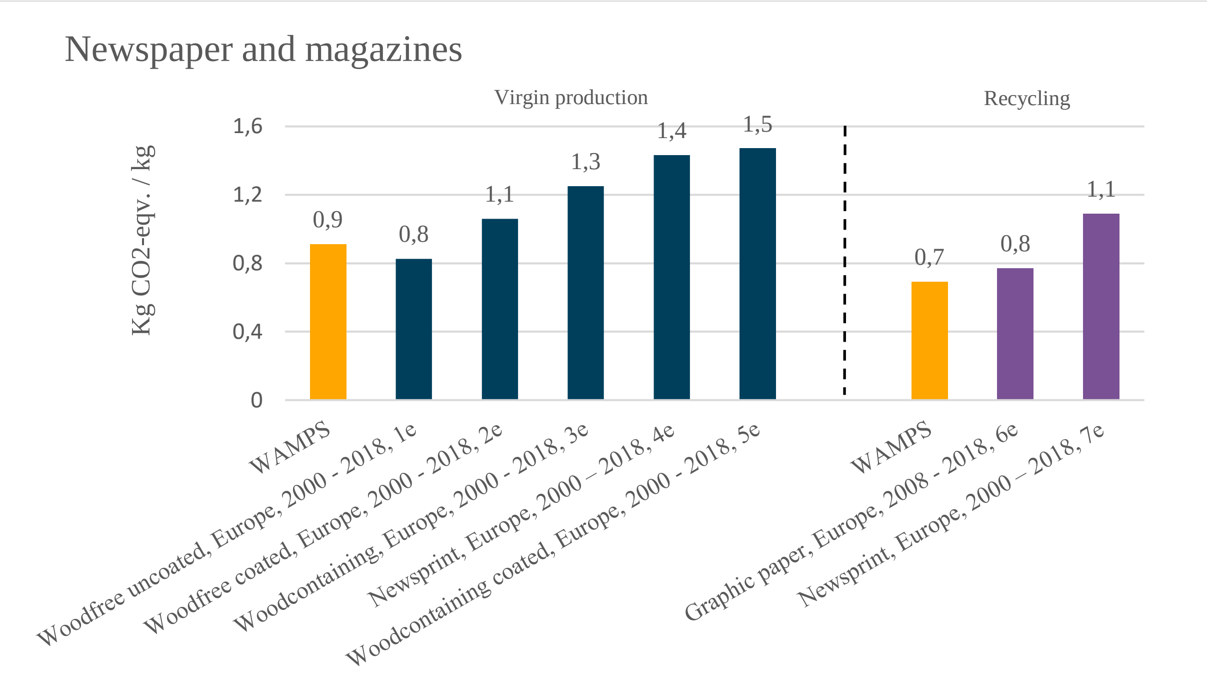

Figure 23. Presentation of the CO_2-equivaents for newspaper production and recycling calculated by WAMPS and identified in literature/databases.

The figure shows that the calculated values in WAMPS are within the values found in literature for virgin production, but lower than the literature values regarding recycling. The datasets for virgin production of newspaper and magazines include similar system boundaries – from extraction of raw material and wood handling to produced paper. The difference between the datasets are the sorts of paper produced and the pulping method. Datasets 1e and 2e include chemical pulping while the other datasets include mechanical pulping. The datasets for recycled newspaper include emissions from collection of paper until production of recycled paper. The dataset 7e includes mechanical pulping but it is uncertain which pulping method that has been utilized in dataset 6e. Merrild et al. (2008) states that the pulping method will have large impacts on the CO_2-equivaents of the process, which could explain the differences between the datasets. It is also stated the mechanical pulping is the process that requires the most energy. The results, from WAMPS and from the collected datasets, for virgin production and recycling of packaging paper can be seen in the Figure 24.

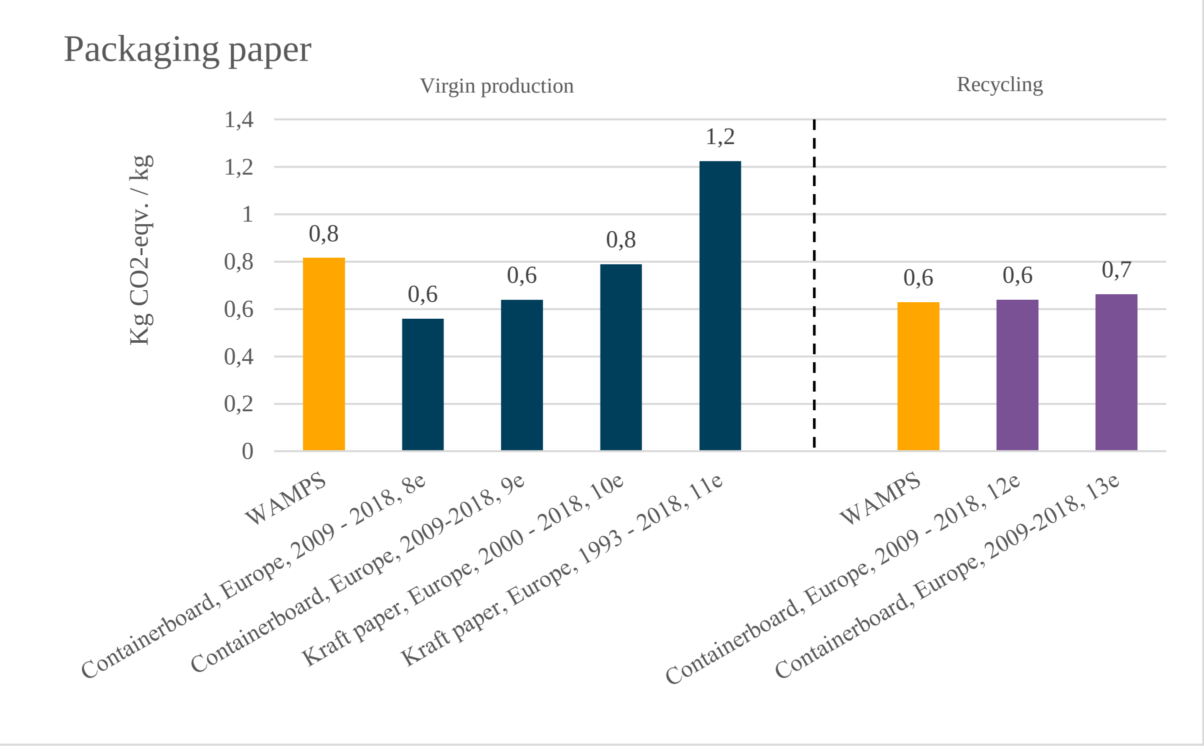

Figure 24. Presentation of the CO_2-equivaents for packaging paper production and recycling calculated by WAMPS and identified in literature/databases.

The figure shows that the calculated values in WAMPS are within the values found for virgin production and recycling. The datasets for virgin production of packaging paper include chemical pulping. The pulp for the recycled paper packaging is created by submerging the sorted paper in water with aiding chemicals. The system boundaries are similar for the datasets for virgin production – from raw materials extraction and wood handling to produced paper. However, dataset 8e includes 0.45 kg of wastepaper to produce 1 kg of packaging paper. Dataset 9e includes 0.1 kg recycled paper. This could explain the low CO_2-equivaents for dataset 8e. The system boundaries for recycled include emissions from treatment of wastepaper to production of recycled packaging paper.

Comparison

The average values for newspaper and magazines were calculated from all the datasets shown in the figure above. The average values, compared to the calculated value in WAMPS, can be seen in Figure 25.

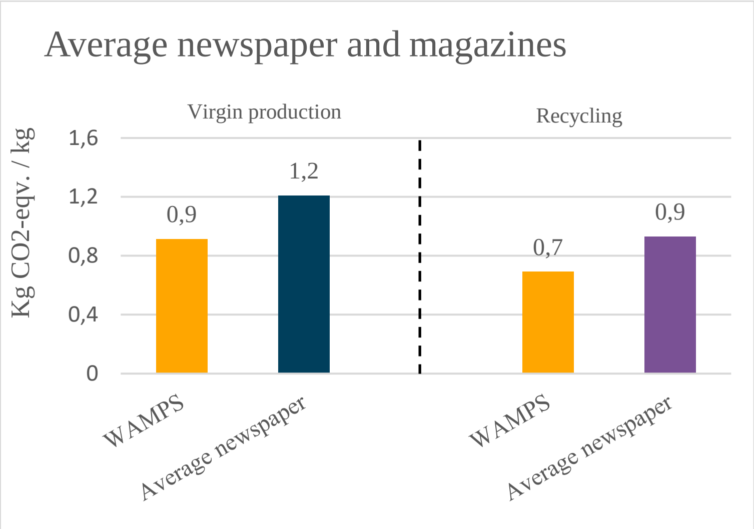

Figure 25. Comparison of the values calculated in WAMPS and the average values from literature/databases for the production and recycling of newspaper and magazines.

The average values for packaging paper were calculated from all the included datasets, except dataset 8e which included a substantial amount of recycled paper. The value for recycled paper was calculated as the average value for the datasets 12e and 13e. The average values, compared to the values calculated in WAMPS, can be seen in Figure 26.

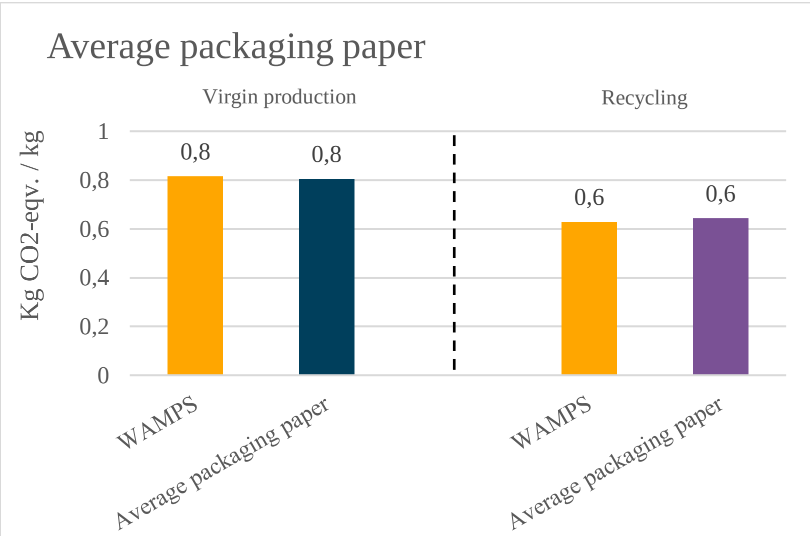

Figure 26. Comparison of the values calculated in WAMPS and the average values from literature/databases for the production and recycling of packaging paper.

From the two figures above, it can be seen that the calculated CO_2-equivalents for virgin production and recycling of newspaper and magazines are somewhat lower for WAMPS than for the corresponding average literature value. The calculated CO_2-equivalents by WAMPS for packaging paper agrees with the corresponding average literature value.

3.2.8 Incineration

Incineration

Incineration is a method of treating a wide variety of wastes. Besides reducing the volume and the hazard of the waste, the treatment method is also used for energy recovery and production of heat and electricity (European Commission, 2006). A simplified description of the components of an incineration plant can be seen in the figure below.

Figure 27.. Basic description of a waste incineration plant. Based on (European Commission, 2006).

The collected waste is delivered to the incineration plant where it is dumped into a bunker. An overhead crane loads the waste into the incineration chamber where it is incinerated. Several technologies for incineration exist. The most common method in Europe (applied by 90% of the incineration plants) is the grate system. The grate functions as a conveyor which transports the waste to and mixes the waste within the incineration chamber. A chain reaction of combustion is created when a certain temperature is reached, alleviating the need for additional fuels. In the process, flue gases are formed which contain most of the energy from the waste. The gas can thereafter be cooled by transferring the heat to a liquid, normally water. The energy transfer can heat or evaporate the water which subsequently can be used to deliver heat and the steam can be used to generate electricity (European Commission, 2006, 2009).

A complete combustion generates mainly water vapor, nitrogen, oxygen and carbon dioxide. There are however also other substances released or generated in the process which should be removed before the emissions can be released to the atmosphere. The cleaning of the gas is constituted by many units that clean the gas from different substances. Which cleaning units that are incorporated however varies from plant to plant. The incineration also generates residues which can be roughly divided into bottom ash (solid ash from the grate) and fly ash (dust from the flue gas). Bottom ash can constitute about 20 to 30% of the incoming waste while fly ash only constitutes a few percent. The treatment of these residues depends on the quality of the ash as well as the location of the incineration plant. The ashes can be used in construction material, landfilled or, in some cases materials, such as metals, can be extracted and recycled from the ash (European Commission, 2006).

Similarly to recycling of materials, it is possible to assume that the benefits of the incineration, e.g. energy recovery, can substitute energy in the background system. There are however several aspects to consider which influence the climate impact of the generated energy, such as ancillary materials used, the recovery efficiency of the incineration plant, which processes that are used in the flue gas cleaning, water content in the waste and how the residues are treated, to mention a few (European Commission, 2006, 2009).

Production

There are also several aspects to consider when determining which energy to substitute in the background system. What energy carriers that are used to produce will impact the climate impact of the energy, for example electricity generated from coal or renewable sources will have significantly different impacts. Which method that has been used for production is also of importance. For example, if heat and electricity has been generated simultaneously (co-production) or if only electricity has been generated in the process. Generally, heat from the incineration process that is used locally in district heating will substitute heat produced from another source and recovered electricity from the incineration process that is supplied to the grid will substitute the national or regional electricity mix (European Commission, 2009).

Results

Since incineration is a multi-output process, the result is presented separately for the foreground (incineration process) and the background system (production of electricity and heat from other sources).

Incineration

The fraction "combustible waste" in WAMPS was not comparable to any corresponding datasets in Ecoinvent since these represented incineration of waste with a greater share of inert material. The most recent dataset for incineration was identified as incineration of plastic waste in Switzerland. It was assumed that this dataset was comparable to incineration of plastic mix in WAMPS. The dataset represented an average Swiss incineration plant in 2012 (Doka, 2015). To make the comparison possible, the small amount of electricity used internally in the incineration process was set to represent average Swedish electricity in WAMPS. Swiss and Swedish electricity was assumed comparable, due to the similarities in CO_2-equivalents per generated kWh (25 g CO_2-eqv./kWh and 29 g CO_2-eqv./kWh respectively, including trade of electricity with surrounding countries (Moro & Lonza, 2018)). The dataset from Ecoinvent presented the energy content in the plastic waste as the upper heating value: 34.05 MJ/kg, and the lower heating value 30.79 MJ/kg. WAMPS calculated the energy content in the plastic waste mixture to 34.1 MJ/kg waste. No information was however available whether this represented the lower or the upper heating value. The results, from WAMPS and from the collected dataset, for incineration of plastic waste can be seen in Figure 28.

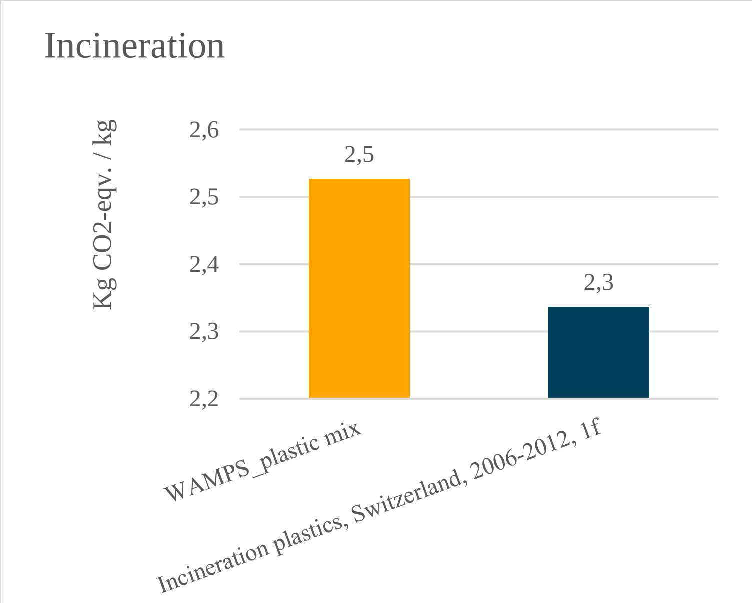

Figure 28. Presentation of the CO_2-equivaents for incineration of plastics calculated by WAMPS and identified in Ecoinvent.

From the figure it can be seen that the calculated CO_2-equivalents from WAMPS were higher for incineration of mixed plastic waste, compared to the corresponding literature value. The values are however uncertain due to the lack of information on what the calculation in WAMPS includes.

Production of heat and electricity

WAMPS includes the options to choose heat generated from Biofuel, Natural gas or Oil. How these values compare to corresponding datasets from literature can be seen in Figure 29.

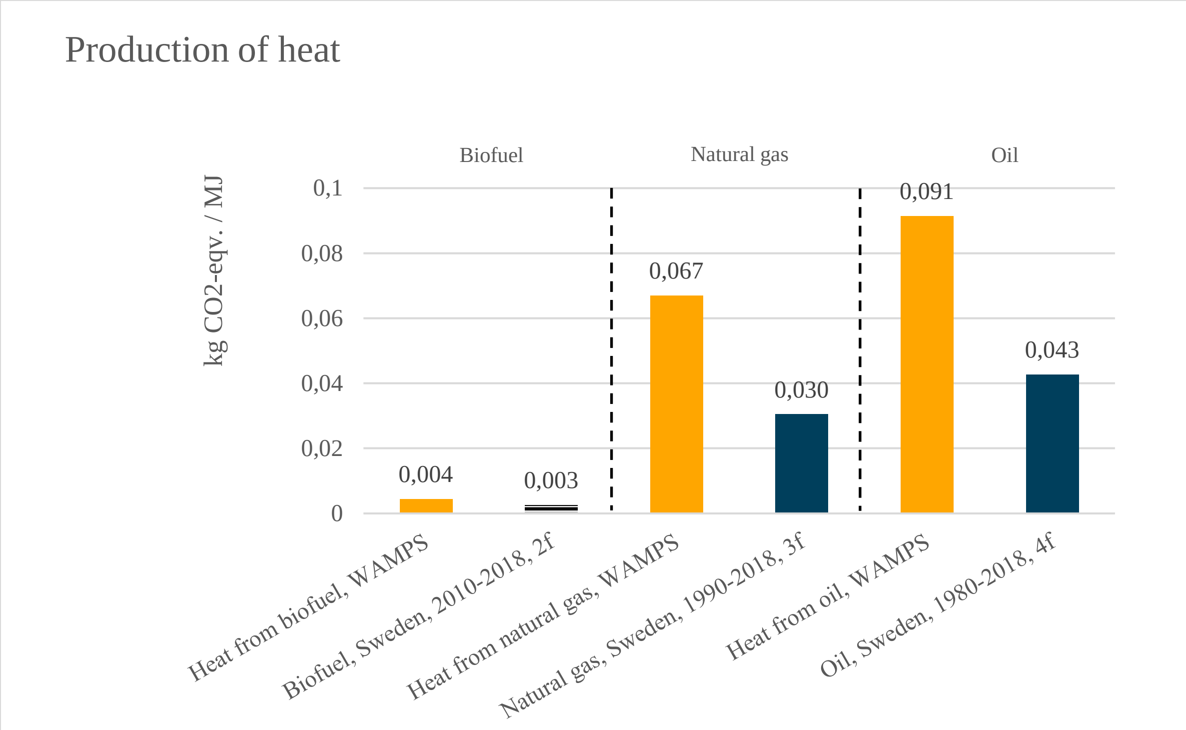

Figure 29. Presentation of the CO_2-equivaents for production of heat from different fuels calculated by WAMPS and identified in Ecoinvent.

The figure shows that the calculated values in WAMPS are higher than the literature values for the corresponding production of heat. The datasets represent production of heat in Sweden. The values calculated by WAMPS have been calculated with Swedish electricity usage, to make the values comparable. The difference is substantial for heat produced from natural gas and oil. One explanation to this difference could be the generation method. The literature values represent the emissions from heat when heat and electricity is co-produced (See Table 23). This production method was chosen as it was assumed that modern heat production would also include electricity production. No information was available on the heat generation method used in WAMPS.

WAMPS includes the options to choose electricity generated from different single energy carriers, or national averages. The values for some of the calculated national averages, and how these compare to corresponding literature values, are presented in Figure 30.

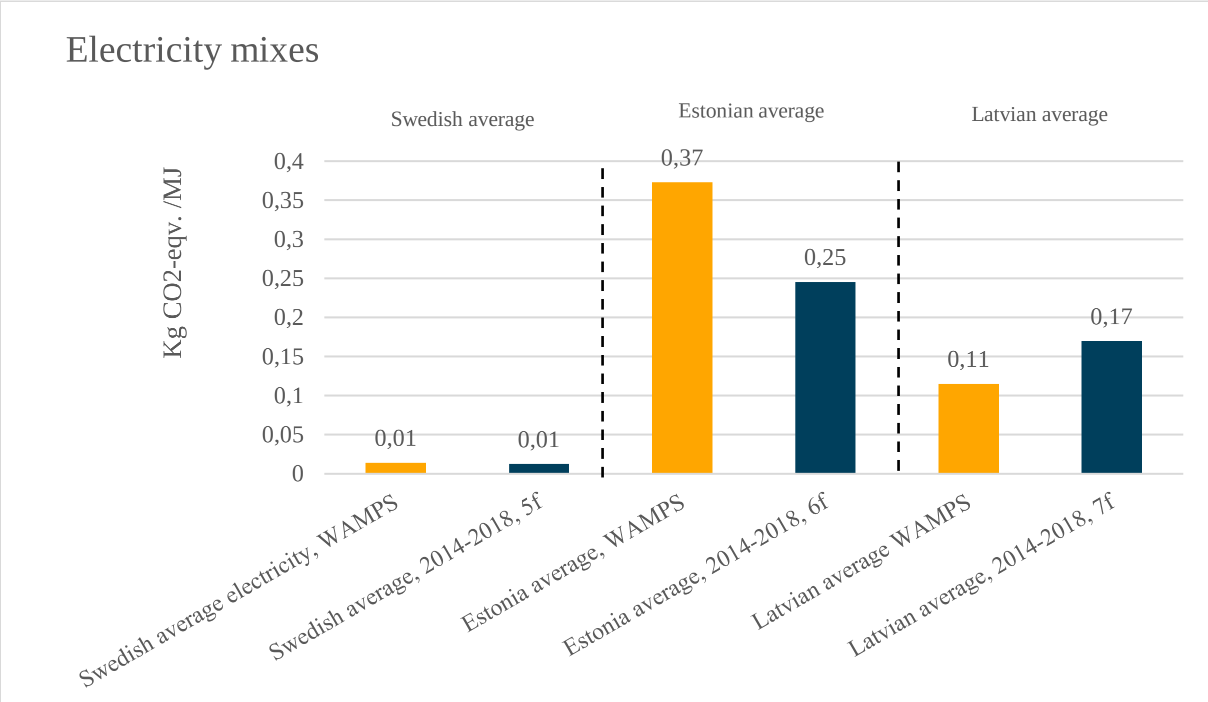

Figure 30. Presentation of the CO_2-equivaents for average electricity in Sweden, Estonia and Latvia calculated by WAMPS and identified in Ecoinvent.

The figure shows that the calculated values in WAMPS in agreement considering the Swedish average, higher than the Estonian average and lower than the Latvian average. The datasets where chosen as market values for electricity, i.e. including domestic production and imported electricity.

Comparison

No average values were calculated since only one corresponding dataset was found for each assessed value in WAMPS. However, a simplified scenario was used to enable a comparison of the incineration and the substituted energy. It was assumed that the plastic waste had the calorific value of 34.1 MJ/kg (which is assumed in WAMPS). It was further assumed that this type of plastic waste was incinerated in an incineration plant in which 10% of the energy in the plastic was lost, 65% of the energy was recovered as electricity, and 25% of the energy was recovered as heat. It was also assumed that the produced electricity from the incineration plant (22 MJ/kg, see Table 7) would substitute Swedish average electricity. The emissions for producing the same amount of electricity in the background system was 0.1 CO_2-eqv./kg incinerated plastic (see Table 7). The same assumptions were made for substitution of heat, with the difference being that the incineration process generated 8.5 MJ heat/kg plastic incinerated, which was assumed to substitute heat generated from Biofuel in the background system. Production of the same amount of heat from Biofuel emits 0.05 CO_2-eqv./kg incinerated waste. The sum of the emissions (from production of heat and electricity) in the background system becomes, for the assumed scenario, 0.15 CO_2-eqv./kg incinerated waste.

Table 7. Description of the calculations for an assumed incineration scenario.

	Energy produced by incineration	Energy production in background system (see Figure 30)	Emissions from generation of the same amount of energy in the background system
Electricity	34.1 (MJ/kg) * 0.65 = 22.2 MJ/kg incinerated plastic	Swedish average: 0.012 CO_2-eqv./MJ	22.2*0.012 = *0.10* CO_2-eqv./kg incinerated plastic
Heat	34.1 (MJ/kg) * 0.25 = 8.5 MJ/kg incinerated plastic	Biofuel: 0.0025 CO_2-eqv./MJ	8.5*0.0025= *0.05* CO_2-eqv./kg incinerated plastic

The same scenario was calculated in WAMPS for production of substituted heat and electricity. I.e. an incineration plant that recovered 65% electricity and 25% heat and where it was assumed that the produced heat would substitute heat from biofuels and that the produced electricity would substitute Swedish average electricity. The result from the calculations can be seen in Figure 31.

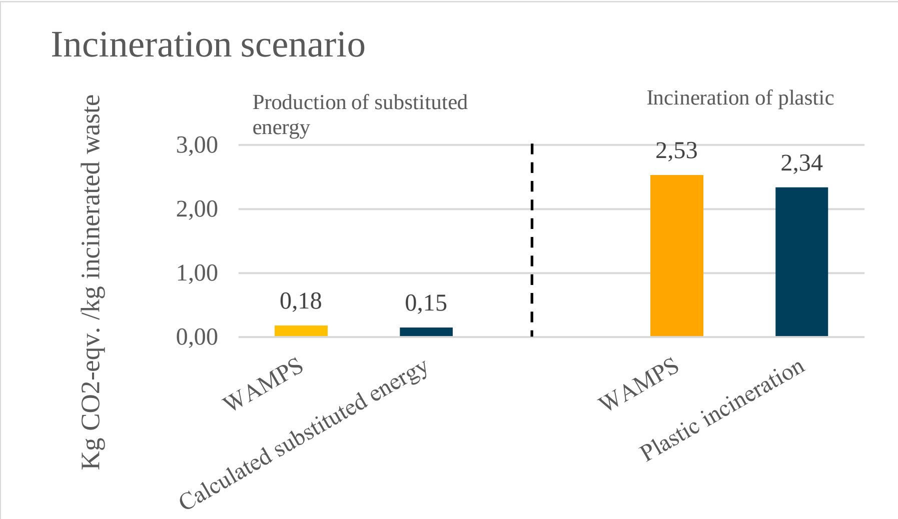

Figure 31. Comparison of the calculated scenario where incineration of plastic substitutes heat from biofuel and average Swedish electricity.

The values for production of substituted energy in the figure are calculated from the scenario described above. Even if the scenario was a simplified case, it is still possible to compare the relative difference between WAMPS and the calculated value based on values from Ecoinvent. The figure shows that WAMPS calculates a somewhat higher value in the background and in the foreground system, compared to the corresponding value from literature. The values contain several uncertainties, since Swedish and Swiss incineration is compared, and since the emissions for the substituted energy is calculated from a specified scenario.

3.2.9 Composting

Composting

Composting is a treatment method suitable for organic waste of good structure, for example garden waste. The structure is important to allow oxygen to penetrate the compost and to have limited moisture content in the compost. There are several technologies used for composting. It can be done as home composting but also in open or closed industrial composts. The benefits of a closed compost are that the important factors such as oxygen and moisture in the process can easily be regulated (European Commission, 2009). Processed compost contains about 0.7% Nitrogen, 0.4% Phosphorus and 0.6% Potassium (Parada Tur, 2012) which can substitute mineral fertilizer. It is possible to achieve a substitution ratio close to or even above 1:1 of the nutrients in compost and fertilizer since the bioavailability is higher for compost. There are also other benefits of compost that are often neglected in LCAs such as improved soil structure and health, reduced need of pesticides and improved water retention of the soil (European Commission, 2009).

Substitution of fertilizers

There are primarily three nutrients that mineral fertilizers contain – Nitrogen (N), Phosphate (P) and Potassium (K) (FAO, 2017), which are also the primary nutrients a plant needs for growth. Mineral fertilizer can contain one, or a combination, of the primary elements. The fertilizer can however also contain a smaller number of elements that plants need to a smaller extent, such as Mg, S and Zn. Several production methods for mineral fertilizers exist. The most common fertilizers in Europe are solid fertilizers which are formed to granulate or solidified from droplets (Environment Agency Austria, 2017).

Results

Reliable data for average European composting was not found. Instead, country specific composting is presented. The result is presented separately for the foreground system (composting) and the background system (production of mineral fertilizers).

Composting

The results, from WAMPS and from the collected datasets, for composting of biowaste can be seen in Figure 32.

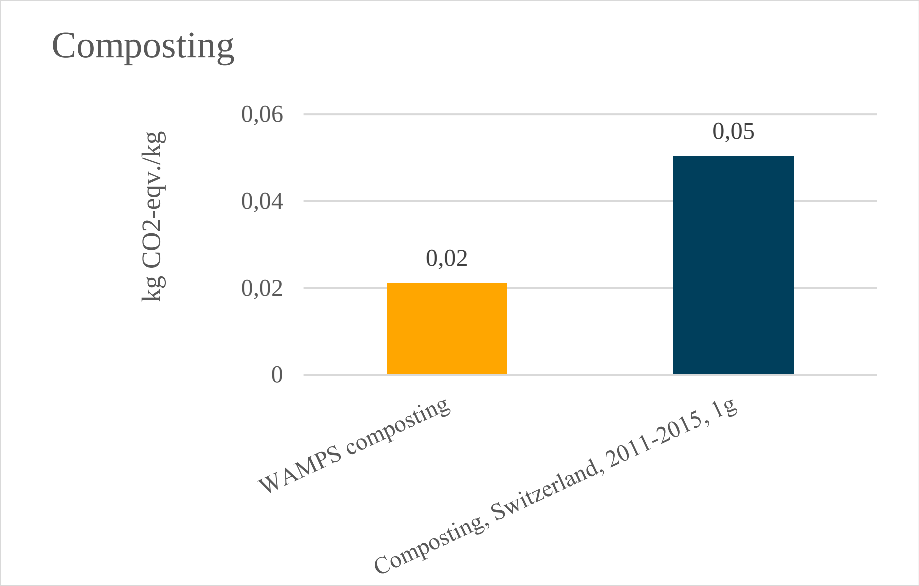

Figure 32. Presentation of the CO_2-equivaents for composting of biowaste calculated by WAMPS and identified in Ecoinvent.

The value for composting of biowaste represents composting in Switzerland. A similar assumption is used as in the case of incineration, that Swiss and Swedish treatment is comparable. The value for WAMPS represents composting of garden waste in Sweden in a closed composting facility. The dataset represents industrial composting of biowaste. From the figure, it can be seen that the calculated value for composting in WAMPS is lower than the corresponding value identified in literature.

Production of fertilizer

WAMPS assumes that the compost substitutes N and P fertilizers. K-fertilizers are included from literature to see how it could impact the result. How the values compare for production of fertilizers can be seen in Figure 33.

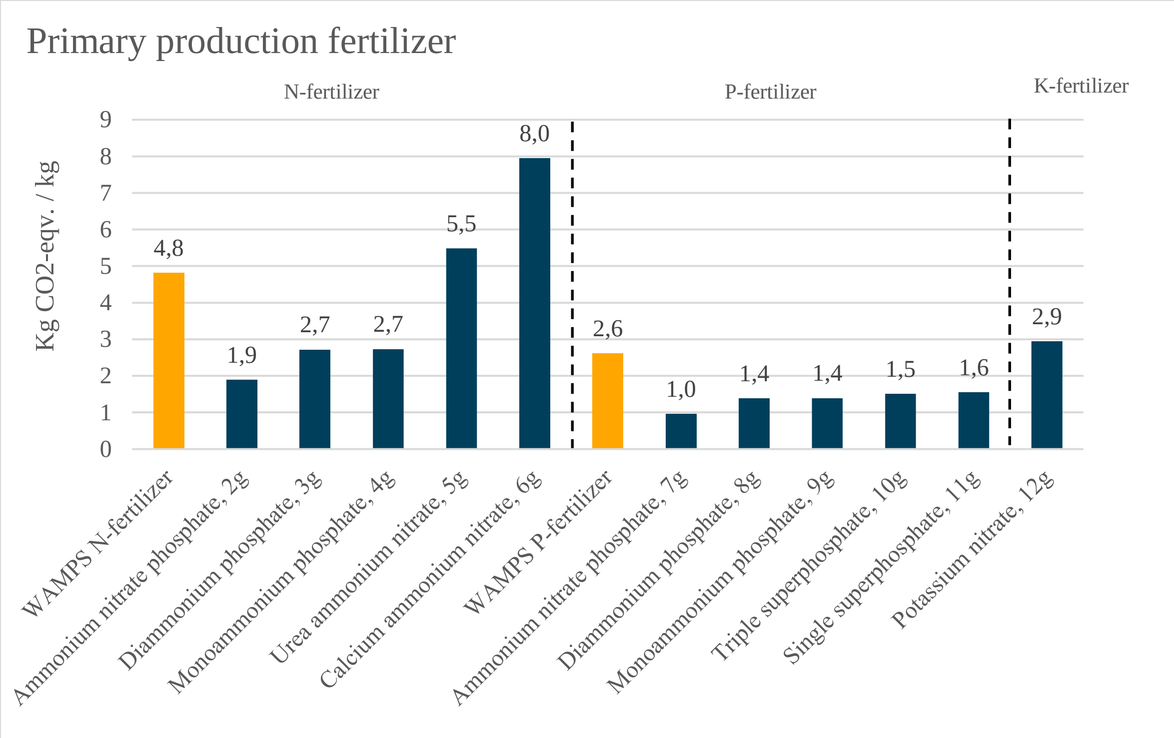

Figure 33. Presentation of the CO_2-equivaents for production of N-, P- and K-fertilizers from different mineral fertilizers.

The figure shows that the calculation for production of N-fertilizer in WAMPS is within the corresponding datasets. The calculated production of P-fertilizer is higher in WAMPS than the corresponding literature. No value for K-fertilizer is included from WAMPS since it is not assumed in WAMPS that compost substitutes K-fertilizers.

Comparison

The share of N-, P- and K-elements in the compost was different from WAMPS and the source used from Ecoinvent. The share of the nutrients can be seen in Table 8. Both sources represent the nutrient content in dry matter, i.e. excluding the water content.

Table 8. The share of nutrients in compost reported by WAMPS and by Parada Tur (2012).

	N-content	P-content	K-content
WAMPS	4.8 g/kg	1.2 g/kg	-
Parada Tur (2012)	7.18 g/kg	3.33 g/kg	6.32 g/kg

A weighted average value was calculated for the emissions of the substituted fertilizer from the literature values. An average value was calculated for each of the nutrients (N, P and K) by calculating the average of the datasets for each nutrient separately (see Figure 32, all the datasets for each nutrient where used in the calculations). The average value for each nutrient was then multiplied with the content of that nutrient in the compost (which can be seen in the table above, in the row with values from Parada Tur (2012)). The weighted averages were added together to obtain an estimation of the emissions from the substituted fertilizers. The K-fertilizer was included in the calculation of the literature values to investigate whether the inclusion of K-fertilizer is necessary. A corresponding value for the emissions of the substituted fertilizers was calculated in WAMPS. This calculation however used the values for the content of the fertilizers in content from WAMPS. The calculated average values can be seen in Figure 34.

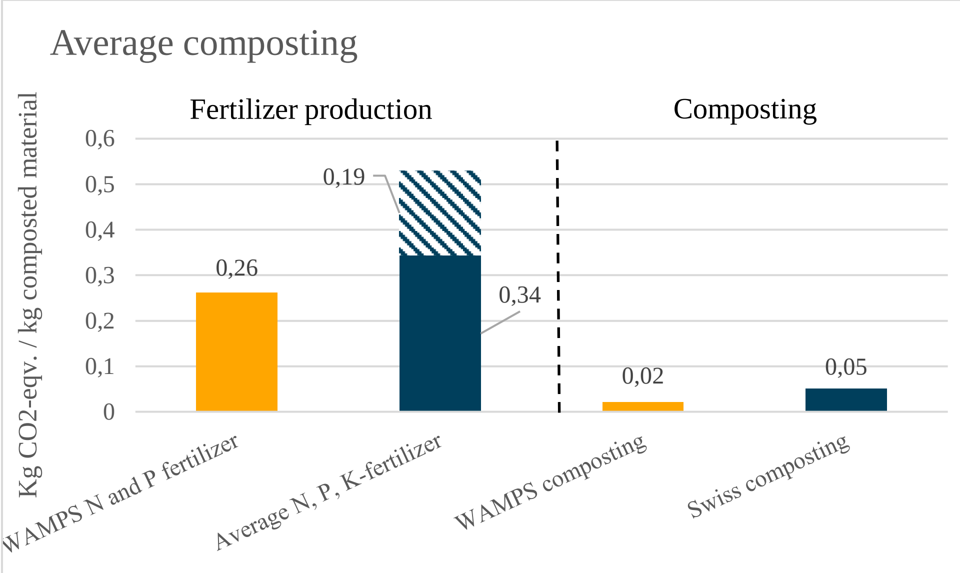

Figure 34. Comparison of the values calculated in WAMPS and the weighted average values from Ecoinvent for composting and production of fertilizers. The dashed area represents the production of K-fertilizer. It is dashed because K-fertilizers are not included in WAMPS.

The figure shows that the calculated values in WAMPS are lower than the corresponding average values for composting and fertilizer production from Ecoinvent.

4 Analysis

In this section, the calculated averages for the treatment systems from the previous sections are presented collectively. A compiled result allows for easier assessment of the differences between WAMPS and literature. The differences will be calculated in absolute numbers and in percentages, to display the differences in absolute and relative quantities. The relative difference can be used as a measurement of how much WAMPS deviates relative to literature, while the absolute value is of importance for comparison of the differences between the fractions and to quantify the effect of the differences. The percentages are calculated relative to the numbers in WAMPS, i.e. a positive percentage/absolute number indicates the corresponding value from literature is higher than the one calculated by WAMPS. The compiled comparison sections for the treatment of waste (the foreground system) can be seen in Figure 35.

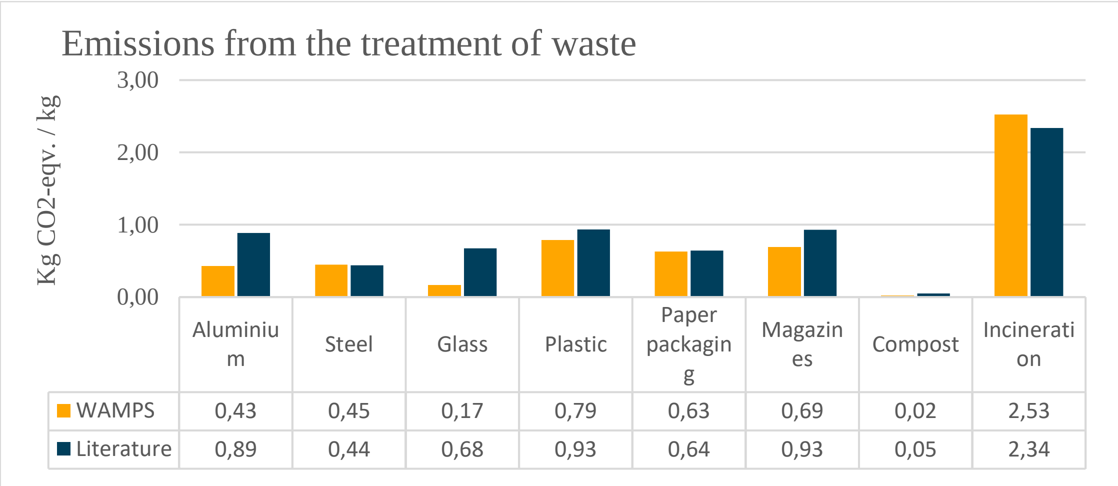

Figure 35. Average values from literature for treatment of waste compared to the corresponding values calculated in WAMPS.

The number of sources used in the calculations of the literature values, and the distribution within the calculated values are: Aluminium - average 0.89, distribution 0.8-1.0, based on 2 sources. Steel – average 0.44, distribution 0.2-0.7, based on 2 sources. Glass – average 0.67, distribution 0.5-0.9, based on 8 sources. Plastic – average 0.93, distribution 0.6-1.1, based on 5 sources. Paper packaging – average 0.64, distribution 0.63-0.66, based on 2 sources. Magazines – average 0.93, distribution 0.7-1.0, based on 2 sources. Composting and incineration based on 1 source.

Table 9. The absolute and relative differences between WAMPS and the average values from literature, for waste treatment.

Difference	Aluminium	Steel	Glass	Plastic	Paper packaging	Magazines	Compost	Incineration
Absolute (kg CO_2-eqv./kg)	0.46	-0.01	0.51	0.14	0.02	0.24	0.03	-0.19
Relative (%)	107	-2	309	18	2	35	144	-8

The figure and The number of sources used in the calculations of the literature values, and the distribution within the calculated values are: Aluminium - average 0.89, distribution 0.8-1.0, based on 2 sources. Steel – average 0.44, distribution 0.2-0.7, based on 2 sources. Glass – average 0.67, distribution 0.5-0.9, based on 8 sources. Plastic – average 0.93, distribution 0.6-1.1, based on 5 sources. Paper packaging – average 0.64, distribution 0.63-0.66, based on 2 sources. Magazines – average 0.93, distribution 0.7-1.0, based on 2 sources. Composting and incineration based on 1 source.

Table 9 above show that the largest relative differences between WAMPS and literature averages are observed for the treatment of glass (309%), compost (144%) and aluminium (107%). The largest absolute differences between WAMPS and literature are identified in the treatment of glass (0.51 kg CO_2-eqv. /kg) and in the treatment of aluminium (0.46 kg CO_2-eqv. /kg).

The compiled results for the production of the substituted products (the background system) can be seen in Figure 36. To make the figure comparable to the figure above (Figure 35), some adjustments were performed. When recycling materials, it can not be assumed that the recycled material substitutes the same amount of virgin material, in all cases. Substitution ratios are used to determine how much of the recycled material that can substitute virgin material in the background system. The substitution ratios only apply to the paper packaging, plastic and newspaper-fractions (see appendix A – substitution ratio). These fractions have therefore been multiplied with their substitution factors. The substitution ratios from WAMPS have been used in the calculations (see appendix A – substitution ratio). For example, plastic has the substitution ratio of 1:0.95, hence, 1 kg of recycled plastic is assumed to substitute 0.95 kg virgin plastic. To make the emissions for virgin production of plastic represent the emissions caused by the substitution, they have been multiplied by 0.95. The compiled result can be seen in Figure 36.

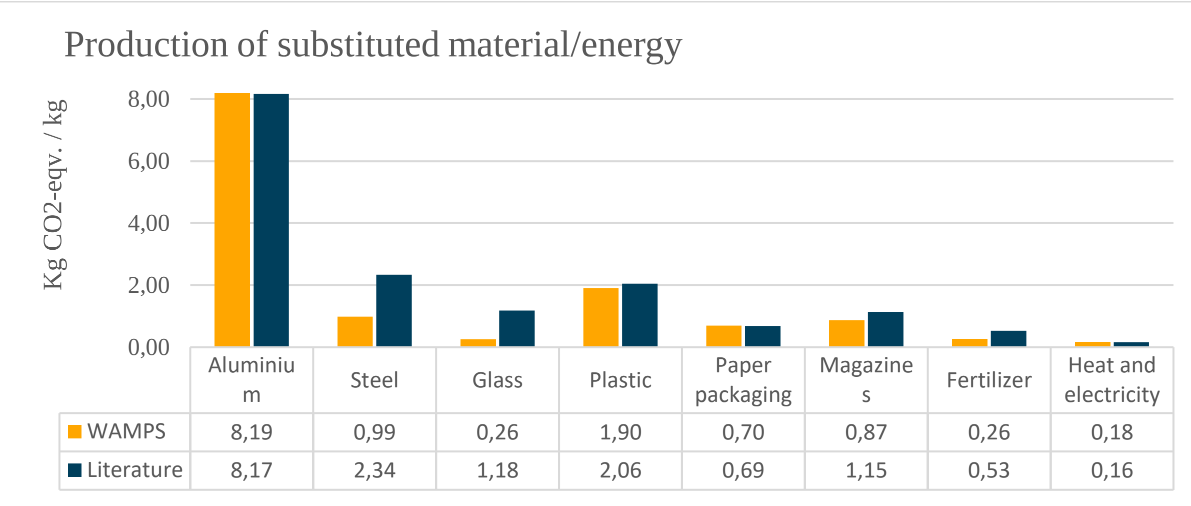

Figure 36. Average values from literature for production of the substituted materials/energy compared to the corresponding values calculated in WAMPS.

The number of sources used in the calculations of the literature values, and the distribution within the calculated values are: Aluminium – average 8.17, distribution 7.3-9.0, based on 2 sources. Steel – average 2.34, distribution 2.2-2.7, based on 4 sources. Glass – average 1.18, distribution 0.9-1.3, based on 4 sources. Plastic – average 2.06, distribution 1.6-3.2, based on 9 sources. Paper packaging – average 0.69, distribution 0.6-1.2, based on 4 sources.

Magazines – average 1.15, distribution 0.8-1.5, based on 5 sources. Fertilizer – average 0.53, which is the CO_2-equivalent for production of the fertilizer substituted by 1 kg of compost. The distribution of the production of the fertilizers (per kg produced fertilizer) were 1.0-8.0, based on 11 sources. The emissions from the heat and electricity was based on 1 source for the heat and the electricity respectively.

Table 10. The absolute and relative differences between WAMPS and the average values from literature, for the substituted products.

Difference	Aluminium	Steel	Glass	Plastic	Paper packaging	Magazines	Fertilizer	Heat and electricity
Absolute (kg CO_2-eqv./kg)	-0.02	1.35	0.93	0.15	-0.01	0.28	0.27	-0.02
Relative (%)	0	137	360	8	-1	32	102	-9

The figure and Table 10 above show that the largest relative difference between WAMPS and literature averages are observed in the virgin production of glass (360%), steel (137%) and fertilizer (102%) (the literature value accounts for K-fertilizer). The largest absolute differences between WAMPS and literature are identified in the production of steel (1.35 kg CO_2-eqv. /kg virgin steel) and in the production of glass (0.93 kg CO_2-eqv. /kg virgin glass).

The analysis so far only address the difference between literature and WAMPS for identified in the foreground- and in the background system separately. The main purpose of WAMPS is however not to calculate the emissions from production or treatment of single fractions, but to calculate the net impact of recycling, i.e. accounting for the impact of the treatment process and the avoided emissions caused by substitution of the produced material/energy from the treatment system. The next comparison will therefore be on the differences in net-result caused by the differences between WAMPS and literature. The formula for calculation of the net result is (as presented in chapter 2.4.2)

$$E_{net} = E_{foreground} - E_{background} \tag{1}$$

Where $E_{foreground}$ are the emissions from the treatment system and $E_{background}$, the emissions from the virgin production of material/energy that is substituted. For example, the emissions for recycling 1 kg of aluminium (calculated in WAMPS) is 0.43 kg CO_2-equivalents (which can be seen in Figure 35). It is assumed that the recycled aluminium will substitute virgin aluminium. Production of virgin aluminium (calculated in WAMPS) results in emissions of 8.19 kg CO_2-equivalents/kg (which can be seen in Figure 36). The net effect of the recycling thus becomes the impact of the recycling process, minus the impact from the virgin production process, i.e. 0.43-8.19= -7.76 kg CO_2-equivalents/kg. The minus sign indicates a net saving. To assess the impact of the differences in the calculations of WAMPS, the net result was calculated by subtracting the values presented in Figure 35 with the values presented in Figure 36. The net result of the treatment systems can be seen in Figure 37.

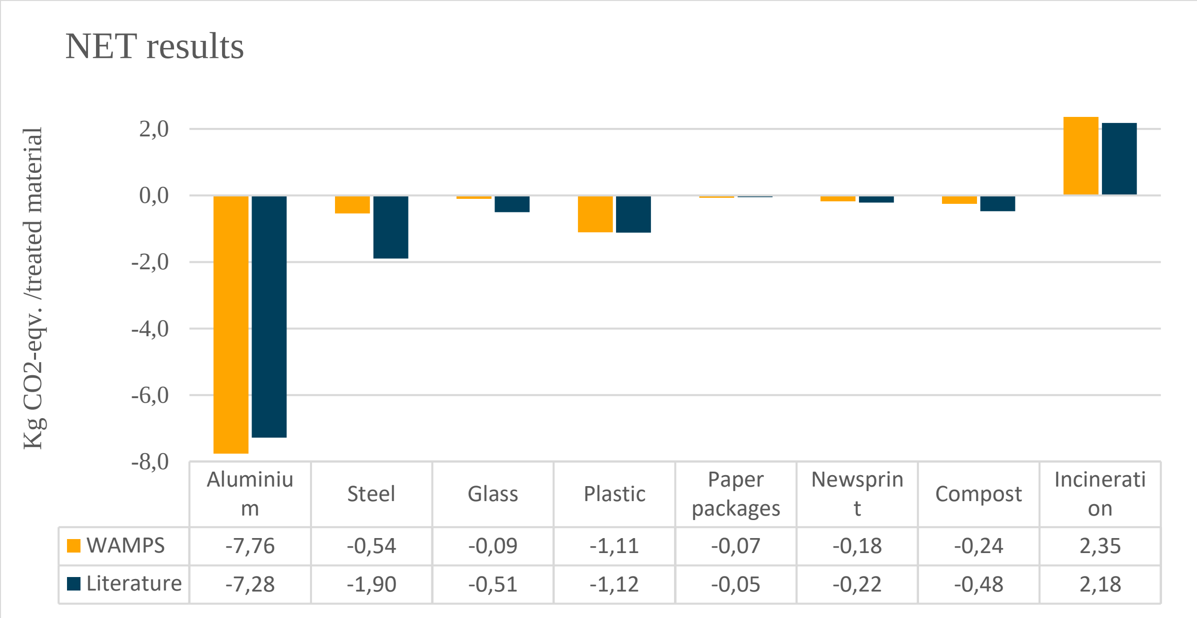

Figure 37. The calculated net-result for each of the treatment systems.

Table 11. The absolute and relative differences between WAMPS and the calculated averages for the net result of the treatment systems.

Difference	Aluminium	Steel	Glass	Plastic	Paper packages	Newsprint	Compost	Incineration
Absolute (kg CO_2-eqv./kg)	0.48	-1.36	-0.42	-0.01	0.02	-0.04	-0.24	-0.17
Relative (%)	-6	253	453	1	-33	23	99	-7

Figure 37 and Table 11 above show that the largest relative difference between the net result for WAMPS and literature are observed for recycling of glass (453%), recycling of steel (253%) and compost production/fertilizer substitution (99%). The largest absolute differences between WAMPS and literature are identified for recycling of steel (-1.36 kg CO_2-eqv. /kg) and recycling of glass (-0.42 kg CO_2-eqv. /kg).

The comparison of the net result showed substantial differences between WAMPS and literature for the different treatment methods. The comparison was however made per kg of treated waste. In reality, the share between the fractions are entirely different. WAMPS is developed primarily for assessment of municipal solid waste management systems. It would therefore be of interest to investigate how the observed differences would impact the net result, when share of each waste fraction has been considered. For example, the amount of waste aluminium is presumably lower than the amount of incinerated waste in a standard municipality. A small difference between WAMPS and literature when calculating the differences per kg can likely render major differences when one relates the differences to how much waste is treated with each treatment system.

This aspect was accounted for by examining how the net result (in Figure 37) would change if the distribution of the waste composition was taken into account. The examination was done by calculating the following scenario: 1000 kg of municipal solid waste (with the composition of average Swedish municipal solid waste - 5% newsprint, 3% paper packaging, 0.2% steel, 0.2% aluminium, 1% plastic, 5% glass and 7% garden waste for composting (described in chapter 3.3.1 - Method and limitations)) was treated in the treatment systems assessed in this study. Incineration was however excluded since incineration of plastic (which the dataset represents) was not considered a fair representation of the incineration of average waste. This rendered treatment of 52 kg newsprint, 31 kg packaging paper, 2 kg steel, 2 kg aluminium, 15 kg plastic, 45 kg glass and 70 kg garden waste for compost. The treated amounts in this scenario were multiplied with the corresponding net-result per kg, which can be seen in Figure 37. The result from the calculations can be seen in Figure 38.

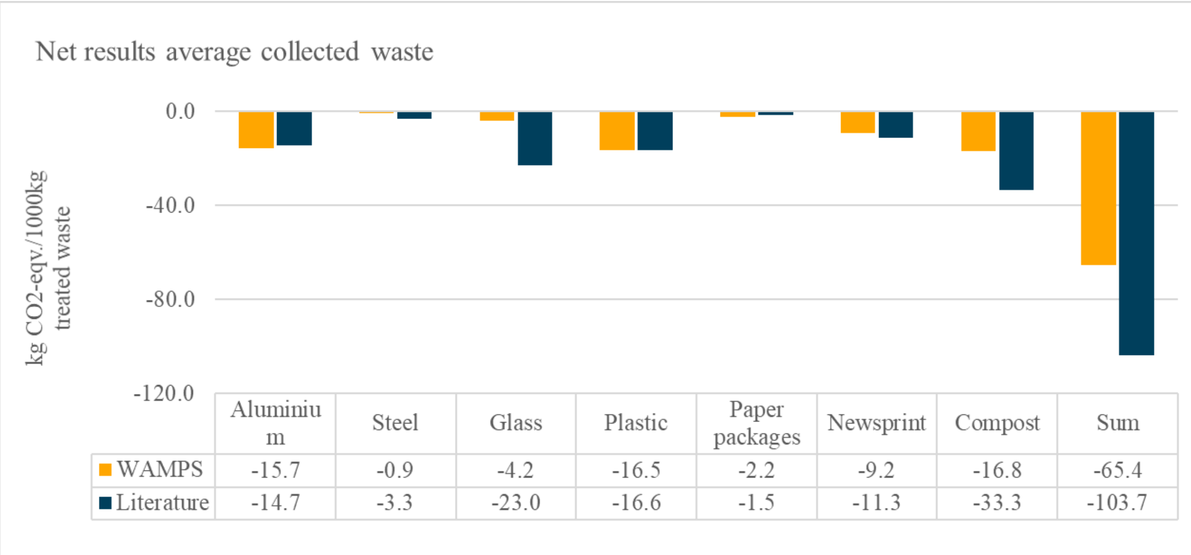

Figure 38. The calculated net-result related to the composition of average municipal solid waste in Sweden for each of the treatment systems.

Table 12. The absolute differences between WAMPS and the calculated averages for the net result related to the waste composition.

Difference	Aluminium	Steel	Glass	Plastic	Paper packages	Newsprint	Compost	Sum
Absolute (kg CO_2-eqv./ 1000 kg waste)	1.0	-2.4	-18.8	-0.1	0.7	-2.1	-16.5	-38.3

Figure 38 and Table 12 above show that the largest absolute differences between WAMPS and literature (when calculating the treatment of 1000 kg waste with average Swedish waste composition) are observed for recycling of glass (- 18.8 kg CO_2-eqv.) and composting of garden waste (-16.5 kg CO_2-eqv.). The summed-up value shows a total difference of -38.8 kg CO_2-eqv. between WAMPS and literature for the assessed fractions. It should however be noted that the assessed fractions only comprise about one fourth of the treated municipal waste in Sweden (see Figure 12).

5 Discussion and Conclusions

Differences between WAMPS and similar tools or studies on waste LCAs was detected by 1) comparing the structure and the included aspects in WAMPS to the structure of similar models. And 2) by comparing the results from the calculations in WAMPS to comparable results found in literature or in databases. The result showed several similarities, but also several differences between WAMPS and literature. These differences will be further interpreted and discussed by answering the stated research questions.

5.1 Structure of WAMPS

- How does the structure of WAMPS compare to similar tools and to literature on waste LCAs?
- What are the major differences in structure?
- Which of these causes of difference in structure are important to integrate into WAMPS?

A literature review performed on reviews assessing and comparing waste LCAs or waste LCA models allowed for a comparison of the structure of WAMPS to similar tools and to waste LCAs. Because WAMPS is a screening tool used for easy assessments, it was expected that the tool would incorporate several simplifications that would compromise the result. The literature review however showed that in the most cases, WAMPS included similar or more complex modules than the assessed tools. It was also shown that WAMPS on several occasions resembled the more advanced ORWARE-model in how it addressed the modeling considerations, which was expected since WAMPS originally was developed from ORWARE.

Despite the overall agreement of WAMPS and the assessed literature, differences were discovered. The level of agreement was judged based on colors depending on the share of the models that incorporated an aspect. A green color was assigned if WAMPS agreed with the assessed models on a topic. A yellow color was assigned if WAMPS did not include an aspect, while some of the assessed tools included it. And a red color was assigned to the row if WAMPS oversaw or did not account for an aspect that was included in all or most of the assessed tools.

The first red category from the evaluation addressed the quality and the documentation of the data and the calculations used in the model. WAMPS include only limited information about the modules in the tool and little to no documentation on the data and the sources of the data used in the calculations. Transparency is a key concept in LCA-methodology. Without it, it is difficult to externally review the calculations. Besides potentially increasing the errors in the result, the lack of transparency foremost effects the trustworthiness of the result. Without the ability to critically state the shortcomings or the limitations of the result based on the shortcomings of the assumptions in the tool, it is not possible to confidently make any conclusions about the reliability of the result. This aspect is especially important since WAMPS sometimes is used for communication of results – either to decisionmakers or to the public regarding the environmental benefits of different waste treatment alternatives. Implementing thorough documentation also enables the user to deal with, and to minimize, potential uncertainty. For example by verifying uncertain parts of the calculations with more reliable sources.

The other red categories address the options for used and substituted energy, and the calculations of the quantity of the reject. The first aspect, the ability to choose one type of energy used in the foreground system and another type of energy for substitution in the background system, is not possible in WAMPS. This is however possible in the assessed models. Even in the models that only allow the user to choose energy mixes and not energy from single sources. How energy is modeled and how customizable the models are, are stressed as important aspects in several of the assessed literature reviews. The second aspect, the calculations of the reject, are only partly integrated in WAMPS. Most of the fractions in WAMPS account only for the reject that arise in the sorting process. There are however also reject formed in the recycling process. How much of the incoming waste that is recycled differs between the fractions (see appendix A – reject). The lack of inclusion of reject from the recycling process mainly influences the plastic and the aluminium fraction. The main consequence of accounting for more reject would be that the emissions from the recycling activity would be greater, since more reject must be treated. The overall result would thus be that the benefit of recycling would decrease.

Several of the categories labeled with a yellow color are categories in which WAMPS agrees with most, or some of the included aspects. There are several aspects in these categories that WAMPS does not include or could improve. It is however not advised that WAMPS should implement all the categories at once. Or that the focus should be on all the aspects for the next revision of WAMPS. For some of the aspects, it is not clear how they could be improved and/or implemented.

Generally, the yellow labeled categories can be divided into two parts. The first part comprises the categories that address large topics in WAMPS and that require a considerable amount of work to implement. It is not clear how an improvement of these aspects would improve the accuracy of the model. These categories are: the aspect of system boundaries – to further assess and examine how the system boundaries are defined, compared to other tools. Elemental composition – it is stated that the elemental composition in the models should be verified, no guidance on how or where to find standardized data is however given. Uncertainty – it is stated that uncertainty should be presented in the calculations, no guidance is however given on how to implement it into the models. These categories are possibly of great importance for the calculations of WAMPS, but they deal with large aspects and would thus require a considerable amount of work and time for implementation. It is therefore not recommended that a first revision of WAMPS starts with these categories (at least if the effort should be focused where it is the most effective).

The second part of the yellow labeled categories contains categories that are needed to keep WAMPS updated and relevant. It is important for WAMPS to be able to model the technologies of the current waste management systems. Otherwise, it is not be possible for WAMPS to assess the current waste management scenarios and even less so, to assess future scenarios. The categories in this section are: impact categories – for example implementing a toxicology category, several energy options – for example to be able to choose electricity from solar power or to choose heat mixes, more treatment options – such as gasification or pyrolysis, and to include K-fertilizer in the calculation of compost and anaerobic digestion. One should however keep in mind that the main purpose of WAMPS is to be a simplified tool for easy assessments. It should thus be further assessed whether these aspects are needed in order to model the current and the future waste management systems. And if the implementation of these aspects would improve the result of WAMPS. Adding complexity to the model without a clear reason should be avoided, since it has been concluded by (Winkler & Bilitewski, 2007) that complexity of a model is not necessarily a measure of the accurateness of the delivered result.

5.2 Calculations in WAMPS

- How does the calculations and the results in WAMPS compare to the results found in literature?
- Which are the most significant differences?
- How do these differences impact the result?

By comparing the calculated results from WAMPS with corresponding values from literature or databases, it was possible to assess the differences in results. The first comparison was conducted by comparing the foreground and the background system separately. This comparison showed how the calculations for each fraction and the substituted material or energy compared to literature. The legitimacy of the comparison is however dependent on the uncertainty in the used literature, which can be divided into two types of uncertainty. The first type is connected to the choice of datasets and what activity or material that the datasets represent. This uncertainty is shown in the result section for each fraction by presenting datasets that represent different types of material or energy. In some cases, the variation between the highest and the lowest value found in literature varied considerably. For example, the relative difference between the lowest and the highest value found for virgin production of steel was greater than 100%. Also the number of datasets included in the calculation of the average values varied for each fraction (which is presented after Figure 35 and Figure 36). It is however not sufficient to only consider the number of datasets used in the calculations since the datasets included different amount of information. For example, the dataset for recycling of aluminium was a weighted average of a large share of the recycled aluminium in Europe, while other datasets only contained information from one facility. More information on the information in each dataset can be found in appendix B.

The uncertainty of choosing representative dataset was reduced by contacting one of the developers of WAMPS[7] to verify that the used datasets were comparable to WAMPS. In some cases however, the assumptions in WAMPS were outdated (for example in the case of plastic) or lacked inclusion of some aspects (for example lack of accounting for substituted K-fertilizer). In these cases, datasets where chosen that best represented the current market, which reduced the risk of choosing unrepresentative datasets. The second type of uncertainty is connected to differences within the datasets, such as system boundaries, assumptions, simplifications and processes that were included in the datasets that could jeopardize the validity of the comparisons. This type of uncertainty was minimized by choosing datasets which clearly presented the system boundaries and the included processes, and by using datasets which resembled WAMPS regarding these aspects.

The result from the comparison of the foreground- and the background system showed that the differences (in percent) between WAMPS and literature was the greatest for glass and compost regarding treatment emissions and that the differences were the greatest for glass, steel and

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[7] Jan-Olov Sundqvist, ILV Swedish Environmental Research Institute.

compost regarding production of substituted material (see Figure 35 and Figure 36). The database values for virgin production of glass represented global production, which could explain the revealed difference. However, looking at the recycling of glass, it can be seen that the value deviates almost as much as for the virgin production (The number of sources used in the calculations of the literature values, and the distribution within the calculated values are: Aluminium - average 0.89, distribution 0.8-1.0, based on 2 sources. Steel – average 0.44, distribution 0.2-0.7, based on 2 sources. Glass – average 0.67, distribution 0.5-0.9, based on 8 sources. Plastic – average 0.93, distribution 0.6-1.1, based on 5 sources. Paper packaging – average 0.64, distribution 0.63-0.66, based on 2 sources. Magazines – average 0.93, distribution 0.7-1.0, based on 2 sources. Composting and incineration based on 1 source.

Table 9), even if European data is used, which indicates that the difference for virgin production of glass can not totally be attributed to the usage of global data. It was expected that the values calculated for fertilizer production would be one of the fractions showing largest differences, since the impact of the K-fertilizer was included in the used dataset.

There are several uncertainties included in the calculated values. For example, that European data was used for comparison of a tool developed in Sweden, that reliable sources for plastic recycling of PP was missing and therefore an older source was used, or that the pre-determined LCIA calculations were used from Ecoinvent. The used LCIA data incorporated connections that were not possible to alter. For example, in some datasets, the activity was supplied by material or energy from the global market. It was however not possible to develop more reliable values from the database without an LCA-software, given the timeframe. Other uncertainties are linked to the lack of information on the most common techniques used in a process. For example, it was not possible to find information on the most common fertilizer types used to substitute composted material. Instead, an average value for the datasets was calculated, which could give misleading results if only some of the fertilizers are commonly used for substitution. Yet another uncertainty is connected to the differences in processing techniques. For example, the processes included in production of plastic may be similar globally, but the technology and methods for paper production may vary between countries. These uncertainties can in part explain the differences between WAMPS and literature. Due to the lack of documentation and transparency of WAMPS, it has not been possible to further examine what is included in WAMPS, and thus has it not been possible to quantify the effects of these uncertainties on the result. It is however important to bear these uncertainties in mind when using and interpreting the results.

To answer the question on how the differences between WAMPS and literature effect the result, the net-result was calculated. That is the difference between the emissions from the treatment process (the foreground system) and the emissions from the substituted material or energy (the background system). The net result was calculated using the values from WAMPS and the values from literature separately. The result showed that the largest differences (per kilo treated material) were observed for steel (-1.36 kg CO_2-eqv.), aluminium (0.48 kg CO_2-eqv.) and glass (-0.42 kg CO_2-eqv.) (see Figure 37). These differences are however only communicating differences per kg treated material and not related to the usual distribution of the different waste fractions.

To account for the distribution of the waste fractions, the result was linked to the distribution of municipal solid waste in Sweden (see Figure 12). The result (see Figure 38) showed that glass and compost (if K-fertilizer was included) displayed the largest differences in the assumed scenario. The overall difference was calculated by summarizing the result of each fraction. The sum indicated a total difference between the saved emissions when using values from WAMPS as opposed to using values from literature (38.3 kg CO_2-eqv. additional savings when using literature values as opposed to using values from WAMPS, per 1000 kg of treated waste). As discussed above, this number is not definite and includes several uncertainties which is why it can only serve as an indication of a difference between the values in WAMPS and the values in literature. It should also be noted that not all municipal waste fractions are included in the summarized result (compare Figure 12 and Figure 38) which further suggests that the result only gives an indication of a difference for the included fractions.

The results revealed that an important factor for the impact is the quantity of the fraction. For example, compost, which was not one of the treatment methods that showed the biggest difference when assessing the difference in net-result per kg treated material, was the fraction that showed the second biggest difference when accounting for the treated amount of each fraction. This shows that it is important to consider both the errors in a fraction, but maybe even more so the amount treated by the different treatment systems. It was not possible to include incineration in the last analysis. However, since incineration is a dominating treatment method in Sweden (50 % of Swedish household waste is incinerated, see Figure 12), it is important to have reliable and accurate calculations for incineration, since only a small difference (when assessing difference per kg) can amount to large total effects when accounting for the treated amount. The assessment of the incineration model also revealed considerable differences between the electricity mixes. These should be further assessed, since electricity is reported to be an important contributor to the results.

5.3 Improvement of the model

- How can the tool be improved?
- Which aspects of the tool are most necessary to develop further?

WAMPS can be improved by implementing the categories in the literature review that differ the most from literature (labeled red in Table 5). Such as including quality checked data and documentation of the model, by allowing the user to have more flexibility in choice of energy in the foreground- and the background system and by including reject from treatment processes. Also, the categories that did not differ as much (labeled yellow in Table 5) should be considered for inclusion. Especially the categories that are easy to implement and that are necessary for WAMPS to be able to model modern waste management systems, such as accounting for K-fertilizer, including energy from solar power and including newly developed waste treatments. In addition, the green categories indicate that WAMPS agrees with other models. It could however be the case that the other models (and WAMPS) are lacking regarding some aspect. Future improvements of WAMPS should therefore not neglect the green categories totally, but rather investigate if those categories are sufficient as is to model the reality, or if further improvement is needed.

The main takeaway from the evaluation of the calculated values was to update the fractions that revealed the biggest difference between WAMPS and literature. This turned out to be glass and compost (when accounting for the distribution of the treatment methods). The evaluation also revealed the importance of not only considering and updating the fractions that deviates the most (per kg treated material), but to focus on the treatment systems that treat most of the waste in a municipality. There are however also other aspects to consider. If WAMPS is used outside its intended application (i.e. to assess municipal solid waste) and instead is used, for example, to assess the waste management of a factory that primarily generates metal scrap. Then it is important to include accurate data not only on the fractions that are most common in municipal waste, but also the other included fractions. Of the assessed fractions, steel, aluminium and glass was the fractions that differed the most when assessing the net-result per kg. These fractions should thus also be reviewed. Yet another aspect is the reliability of WAMPS. Winkler & Bilitewski (2007) states that it is important for similar models to be able to model the complexity of the reality. Therefore, the fractions that differed the most in the assessment of the background- and the foreground system, should also be reviewed.

5.4 Discussion of method

The evaluation of the structure of WAMPS was conducted to find possible reasons for deviations in the calculated result. The method used to compare WAMPS and literature was to examine literature on waste-LCAs and reviews that addressed what similar tools ought to include. The structure of the evaluation followed that of the most comprehensive study – Gentil et. al. (2010). Additional categories were added to the assessment if other aspects were stressed in the reviewed literature. The evaluation was performed by assigning a color to each section according to the agreement between the assessed literature and WAMPS. A drawback with this method was that the assessed categories included several aspects of which WAMPS usually agreed with some, but disagreed or did not incorporate other aspects. In most of these cases, the category was labeled with a yellow color, i.e. the color representing an agreement with some of the assessed models. This resulted in that categories that included few aspects where more likely to be labeled red (categories in which all, or a majority of the assessed models, incorporated an aspect that WAMPS did not) and that categories which included more aspects were more likely to be labeled yellow. Another negative aspect of the method was that it did not primarily consider the necessity of adding a certain aspect. An aspect in a yellow category could thus be just as, or even more necessary to incorporate into WAMPS, than an aspect included in a red category. It is therefore advised that all the deviating aspects found in the categories labeled yellow and red (and possibly even green) are assessed, when updating and improving WAMPS.

An aspect that has not been considered in the analysis is the possible limitation in the used literature. The literature that was used for comparison excluded some aspects which thus also were excluded from this study. Some examples of aspects that could be of interest to further examine are: if it is accurate that plastic mix is sent to incineration, or if it is sufficient to only include CO_2, CH_4 and N_2O when accounting for the global warming potential. Another limitation of the study was that the information found in the literature was regarded as truth or the only answer. It is however possible that the literature included errors or that some aspects could be handled in a different way than it was portrayed in the literature. Due to the scarcity of available literature on the subject and due to time limitations it was not possible to quantify or further analyze the reliability of the literature in this study. A more comprehensive study should however be conducted which takes this aspect into account when considering the uncertainty in the results.

The evaluations of the calculations and the result of WAMPS was conducted by comparing the fractions of WAMPS to similar fractions/treatment methods found in literature, or primarily in the database Ecoinvent. As discussed in the section above, 5.2 Calculations in WAMPS, the comparison includes several sources for uncertainty which is why the result should rather be seen as an indication than a proof of deviating calculations. Another option for comparison could have been to compare WAMPS to the result of similar tools. As discussed in the method section, this was however avoided due to previous studies concluding significant differences between the models. The decision on what to include in the assessment, i.e. which fractions, treatment methods and impact categories, was based on the criteria that it should be possible to find reliable data for the processes, and that most of the generated waste from an average municipality should be treated by the included treatment methods. The fractions that were included were conventional fractions or treatment methods that had not changed much during the past years (it was assumed that data with better quality could be acquired for conventional treatment methods). A drawback with only assessing conventional treatment methods is however that the evaluation did not consider the treatment systems with little or uncertain data. If there is little or no data on an aspect, it is possible that also the calculations in WAMPS are lacking in that area. These areas are therefore maybe the most critical to evaluate. A justification of the chosen limitations is however that the study can be seen as a pre-study to a more comprehensive study. The basic fractions and treatment methods were assessed, which should be reliable due to accurate and available data. Large differences in these aspects could however alert the developers that there probably exists greater deviations within the model for the lesser researched fractions, treatment methods and impact categories.

The methods used for the evaluation allows for a relatively narrow evaluation in that it becomes easy to find the cause and relationship of the differences. It thus also becomes easy to pinpoint where, or from which fraction, the deviation originates from. Another possibility would have been to conduct the study on a broader level, by investigating how the deviations in the calculations impact the overall performance of WAMPS. For example, to examine whether the differences could lead to different prioritizing order of the treatment system. Or if WAMPS could recommend treatment options that are not in agreement with the waste directive. This would give interesting and meaningful information. However, the possibility to easily track the cause of the deviations would have been lost in such a broad study. Another possibility would have been to look more narrowly on the tool and to assess the underlying calculations. This was however not possible due to the lack of documentation, which needs to be improved.

5.5 Future research

This study can be seen as a first study to examine the reliability of WAMPS. One natural extension of the study would be to review how the deviating aspects found in this study could be implemented into WAMPS. For example, how to develop an impact category for toxicology. Another possibility is to conduct a more broad and comprehensive study of WAMPS and other models. This could be done in several ways. Either by analyzing additional categories to see how WAMPS comply with other models on those aspects. Or, a more elaborate study could examine categories that might need to be improved in all the models. This could be done by further examining the categories that were labeled with a green color in this study to see how well they comply with LCA-methodology. Or by considering additional categories in the models to see how they comply with LCA-methodology. For example to examine the consequential modeling approach that is used by the models to see if additional aspects should be included, such as avoided landfill or avoided incineration due to material recycling.

5.6 Conclusions

This research aimed to evaluate the structure and the performance of WAMPS, an LCA-based model used for assessments of waste management systems. The evaluation was conducted by analyzing the structure of WAMPS compared to the structure of similar models, and by evaluating the calculations and results to corresponding results found in literature and in databases. The result revealed that similar structural aspects are included in WAMPS, as in most of the other tools. And that the some of the calculations in WAMPS are comparable to similar values found in literature. The evaluation however also suggested that WAMPS is lacking regarding some aspects when compared to other models.

Some of the aspects that impact the performance and reliability of WAMPS deals with the structure of the model. One of these aspects is the lack of transparency and documentation of what is included in the model. The lack of transparency does not only complicate reviewing and quality assurance of the model and it prevents the user from fully understanding the underlying assumptions of the calculated values. It also effects the reliability of communicated results. To avoid this disadvantage of the model, it is recommended that the documentation of WAMPS is further developed.

Another structural difference, which was reported by several sources to be of importance, is the energy-modelling. Especially the choices regarding electricity. Compared to other models, WAMPS differs regarding the ability to choose different energy used in the foreground system as the energy that is being substituted in the background system. The user also lacks the ability to choose electricity generated from some specific sources. A comparison of the electricity mixes further indicated differences between WAMPS and literature on electricity mixes from different countries. It is therefore recommended that the energy modules in WAMPS are further assessed.

Some of the structural differences would directly influence the result. For example, the lack of including substituted potassium fertilizer from compost was demonstrated to produce differences between literature values and WAMPS. Another aspect, that influences several treatment systems in WAMPS, is that only the reject from the pre-treatment of material recycling is included in the calculations. This can however be changed by users with admin access.

The comparison of the calculated values in WAMPS compared to literature indicated differences in the waste fractions glass and compost, when accounting for the distribution of waste in an average municipality in Sweden. When only comparing the treatment methods per treated kg of waste, differences were also indicated for steel. It is recommended that these fractions are further assessed. From the result it could also be concluded that not only the difference in the impact of the treatment (per kg treated material) should be assessed, but also aspects such as how much of the waste that is treated in a specific treatment method should be considered. Small differences between WAMPS and literature per kg treated material could render major differences in the treatment systems that process large quantities of waste. It is therefore also recommended that effort is put into quality checking and examining especially the treatment systems that process large quantities of waste.

The presented result however contains several uncertainties. The result should therefore be seen as an indication of areas which could be deviating, but where more research is needed to verify this. The study is also limited in its extensiveness. To get a more complete evaluation of WAMPS it is recommended that a more comprehensive study is preformed where more aspects are examined and where the structure of WAMPS is compared, not only to other models, but also to LCA-methodology. Another important aspect for future developments is to keep the model updated. The waste management industry is constantly developing. New technologies are being implemented which in turn changes the values that should be used in the calculations. It is therefore recommended that WAMPS continues to be updated and developed to be a competitive and robust LCA-tool for waste management systems, also in the future.

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7 Appendix

7.1 A

System boundaries

A comparison between the system boundaries and what is included in the in- and outputs from WAMPS and the other models can be seen in the table below.

Table 13. Comparison of system boundaries between WAMPS and the models assessed by Gentil et. al. (2010).

Inputs	**Gentil et. al. (2010)**	**WAMPS**
MSW (including zero-burden approach)	9/9	Yes
Fuel	9/9	Yes
Energy	9/9	Yes
Materials	6/9	No
Water	6/9	No
Construction	5/9	No
Maintenance	2/9	No
Decommissioning	2/9	No
Outputs		
Energy	9/9	Yes
Products	9/9	Yes
Direct emissions	9/9	Yes
Construction	3/9	No
Maintenance	2/9	No
Decommissioning	2/9	No

Waste composition and properties

A comparison of the properties of the modeled waste between WAMPS and the assessed models can be seen in the table below.

Table 14. Comparison regarding waste properties between WAMPS and the assessed models.

Waste properties included	**Gentil et. al. (2010)**	**WAMPS**
Number of waste fractions	48, 7, 9, 11, 48, 22, 13, 34, 67	24
Elemental composition (and number of elements considered)	30, 18, 17, 39, 8, 26, 26 Two models do not include elemental composition.	17
Moisture content	8/9	Yes
Calorific value[1]	7/9	Yes, calculated from the elemental composition
Total carbon	7/9	Yes
Carbon fossil	7/9	Yes
Carbon biological	6/9	Yes
Ash content[2]	6/9	Yes
Methane potential	6/9	Yes, calculated from the composition of carbon.
Total solids	5/9	Yes
Volatile solids	5/9	Not directly, but WAMPS differentiates on carbon with different degradability which fills the same purpose.

COD	1/9	Yes, in some modules in WAMPS include Chemical Oxygen Demand (COD).
Differentiation on carbon based on degradability	1/9	Yes, WAMPS differentiates carbon as slowly degradable (biogen/fossil), moderately degradable and easily degradable. This differentiation affects how the degradation of carbon will occur in biological treatment and in landfill (Gentil et al., 2010).

[1] – The calorific value is a measure of the energy content in the waste (CNG Europe, n.d.)
[2] – Noncombustible material (WAMPS)

Reject

Not all materials will be recycled. Some of the incoming weight will be removed in the sorting process, and some will be discarded/lost in the reprocessing or recycling stage. The discarded material is called reject. WAMPS accounts for the reject in different ways for different materials. Most modules include reject as the fraction that is removed during the sorting process only. The reject for paper is however calculated as all the of the incoming material that is lost in the sorting and in the reprocessing stage[8]. The table below is a comparison of the reject assumed in WAMPS and the reject assumed by Rigamonti et. al. (2009). The table however does not present the fraction of reject but rather the amount of material that is treated in the process. The parenthesis indicates which process that is accounted for. For example, WAMPS accounts for the loss of aluminium that will occur during the sorting, but not the aluminium loss during the reprocessing stage. In the next column it is possible to see the calculated value by Rigamonti et. al. (2009). They have calculated that 95% of the incoming aluminium will go through the sorting and that 83.5% of the sorted aluminium will be recovered in the remelting process.

Table 15. Recycling efficiency compared between WAMPS and literature.

	Recycling efficiency WAMPS (%)	**Recycling efficiency (%)** (Lucia Rigamonti et al., 2009)
Aluminium	99 (Sorting)	95 (Sorting), 83.5 (recycling)
Steel	99 (Sorting)	90 (Sorting), 90.5 (recycling)
Glass	95 (Sorting)	90.1 (Sorting), 100 (recycling)
Plastic	75 (Sorting)	74.75 (Sorting), 74,5 (recycling)
Paper packages	85 (Sorting + recycling)	86.11 (Sorting + recycling)
Newsprint	85 (Sorting + recycling)	86.11 (Sorting + recycling)

[8] Jan-Olov Sundqvist, IVL Swedish Environmental Research Institute. Phone call – 28 May 2019.

Substitution ratio

The substitution factor indicates how much recycled material is needed to substitute virgin material. For example, a substitution ratio of 1:0.95 means that 1 kg recycled material can substitute 0.95 kg virgin material. The substitution rates used in WAMPS and the substitution rates found in literature can be seen in the table below.

Table 16. Substitution ratios in literature and in WAMPS.

WAMPS	Substitution ratio WAMPS	Substitution ratios found in literature
Aluminium	1:1	1:1 (L. Rigamonti, Grosso, & Giugliano, 2010)
Steel	1:1	1:1 (L. Rigamonti et al., 2010)
Glass	1:1	1:1 (L. Rigamonti et al., 2010)
Plastic	1:0.95	1:1 (WRAP, 2008) 1:0.95 (H. Raadal, A. Brekke, 2008) 1:0.81 (L. Rigamonti et al., 2010)
Paper packages	1:0.86	The literature does not differentiate between paper packaging and newspaper: 1:0.83 (L. Rigamonti et al., 2010) 1:0.8-1 (European Environment Agency, 2005)
Newsprint	1:0.95	

Thermal treatment

A comparison for what is included in the incineration module in WAMPS and the assessed models can be seen in the figure below. The fields marked with yellow are areas in which WAMPS is differentiated from most of the models.

Table 17. Comparison of which aspects on incineration that are included in WAMPS.

Process	Gentil et. al. (2010)	Included in WAMPS
Process related emissions	8/9	Yes
Input related emissions	9/9	Yes
Electricity recovery efficiency[9]	7/9	Yes
Steam recovery efficiency	4/9	Yes
User-defined energy efficiency	5/9	Yes
District heating offset	6/9	Yes

[9] Described as amount of waste heat generated

Marginal energy input	3/9	Yes, the user is however not able to choose different energy for input and offset
Marginal energy output	4/9	Yes
Average energy mix input	9/9	Yes, the user is however not able to choose different energy for input and offset
Average energy mix output	8/9	Yes
Ancillary materials	8/8	No
Elemental mass balance	6/9	Yes
Biological and fossil carbon	7/9	Yes
Fly ash	9/9	Yes (no differentiation between bottom and fly ash)
Bottom ash	9/9	Yes (no differentiation between bottom and fly ash)
Transport of ashes	8/9	Yes
Disposal modelling of ashes	6/9	Yes
Recycling of ashes	4/9	No
User-defined ash quantity	4/9	No
Waste related ash composition	3/9	Yes
Waste related calorific value	7/9	Yes

7.2 B

Aluminium

Table 18. Description of the datasets depicting the recycling and the virgin production of aluminium.

	Name of dataset	Secondary production (Kg CO2 eqv. /kg)	Primary Production (Kg CO2 eqv. /kg)	Year	Country /region	Source	System boundaries	Characterization method	Representativeness	Technology
1a	Aluminium produced in Europe Semi-production (sheet)		6.7 (ingot production) 0.43 (sheet production)	2015	Europe	(European Aluminium, 2018)	Ingot production includes: Extraction of raw material to aluminium ingots and all the steps in between. Process scrap during the production is directly recycled into the production route. Alloying elements have been replaced by pure aluminium to only account for the impact of the aluminium. Transports included. Semi-production into aluminium sheet includes: Transformation of ingot into sheet. Includes recycling of dross and aluminium residue that is produced in the process.	CML2001	Represents primary aluminium production in Europe.	Representative of the current technologies used in the aluminium industry for all the production steps.
2a	aluminium alloy production, AlMg3, RER sheet rolling, aluminium, RER		6.7976 (alloy production) 0.51039 (sheet rolling)	1998-2018 2000-2018	Europe + Imported	Ecoinvent 3.5, Allocation, cut-off by classification	Alloy production includes: Production of alloyed aluminium ingot. The alloy contains 3% Magnesium. The dataset represents the market of aluminium in Europe, i.e. the actual composition of aluminium in Europe, both aluminium produced in Europe and imported aluminium as well as a mix between recycled and virgin aluminium. Transport and infrastructure. Sheet production: Includes rolling of aluminium ingots into a sheet. The scrap that is generated is accounted for.	IPCC2013	Alloyed aluminium used in Europe. Sheet rolling of one producer in Europe.	The technology used is different for the different aluminium compositions in the dataset.
3a	aluminium production, primary, ingot, IAI Area, EU27 & EFTA		8.3285 (ingot production)	2015-2018 2000-2018	IAI Area, EU27 & EFTA (Europe)	Ecoinvent 3.5, Allocation, cut-off by classification	Ingot production includes: Extraction of raw material to aluminium ingots. Transportation, Infrastructure. No recycled aluminium or alloying elements included.	IPCC2013	Represents primary aluminium production in Europe. Sheet rolling of one producer in Europe.	Produced by electrolytic process.

	sheet rolling, aluminium, RER		0.51039 (sheet rolling)				Sheet production: Includes rolling of aluminium ingots into a sheet. The scrap that is generated is accounted for.			
4a	Aluminium used in Europe Semi-production (sheet)		8.6 (ingot production) 0.43 (sheet production)	2015	Europe + Imported	(European Aluminium, 2018)	Ingot production includes: Extraction of raw material to aluminium ingots and all the steps in between. Process scrap during the production is directly recycled into the production route. Alloying elements have been replaced by pure aluminium to only account for the impact of the aluminium. Transports included. Semi-production into aluminium sheet includes: Transformation of ingot into sheet. Includes recycling of dross and aluminium residue that is produced in the process.	CML2001	Represents the primary aluminium used in Europe, i.e. production and imports (49%)	Representative of the current technologies used in the aluminium industry for all the production steps.
5a	Aluminium recycled in Europe – remelting Semi-production (sheet)	0.33 (Remelting) 0.43 (sheet production)		2010	Europe	(European Aluminium, 2018)	Included in the remelting: Remelting of collected aluminium to ingots. Process scrap during the production is directly recycled into the production route. Alloying elements have been replaced by aluminium to only account for the impact of the aluminium. Pre-treatment in recycling facility included. Dross recycling included. Transports included. Semi-production into aluminium sheet includes: Transformation of ingot into sheet. Includes recycling of dross and aluminium residue that is produced in the process.	CML2001	Recycling of aluminium of known content and origin in Europe.	Melted in reverberatory furnaces.
6a	treatment of aluminium scrap, new, at remelter, RER sheet rolling, aluminium, RER	0.50541 (Remelting) 0.51039 (sheet rolling)		2005-2018 2000-2018	Europe	Ecoinvent 3.5, Allocation, cut-off by classification	Included in the remelting: Processing of aluminium scrap to wrought aluminium billets. It is assumed that the waste stream is so clean that no preparation is needed. Excluded: salt slag and dross recycling Sheet production: Includes rolling of aluminium ingots into a sheet. The scrap that is generated is accounted for.	IPCC2013	Representative for Europe. Sheet rolling of one producer in Europe.	Melted in reverberatory furnaces. Average technology used in Europe.

Steel

Table 19. Description of the datasets depicting the recycling and the virgin production of steel.

	Name of dataset	Secondary production (Kg CO2 eqv. /kg)	Primary Production (Kg CO2 eqv. /kg)	Year	Country /region	Source	System boundaries	Characterization method	Representativeness	Technology
1b	reinforcing steel production, RER		2.1829	2001-2018	Used in Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: A mix of unalloyed and low-alloyed steel. Includes extraction, production of pig iron and unalloyed/low-alloyed steel. Includes hot rolling. Transportation and Infrastructure.	IPCC2013	Consumption mixes in Europe	Blast furnace process.
2b	Steel production, converter, unalloyed, RER hot rolling, steel, RER		1.9474 (production) 0.26183 (rolling)	2001-2018 1997-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, production of pig iron, production of unalloyed steel. Transportation and Infrastructure. Hot rolling.	IPCC2013	Production in Europe with global market for raw materials. Average rolling in Europe.	Blast furnace process.
3b	Production of tinplate coil		2.27	2012-2013	Europe	(APEAL, 2015)	Included: Extraction of raw materials to manufacturing of tinplate coil (tinplate is steel sheets covered with a thin layer of tin)	-	Representative for European steel packaging.	European production mix.
4b	Steel production – integrated route		2.3	2005-2008	Europe	(European Commission, 2014)	Included: Production of hot rolled steel.	-	-	Integrated route

5b	Steel production, converter, low-alloyed, RER hot rolling, steel, RER		2.4071 (production) 0.26183 (rolling)	2001-2018 1997-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, production of pig iron, production of primary steel. Transportation and Infrastructure. Hot rolling.	IPCC2013	Production in Europe with global market for raw materials. Average rolling in Europe.	Blast furnace process.
6b	steel production, converter, chromium steel 18/8, RER hot rolling, steel, RER		4.6711 (production) 0.26183 (rolling)	2001-2018 1997-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, production of pig iron, production of chromium steel. Transportation and Infrastructure. Hot rolling.	IPCC2013	Production in Europe with global market for raw materials. Average rolling in Europe.	European production mix
7b	Steel production – Electric arc furnace route	0.21		2005-2008	Europe	(European Commission, 2014)	Included: Recycling of steel to hot rolled steel.	-	-	-
8b	steel production, electric, low-alloyed, RER hot rolling, steel, RER	0.4049 (production) 0.26183 (rolling)		2001-2018 1997-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Collecting of new and old iron scrap, sorting and pressing to blocks. Transport. Results in low-alloyed casted steel. Infrastructure included. Hot rolling.	IPCC2013	Recycling in Europe with global market for scrap metal. Average rolling in Europe.	Electric arc furnace.
9b	Production of tinplate coil (74% metal scrap)	1.23		2012-2013	Europe	(APEAL, 2015)	Included: Manufacturing of tinplate coil (tinplate is steel sheets covered with a thin layer of tin) from 74% metal scrap, and the rest from virgin steel.	-	Representative for recycling in Europe.	-

10b	steel production, electric, chromium steel 18/8, RER hot rolling, steel, RER	3.8497 (recycling) 0.26183 (rolling)		2001-2018 1997-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Collection of iron scrap, sorting, pressing, production of chromium steel. Results in cast alloys. Includes only scrap iron. Transportation and Infrastructure.	IPCC2013	Recycling in Europe with global market for scrap metal. Average rolling in Europe.	Electric arc furnace.

Glass

Table 20. Description of the datasets depicting the recycling and the virgin production of glass.

	Name of dataset	Secondary production (Kg CO2 eqv. /kg)	Primary Production (Kg CO2 eqv. /kg)	Year	Country /region	Source	System boundaries	Characterization method	Representativeness	Technology
1c	Glass		0.921	2008-2009	Austria	(Frischenschlager et al., 2010)	Included: Extraction of raw materials. Production of glass with 5% cullet.	IPCC 2007	-	-
2c	packaging glass production, white, without cullet, GLO		1.2689	2000-2018	Global	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Includes extraction of raw materials, production of packaging glass. No cullet included.	IPCC2013	Global production without cullet.	Mix of European technology.
3c	packaging glass production, brown, without cullet, GLO		1.2699	2000-2018	Global	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Includes extraction of raw materials, production of packaging glass. No cullet included.	IPCC2013	Global production without cullet.	Mix of European technology.
4c	packaging glass production, green, without cullet, GLO		1.27	2000-2018	Global	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Includes extraction of raw materials, production of packaging glass. No cullet included.	IPCC2013	Global production without cullet.	Mix of European technology.

5c	packaging glass production, green, DE	0.49745		2002-2018	Germany + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, sorting of waste glass, production of packaging glass. 0.85 kg cullet used to produce 1 kg packaging glass.	IPCC2013	Average German production	Pressing and blowing process.
6c	Glass	0.506 (80 % cullet)		2008-2009	Austria	(Frischenschlager et al., 2010)	Secondary: Glass production with 80% cullet.	IPCC 2007	European recycling	
7c	Glass	0.535 (75% cullet)		2008-2009	Austria	(Frischenschlager et al., 2010)	Secondary: Glass production with 75% cullet.	IPCC 2007	European recycling	
8c	packaging glass production, brown, DE	0.57506		1996-2018	Germany + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, sorting of waste glass, production of packaging glass. 0.69 kg cullet used to produce 1 kg packaging glass.	IPCC2013	Average German production.	Pressing and blowing process.
9c	packaging glass production, white, DE	0.59765		1996-2018	Germany + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, sorting of waste glass, production of packaging glass. 0.63 kg cullet used to produce 1 kg packaging glass.	IPCC2013	Average German production	Pressing and blowing process.
10c	packaging glass production, green, RER w/o CH+DE	0.85119		2000-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, sorting of waste glass, production of packaging glass. 0.84 kg cullet used to produce 1 kg packaging glass.	IPCC2013	Average European production, without Switzerland and Germany	Pressing and blowing process.
11c	packaging glass production, white, RER w/o CH+DE	0.91129		2000-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, sorting of waste glass, production of packaging glass. 0.61 kg cullet used to produce 1 kg packaging glass.	IPCC2013	Average European production, without Switzerland and Germany	Pressing and blowing process.
12c	packaging glass production, brown, RER w/o CH+DE	0.92655		2000-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, sorting of waste glass, production of packaging glass. 0.56 kg cullet used to produce 1 kg packaging glass.	IPCC2013	Average European production, without Switzerland and Germany	Pressing and blowing process.

Plastic

Table 21. Description of the datasets depicting the recycling and the virgin production of plastic.

ID	Name of dataset	Secondary production (Kg CO2 eqv. /kg)	Primary Production (Kg CO2 eqv. /kg)	Year	Country /region	Source	Included	Characterization method	Representativeness	Technology
1d	High-density Polyethylene (HDPE)		1.80	2011	Europe	(PlasticsEurope, 2014b)	Included: Extraction of raw materials, production of precursors, production of polymers. Transports included. Excluded: Infrastructure.	IPCC 2007	Represents the European production to 68%.	Average of 52 European production sites
2d	polyethylene production, high density, granulate, RER		2.0469	1999-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, production of HDPE granulates.	IPCC 2013	Representative for production in Europe	Average of 24 European production sites.
3d	Low-density Polyethylene (LDPE)		1.87	2011	Europe	(PlasticsEurope, 2014b)	Included: Extraction of raw materials, production of precursors, production of polymers. Transports included. Excluded: Infrastructure.	IPCC 2007	Represents the European production to 72%.	Average of 52 European production sites
4d	polyethylene production, low density, granulate, RER		2.1867	1999-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, production of LDPE granulates.	IPCC 2013	Representative for production in Europe	Average of 27 European production sites.
5d	Linear Low-density Polyethylene (LLDPE)		1.79	2011	Europe	(PlasticsEurope, 2014b)	Included: Extraction of raw materials, production of precursors, production of polymers. Transports included. Excluded: Infrastructure.	IPCC 2007	Represents the European production to 86%.	Average of 52 European production sites
6d	polyethylene production, linear low density, granulate, RER		1.9264	1999-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, production of LLDPE granulates.	IPCC 2013	Representative for production in Europe	Average of 8 European production sites.

7d	PET		2.19	2015	Europe	(CPME, 2017)	Included: Extraction of raw materials, production of precursors, production of polymers. Transports included. Excluded: Infrastructure.	IPCC 2007	Represents the European production to 85%.	Average of 12 European production sites
8d	polyethylene terephthalate production, granulate, amorphous[10], RER		3.0179	1999-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, production of PET granulates.	IPCC 2013	Representative for production in Europe	Average European production.
9d	polyethylene terephthalate production, granulate, bottle grade[11], RER		3.2655	1999-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, production of PET granulates.	IPCC 2013	Representative for production in Europe	Average European production.
10d	Polypropylene (PP)		1.63	2011	Europe	(PlasticsEurope, 2014a)	Included: Extraction of raw materials, production of precursors, production of polymers. Transports included. Excluded: Infrastructure.	IPCC 2007	Represents the European production to 77%.	Average of 35 European production sites.
11d	polypropylene production, granulate, RER		2.0542	1999-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, production of PP granulates.	IPCC 2013	Representative for production in Europe	Average of 28 European production sites.
12d	polyethylene production, high density, granulate, recycled, Europe without Switzerland	0.68037		2010-2018	Europe without Switzerland	Ecoinvent 3.5 (Haupt, Hellweg, et al., 2017)	Included: Collection, transportation, sorting, baling, cleaning, shredding and melting to HDPE granulate.	IPCC 2013	Representative for recycling in Europe.	Sorting by sink-float separation or NIR.
13d	PET	0.96		2004	Europe	(Prognos, 2008b)	Included: Collection, sorting and treatment to secondary flakes. Excluded: Granulation process.	-	Representative for Europe.	-

[10] Amorphous PET is a variant of PET which is transparent in its basic state and which can be used for packaging material (Treform packaging, n.d.).
[11] A bottle-grade PET means that the PET has been produced to have a certain viscosity which can be used in food packaging and bottle production (Ecoinvent).

14d	PP	0.966		2017	Germany	(Alba Group, 2017)	Included: Recycling of PP at ALBA facilities. Unclear if the data represents recycling in Germany or recycling in Austria, Germany, Poland, Slovenia.	-	Representative for recycling process by ALBA group.	ALBA group technology.
15d	PE/PP	1.04		2004	Europe	(Prognos, 2008b)	Included: Collection, sorting and treatment to secondary flakes. Includes a mixture containing 50% PP, 25% HDPE and 25% LDPE. 20% is assumed to be incinerated. Excluded: Granulation process.	-	Representative for Europe.	System boundary secondary production: From sorting of the waste until produced product.
16d	polyethylene terephthalate production, granulate, amorphous, recycled, Europe without Switzerland	1.1435		2010-2018	Europe without Switzerland	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Collection, transportation, sorting, baling, cleaning, shredding and melting to PET granulate. Excluded: Machinery infrastructure.	IPCC 2013	Representative for recycling in Europe.	Average technology of USA which has been extrapolated to Europe.

Paper

Table 22. Description of the datasets depicting the recycling and the virgin production of glass.

ID	Name of dataset	Secondary production (Kg CO2 eqv. /kg)	Primary Production (Kg CO2 eqv. /kg)	Year	Country /region	Source	Included	Characterization method	Represent-ativeness	Technology
1e	paper production, woodfree, uncoated, at integrated mill, RER, (UWF)[12]		0.82532	2000 - 2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: extraction of raw materials, transports, wood handling, pulping, bleaching, paper production.	IPCC 2013	Average for European production.	Chemical pulping.

[12] UWF is used for printing and writing papers (Eurograph, n.d.).

2e	paper production, woodfree, coated, at integrated mill, RER, (CWF)[13]		1.0601	2000 - 2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: extraction of raw materials, transports, wood handling, pulping, bleaching, paper production.	IPCC 2013	Average for European production.	Chemical pulping.
3e	paper production, woodcontaining, supercalendered, RER, (SC)[14]		1.2513	2000 - 2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, transports, wood handling, mechanical pulping, bleaching, deinking, paper production. Includes 6% wastepaper. Excluded: Sorting.	IPCC 2013	Average for European production.	Mechanical pulping.
4e	paper production, newsprint, virgin, RER		1.4317	2000 – 2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: extraction of raw materials, transports, wood handling, mechanical pulping, bleaching, paper production.	IPCC 2013	Average for European production.	Mechanical pulping.
5e	paper production, woodcontaining, lightweight coated, RER (LWC)[15]		1.4716	2000 - 2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, transports, wood handling, mechanical pulping, bleaching, deinking, paper production. Includes 4% wastepaper. Excluded: Sorting.	IPCC 2013	Average for European production.	Mechanical pulping.
6e	graphic paper production, 100% recycled, RER	0.77155		2008 - 2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Collection of wastepaper, transports, deinking, paper production. Excluded: Uncertain if sorting is included or not.	IPCC 2013	Represents main producers in Europe.	Average or present technology.
7e	paper production, newsprint, recycled, Europe without Switzerland	1.0898		2000 – 2018	Europe without Switzerland	Ecoinvent 3.5 Allocation, cut-off by classification	Included: transport, mechanical pulping, bleaching, deinking, paper production.	IPCC 2013	Average for European production.	Mechanical pulping.

[13] CWF is used for printing and writing papers (Eurograph, n.d.).
[14] SC is primarily used for production of magazines and advertising catalogues (Eurograph, n.d.).
[15] LWC can have either glossy or matte finish. The paper type is usually used in magazines and catalogues (Eurograph, n.d.).

							Excluded: Collection and sorting of the wastepaper. The losses during sorting has been accounted for, but not the emissions.			
8e	containerboard production, linerboard[16], kraftliner, RER		0.55903	2009 - 2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: extraction of raw materials, transports, wood handling, pulping, cleaning, paper production. Includes 0.45 kg wastepaper/ kg output. Excluded: Collection.	IPCC 2013	Represents main producers in Europe.	Chemical pulping process.
9e	containerboard production, fluting medium, semichemical, RER		0.63819	2009-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: extraction of raw materials, transports, wood handling, pulping, cleaning, paper production. Includes 0.1 kg wastepaper/ kg output. Excluded: Collection.	IPCC 2013	Represents main producers in Europe.	Semichemical cooking of pulp, average or present technology.
10e	Kraft paper production, unbleached		0.78833	2000 - 2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: extraction of raw materials, transports, wood handling, pulping, paper production.	IPCC 2013	Represents one mill in Europe but used as European average.	Chemical pulping process.
11e	Kraft paper production, bleached, RER		1.2237	1993 - 2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: extraction of raw materials, transports, wood handling, pulping, paper production.	IPCC 2013	Represents one mill in Switzerland but used as European average.	Chemical pulping process.
12e	containerboard production, linerboard, testliner, RER	0.63846		2009 - 2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: extraction of raw materials, sorting of wastepaper, transports, pulping, cleaning, paper production. Includes 1.1 kg wastepaper/ kg output. Excluded: Collection.	IPCC 2013	Represents main producers in Europe.	Average or present technology.

[16] Linerboard is the outer layers in corrugated board. Kraftliner is usually produced from virgin sources and testliner is usually produced from wastepaper (Ecoinvent).

13e	containerboard production, fluting medium[17], recycled, RER	0.66281		2009-2018	Europe	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Sorting of wastepaper, pulping, cleaning, paper production. Excluded: Collection.	IPCC 2013	Represents main producers in Europe.	Average or present technology.

Incineration

Table 223. Description of the datasets depicting incineration and heat and electricity production.

ID	Name of dataset	Secondary production (Kg CO2 eqv. /kg)	Primary Production (Kg CO2 eqv. /MJ)	Year	Country /region	Source	Included	Characterization method	Representativeness	Technology
1f	treatment of waste plastic, mixture, municipal incineration with fly ash extraction, CH	2.34		2006-2012	Switzerland	Ecoinvent 3.5 Undefined	Included: Incineration of average plastic mixture. Slag and residues are landfilled. Recovers electric and thermal energy.	IPCC 2013	-	Incineration in average Swiss incineration plant 2010.
2f	heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014, SE		0.0025026	2010-2018	Sweden	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Production of heat and electricity with wood chips. Infrastructure. Reference product: heat.	IPCC 2013	Representative for Switzerland but has been adjusted to Swedish conditions.	Modern unit installed 2014 in Switzerland.
3f	heat and power co-generation, natural gas, conventional power plant, 100MW electrical, SE		0.030457	1990-2018	Sweden	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Production of heat and electricity in a steam boiler natural gas plant. Reference product: heat.	IPCC 2013	-	Conventional gas power plant. Current technology.
4f	heat and power co-generation, oil, SE		0.042691	1980-2018	Sweden	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Production of heat and electricity in oil plant. Reference product: heat.	IPCC 2013	-	Conventional oil power plant.

[17] Fluting medium is the in-between layer in corrugated board (Ecoinvent).

5f	market for electricity, medium voltage, SE		0.012380556	2014-2018	Sweden	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Swedish average electricity.	IPCC 2013	-	-
6f	market for electricity, medium voltage, LV		0.245502778	2014-2018	Latvia	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Latvian average electricity.	IPCC 2013	-	-
7f	market for electricity, medium voltage, EE		0.169569444	2014-2018	Estonia	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Estonian average electricity.	IPCC 2013	-	-

Compost

Table 24. Description of the datasets depicting composting and production of mineral fertilizers.

		Name	Secondary production (Kg CO2 eqv. /kg)	Primary Production (Kg CO2 eqv. /kg)	Year	Country /region	Source	System boundaries	Characterization method	Representativeness	Technology
1g		treatment of biowaste, industrial composting, CH	0.05047		2011-2015	Switzerland	Ecoinvent 3.5 Undefined	Included: Processing of biowaste to compost. Process emissions and energy demand was included. Transports and infrastructure.	IPCC 2013	Composting in Switzerland.	Industrial compost.
2g	N-fertilizer	ammonium nitrate phosphate production, RER		1.896	1999-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw material, transport, production of ammonium nitrate phosphate. Allocated for N-fertilizer.	IPCC 2013	Several European facilities.	Current technology.
3g	N-fertilizer	diammonium phosphate production, RER		2.72	1999-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw material, transport, production of diammonium phosphate. Allocated for N-fertilizer.	IPCC 2013	Represents several production facilities in Europe.	Current technology.
4g	N-fertilizer	monoammonium phosphate production, RER		2.7316	1999-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw material, transport, production of diammonium phosphate. Allocated for N-fertilizer.	IPCC 2013	Represents several production facilities in Europe.	Current technology.

5g	N-fertilizer	urea ammonium nitrate production, RER		5.4816	1999-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw material, transport, production of urea ammonium nitrate. Allocated for N-fertilizer.	IPCC 2013	Represents several production facilities in Europe.	Current technology.
6g	N-fertilizer	calcium ammonium nitrate production, RER		7.9522	1999-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw material, transport, production of calcium ammonium nitrate. Allocated for N-fertilizer.	IPCC 2013	Representative for European production.	Current technology.
7g	P-fertilizer	ammonium nitrate phosphate production, RER		0.96605	1999-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw material, transport, production of ammonium nitrate phosphate. Allocated for P-fertilizer.	IPCC 2013	Represents several production facilities in Europe.	Current technology.
8g	P-fertilizer	diammonium phosphate production, RER		1.3859	1999-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw material, transport, production of diammonium phosphate. Allocated for P-fertilizer.	IPCC 2013	Represents several production facilities in Europe.	Current technology.
9g	P-fertilizer	monoammonium phosphate production, RER		1.3918	1999-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw material, transport, production of monoammonium phosphate. Allocated for P-fertilizer.	IPCC 2013	Represents several production facilities in Europe.	Current technology.
10g	P-fertilizer	triple superphosphate production, RER		1.5133	1999-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw material, transport, production of triple superphosphate. Allocated for P-fertilizer.	IPCC 2013	Represents several production facilities in Europe.	Current technology.
11g	P-fertilizer	single superphosphate production, RER		1.5542	1999-2018	Europe + imports	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw material, transport, production of triple superphosphate. Allocated for P-fertilizer.	IPCC 2013	Represents several production facilities in Europe.	Current technology.
12g	K-fertilizer	nutrient supply from potassium nitrate, GLO		2.9427	2008-2018	Global	Ecoinvent 3.5 Allocation, cut-off by classification	Included: Extraction of raw materials, transport, production, transformation. Allocated for K-fertilizer.	IPCC 2013	-	Current technology.