LCA of Decentralised Toilets in comparison with Flushing and Composting Toilets

Life Cycle Assessment of Products and Systems – 42372
Fall 2017

Group 15

Daphne Keulen,	s172218
Lucas Jacquot,	s172643
Marcel Kaimer,	s172794
Mourad Boucenna,	s173110
Yin Jia,	s161444
Ziyi Liu,	s171311

Executive summary

DTU Diplom, in conjunction with NP Flint, are in the early stages of designing a decentralised toilet with the purpose of reducing environmental impacts compared to other, currently available toilet systems. The decentralised toilet design does not use water from the water supply network for flushing, but instead extracts and recovers water from urine. This is achieved through the incorporation of a slingshot boiler, which heats up the faeces and urine, and produced purified water. Since, the water is recycled and the faeces can be used as fertiliser, this preliminarily design has been identified as providing the opportunity to achieve reductions in the environmental impacts of toilet products.

The aim of this study is to perform a Life Cycle Assessment for the decentralised toilet design and to compare the results with Life Cycle Assessments of a flushing and composting toilet. Furthermore, the aim of this study is to identify areas in which the current design of the decentralised toilet can be improved. The functional unit considered in this study is the handling human faeces and urine for a household of 4 people over 35 years.

In addition to performing their primary service (handling human waste) the toilets provide additional useful services. Both the decentralised and the composting toilets are assumed to recover nutrients from the human waste, which can then be used as fertiliser. Additionally, the decentralised toilet provides indirect heating from the process of boiling water. Sludge from the flushing toilet is anaerobically digested, producing biogas.

The life cycle assessments of the three toilets indicate that the decentralised toilet design is a viable concept for reducing the environmental impact, particularly compared to the water-flushing toilet. Additionally, it is also appears attractive when compared to the composting toilet, however the differences are not as conclusive. Considering that the decentralised toilet has a flushing capability, the decentralised toilet may present an acceptable option for consumers who prefer to “flush-and-forget” rather than to handle their waste.

For all toilets, the use stage was identified as the hotspot for all three of the toilets, which indicates that improving the environmental impacts in the use stage, for example reducing the electricity consumption of the decentralised toilet for purifying water, will have the most significant impact on the overall performance.

Technical summary

DTU Diplom, in conjunction with NP Flint, are in the early stages of designing a new kind of toilet with the purpose of reducing environmental impacts compared to other, currently available toilet systems. A decentralised toilet design, i.e. a toilet that is not connected to the water supply network, has preliminarily been identified as providing the opportunity to achieve such reductions.

The decentralised toilet design investigated in this study does not use water from the water supply network for flushing, unlike conventional water-flushing toilet technologies. Instead, water is extracted from human excrement by the slingshot boiler incorporated in the toilet and then stored in a tank, where it can later be used for flushing. Alternatively, the collected water can also be used for other purposes such as irrigation. Flushing of the decentralised toilet with water is considered a desirable positioning property when compared to other decentralised toilet designs, such as composting toilets.

This study investigates the environmental impacts of the proposed decentralised toilet product system, throughout the entire lifecycle of the product, comprising the following life cycle stages: raw material extraction, manufacturing, transportation, use and disposal. Life Cycle Assessments of two competing products (water-flushing and composting toilets) are conducted as well. In this way, conclusions can be drawn whether the decentralised toilet actually reduces the environmental impacts compared to the other two systems. In addition to drawing a conclusion about the comparison between the three toilets, the aim of this study is to identify areas in which the current design of the decentralised toilet can be improved.

Although all three toilet systems fulfill the functional unit of handling human faeces and urine for a household of 4 people over 35 years, they differ in the secondary functions aligned with the handling of the faeces. The decentralised and the composting toilet make use of the nutrient value by providing compost and therefore substituting the production of fertiliser. Additionally, the decentralised toilet provides indirect heating from the process of boiling water. In the flushing toilet product system, the faeces and urine go to wastewater treatment where the sludge is anaerobically digested, producing biogas, and residual waste is subsequently incinerated.

All the processes from the material to the disposal stage are determined and quantified in the Life Cycle Inventory Analysis which is the basis for the modelling of the systems in the software, SimaPro. By modelling the respective toilet product systems, the actual environmental impacts are calculated in the Life Cycle Impact Assessment, using the ReCiPe 2008 method. General data for all three systems is mainly collected by research on scientific statistics about human excrement. The technical data for the flushing and composting toilet is quite accurate since enough data is available, some small estimations had to be made. However, the design of the decentralised toilet is still an ongoing project therefore a lot of data had to be assumed and estimated.

The decentralised toilet performs best in most of the impact categories in the outcome of the characterised results. When applying external normalisation, i.e. normalising the results with an external reference, the midpoint impact results are obtained. Due to an underestimation of the normalisation factors applied, the scores in the freshwater and marine ecotoxicity categories were exceptionally large. The life cycle stage analysis showed that the use stage was the hotspot for all three of the toilets, which indicates that improving the environmental impacts in the use stage will have the most significant impact on the overall performance.

The weighted endpoint results were determined by applying weighting to the normalised midpoint category results from the ReCiPe 2008 method. Endpoint impacts occur in three categories: human health, ecosystems and resources. In all three of the endpoint impact categories, the flushing toilet has the highest impact. Both the composting and decentralised toilet obtain negative scores, in which the composting toilet performs slightly better than the decentralised toilet in human health and resources categories. The composting and decentralised toilet scores are approximately equal in the ecosystems category.

When the endpoint results from the ReCiPe 2008 method are compared with additional impact assessment methods (ReCiPe 2016 and IMPACT 2002+), the conclusion regarding which option is preferred between the composting and decentralised toilets changes partly. The flushing toilet still performs worst, which can therefore be stated as a robust conclusion. in contrast, the decentralised toilet performs significantly better than the composting toilet in the human health and ecosystems categories, according to both other methods. The endpoint impact on resources is best for the composting toilet for both ReCiPe methods, but not using the IMPACT 2002+ method. As the ReCiPe 2016 method is the latest version and the results are better supported by a second method, the decentralised toilet is considered to be the best option.

Since the decentralised toilet is still an ongoing project, there is the opportunity to implement further improvements. It appears that the highest potential for improvements is in the use-stage, as the highest impact scores (negative and positive ones) are located there.

Table of content

1. Introduction

Concerns about the sustainability of products and processes is increasing around the globe, and consensus is building that the impact of human activities needs to be reduced in order to ensure quality of life and quality of environment for future generations and ecosystems. One method of decreasing the impact of human activities is to consume less resources, either through efficiency improvements or substitution with less impactful products or processes. This can be achieved at many scales: from the industrial scale to domestically.

In this study the life cycle of a decentralised toilet, designed to reduce the environmental impact of handling human waste by not using water from the water supply network, is analysed. The environmental impacts of flushing and composting toilets are also analysed, as a comparison. The aim of the life cycle assessments is to identify the toilet with the lowest environmental impact, throughout the entire product life cycle, and to identify the environmental impact hotspots of each system. Particular focus is placed on identifying areas in which the design of the decentralised toilet can be improved to reduce its impacts.

The most common toilet in every household is the flushing toilet, Figure 1.1. When the button on the toilet is pressed, water from the basket flows through the toilet taking the faeces and urine away into the sewage system. The second toilet, shown in Figure 1.1, is the composting toilet. Composting toilets are most often used in camping or other remote areas within nature, but these can also be installed within urban buildings. The composting toilet separates urine and faeces using a physical barrier. Sawdust is then placed on top of the faeces by the user of the toilet, to keep the faeces dry. A fan can also be installed within the composting toilet to ventilate the air from the toilet, which may be particularly desirable in urban building applications.

Figure 1.1: Flushing (left) and composting toilet (right)

DTU Diplom is developing a design for a decentralized toilet. The current design of the toilet is presented in Figure 2. The design incorporates a slingshot water distillation system. A schematic of the slingshot water distillation system is also presented in Figure 1.2. In the first chamber of the slingshot system (1), the dirty water enters the first chamber, where a heat exchanger heats the input water and cools down the return water. Next, in the boiling chamber (2), the water is heated and evaporated as steam, while the separated contaminants are collected and discharged as refuse water (5), to a waste storage tank. The evaporated steam flows through a compressor, which raises the pressure and temperature of the steam (3). Clean water subsequently condenses on the cooler surfaces in the condensing chamber (4) and heat is exchanged between the boiling chamber and the condensing chamber. In the last chamber the clean water is collected (6).

Although both the composting toilet and the new designed toilet by DTU Diplom may be considered to be decentralised toilets, i.e. toilets that are not connected to either the water supply or sewage networks, the toilet designed by DTU Diplom will henceforth be referred to as the "decentralised toilet" in this report to avoid circuitous descriptions, i.e. this term will refer to the DTU Diplom toilet design only, not the composting toilet.

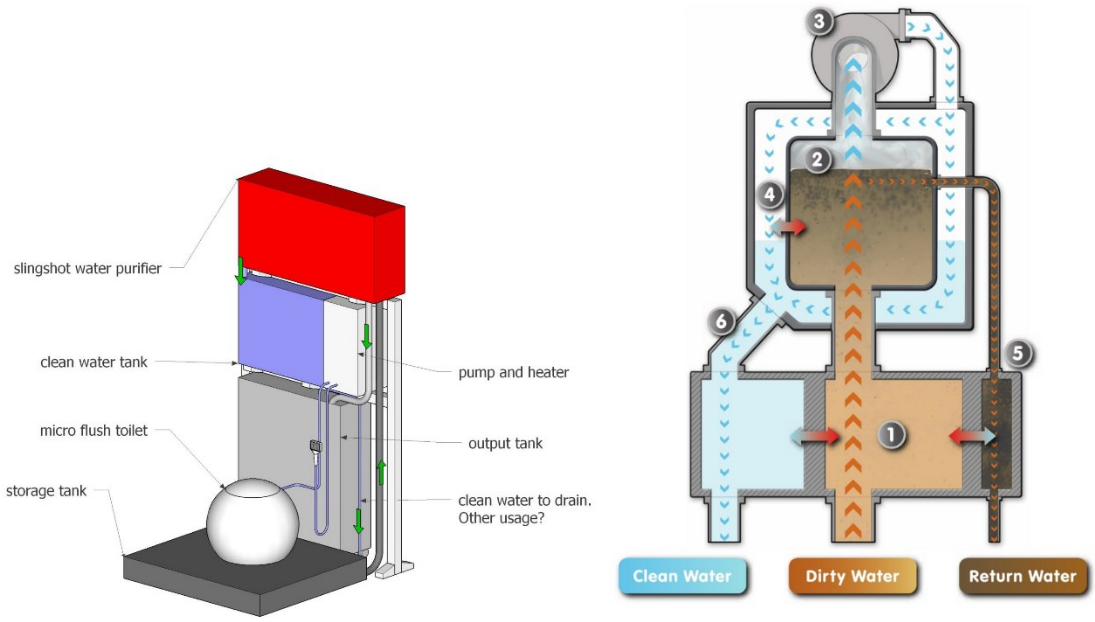


Figure 1.2: Design (left) and process (right) of the decentralised toilet.

This report will first define the goal and scope of the study. Subsequently, results of the inventory analysis and impact assessment are presented. These results are discussed and conclusions are made, considering the assumptions that have been made during the study. The study investigates whether the current decentralised toilet design has the lowest impact on the environment, when compared to other available toilet concepts (flushing or composting toilets) and what could be improved to make this toilet the most sustainable option.

2. Goal definition

2.1 Intended Applications of the Result

The main application of this Life Cycle Assessment (LCA) is the comparison of the environmental impacts of the three different toilets studied: water-flushing, composting and decentralised. The LCA is used to identify the parts of the product system that contribute the most to its environmental impact. This leads to the detection of the highest improvement potential from changes in the product design for the ongoing development.

2.2 Limitations Due to Methodological Choices

The main method used in this study is the ReCiPe 2008 method. A newer version of the ReCiPe method (ReCiPe 2016) is available for use in SimaPro. However, the latest version does not provide externally normalised results. The ReCiPe 2008 method is therefore selected, as externally normalised midpoint results are to be presented in the life cycle impact assessment.

In ReCiPe 2008, not all processes are completely up-to-date and there are some methodological differences. In order to check the robustness of the method, the ILCD method is used for a comparison at midpoint level. The endpoint results are compared with those of the ReCiPe 2016 and IMPACT 2002+ method. As the units for the impacts on ecosystems and resources differ between the three methods, this is limited to a qualitative comparison, for example only looking at the ranking of the different toilets.

2.3 Decision Context and Reasons for Carrying Out the Study

The LCA study should support the decision of which of the three toilets has the least impact on the environment. Since the design of the decentralised toilet is still ongoing, the results of the LCA can be used for improving the design and technology of the toilet system, thereby reducing the environmental impact of the product.

The LCA is carried out in the context of usage within a single building, concerning internal consequences. Therefore, large scale effects on the background-system (for example the sewage system) can be excluded (Situation A). However, in the long-term it could be possible that more buildings will substitute the flushing toilet by the decentralised toilet. This might have a consequence on the larger scale, such as on the market, the sewage system and the water usage and treatment.

2.4 Target Audience, Commissioner and Other Influential Actors, Disclosure to Public

The target audience of this study are DTU Diplom and NP Flint consultancy. Jacob Hvidtved Lawaetz from DTU Diplom developed the new system for decentralized toilets cooperated with NP Flint. Aiming at developing innovative sustainable lifestyle concepts for primarily the building industry, NP Flint would like to implement the decentralized toilet in the new Musicon building at Roskilde and use the decentralized system in future housings as well. This LCA study is a group project on Course 42372 in DTU, and it is confidential and not to be disclosed to the public.

Moreover, other influential actors are the course leader Alexis Laurent and the supervisor Mirko Dal Maso, both of whom have given important guidance for the project. Alexis Laurent is Associate Professor in division for Quantitative Sustainability Assessment (QSA), with research experience in LCA to various domains, including energy technologies and systems, waste management systems, etc. Mirko Dal Maso is a research assistant in QSA, with several LCA projects finished and proceeding.

3. Scope Definition

3.1 Deliverables

The comparison of the different toilet systems and the detection of hot-spots in the life cycle is the main goal of this LCA, which therefore consists of two parts: a Life Cycle Inventory (LCI) and a Life Cycle Impact Assessment (LCIA). Firstly, the LCI is performed for each system to detect all elementary flows from all the unit processes within the system boundary. As the impact of various elementary flows are expected to differ, an LCIA is subsequently performed to assess the particular impact of each flow and determine the overall environmental impact of each system. The first step of the LCIA is selecting the impact categories in which the elementary flows are classified.

3.2 Object of Assessment

The functions of the systems have to be defined and understood, especially because of the comparison between the different systems being analysed. The obligatory and positioning properties are determined and given in Table 3.1. The functional unit, containing qualitative, quantitative and durability aspects, and the reference flow are described below in Table 3.1. The primary function, defining the functional unit, of the three different toilets considered in this study have already been introduced in the Introduction section (Section 1). The different secondary functions are explicated in the following section (Section 3.3).

Table 3.1: Overview of the obligatory and positioning properties, the functional unit and the reference flow.

Obligatory Properties	Positioning Properties
- Handle faeces and urine of humans - Safety and regulations	- Comfortable seat - Smell-avoidance - Price - Design/Shape - Easy to use - Height of seat - Easy to clean - Material - Included douche - Hygiene - Capacity/storage volume - Mounting possibilities - Water and energy consumption
Functional Unit: handling of the average amount of faeces (128 g/person) and urine (1.42 L/person) produced per day by 4 people, every day for 35 years [1]. **Reference Flow:** Number of toilets needed over the usage period of 35 years.	

Obligatory Properties	Positioning Properties
number of flushing toilets: number of composting toilets: number of decentralized toilets:	1 2 1.5

The estimated usage period of the flushing toilet is based on a recommendation for rented apartments, suggesting a lifespan of 35 years for a flushing toilet. Besides the flushing toilet, which consists mainly of ceramics, the composting toilet is made out of polypropylene. Although this is a very durable plastic, it is not as durable as ceramics. The usage period has been estimated to be half of the one of the flushing toilet, leading to a reference flow of 2 composting toilets per functional unit. As the decentralised toilet contains many technologically complex parts, some of them may not last for 35 years, whereas others such as the ceramic bowl are similar to the one of the flushing toilet. This is why the reference flow has been estimated to be 1.5.

3.3 LCI Modelling Framework and Handling of Multifunctional Processes

The three different types of toilet considered in this study all provide the same primary function of handling human waste. All of the toilets also produce nutrient-rich waste as a byproduct of performing their primary function. However, how this nutrient-rich waste is handled and/or recovered differs significantly between the three toilets.

The waste from the flushing toilet enters the sewage system and ultimately undergoes wastewater and sludge treatment processes. During the sludge treatment process (anaerobic digestion), biogas is produced. The treated sludge is subsequently incinerated. The flushing toilet therefore provides fuel as a secondary service, and the nutrient content of the sludge is not utilised directly. This is considered the base case for the flushing toilet. A sensitivity analysis will also be conducted to investigate the impact of utilising the nutrient value of the sludge, instead of incinerating it to produce heat and power.

Conversely, the nutrient-rich waste is recovered and utilised for both the composting and decentralised toilet. The composting toilet separates urine and faeces, the latter of which is composted, using the addition of sawdust to reduce the overall water content. The decentralised toilet combines the urine and faeces, and concentrated waste is collected in a storage tank. Both toilets therefore produce secondary products which can be used as fertiliser. In addition to the aforementioned secondary service, the design of the decentralised toilet is such that, due to the boiling of the water in the human waste, heat is provided to the environment and clean water is produced.

Furthermore, recyclable materials may be incorporated into the design of the decentralised toilet, which would lead to the opportunity for recycling. This may not be considered a process as such, but can be accounted for by crediting a reduction in environmental impact of reduced material usage in the disposal phase.

All of these secondary services impact the environment and so should be taken into account in the life cycle analysis. A summary of the secondary products and services provided by the toilets being considered in this study is given in Table 3.2.

Table 3.2: Overview of the three different toilets and their secondary functions.

Toilet	Secondary function
Flushing	Biogas Heating from incineration Nutrient-rich waste - sludge Note 1
Composting	Nutrient-rich waste - urine and compost Note 2 (Recyclable materials)
Decentralised	Nutrient-rich waste - combined urine and faeces Note 2 Heating service from boiler Clean water produced (Recyclable materials)

Notes

1. As the base case, the nutrient-value of the sludge will not be considered, since the sludge will be incinerated rather than utilised as fertiliser, thereby producing heat and power.
2. It should be noted that, due to regulatory requirements regarding the handling and usage of human waste, the nutrient-rich waste from the toilets may need to be incinerated, rather than handled. However, this study will focus on the scenario that the nutrient-rich waste from the decentralised toilet can be utilised as a byproduct for fertiliser.

The secondary products and services discussed above, can be further summarised as general processes as follows:

1) Fuel
2) Heating (including indirect heating)
3) Fertiliser
4) Water production

The functions provided by the flushing toilet, composting toilet and decentralised are presented graphically in Figure 3.1.

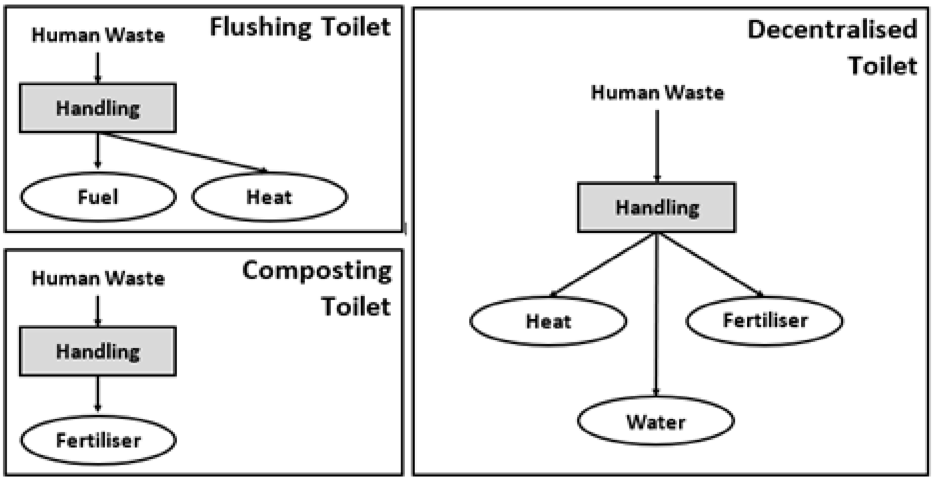


Figure 3.1: Schematic Representation of the Multifunctional Processes

To determine how to handle the multifunctional process of the toilets, the steps recommended in the ISO 14044 standard are followed as shown below:

(1) Can the multi-functional process be divided? No
(2) Can conventional or most-probable alternative ways to produce the secondary functions be identified? Yes. Some possible alternatives would be: production of alternative fuels such as diesel; nitrogen can be fixed by the Haber-Bosch process for production of industrial fertilisers; heating services can be supplied by many means, such as electrical heaters, combustion of biomass etc.; and water can be taken from water supply background processes.

Consequently, since all the secondary functions (fuel, fertiliser, heating and water) can be provided by alternative means, the ISO 14044 standard recommends that the secondary processes should be accounted for by performing system expansion. The toilet product systems will therefore be expanded so that avoided impacts of providing the secondary services by other means can be credited to the system.

Installing decentralised or composting toilets is unlikely to cause changes to any background system processes, since water supply will still be required for many other services in domestic and industrial use. Consequently, installing the toilets should be considered micro-level decision support (Situation A). For micro-level decision support (Situation A), the ILCD framework recommends using average processes when modelling background systems.

An additional consideration for this project is that the decentralised toilets may be designed to produce clean water in times of electricity surplus in the grid, e.g. at times of excessive wind power production. Thus, taking advantage of cheaper electricity rates and helping to dispose of surplus electricity output. In this case, surplus supply may be from renewable sources, as opposed to an average of the electricity mix including fossil fuel contributions. Consequently, the environmental impact of the decentralised toilet may be significantly reduced. Sensitivity analysis should therefore be conducted to investigate the impact of utilising excess electricity generated from renewable sources on the environmental impact of the decentralised toilet.

3.4 System Boundaries and Completeness Requirements

The system boundaries for each of the three toilets considered in this study are presented in Figure 3.2, 3.3 and 3.4. For all three toilets, the full product system will be considered, i.e. none of the product system will be excluded from the analysis. This is because, despite conducting a comparative study, the materials and processes used to manufacture the toilets, and the byproducts produced from each toilet, differ significantly.

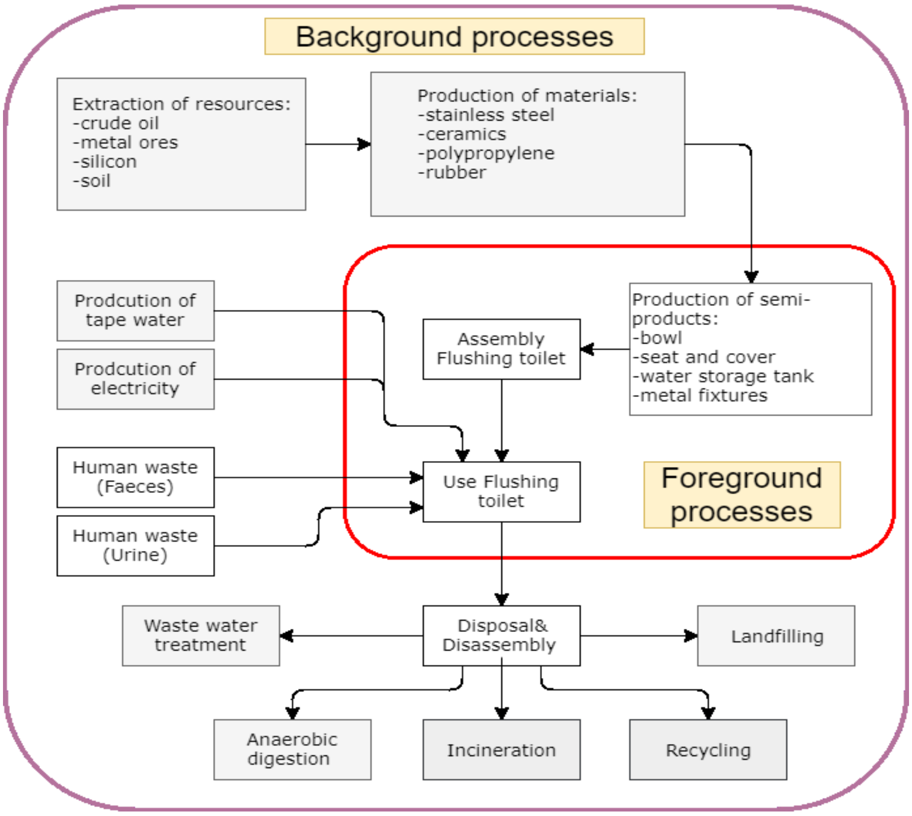


Figure 3.2: System boundaries scheme of the flushing toilet.

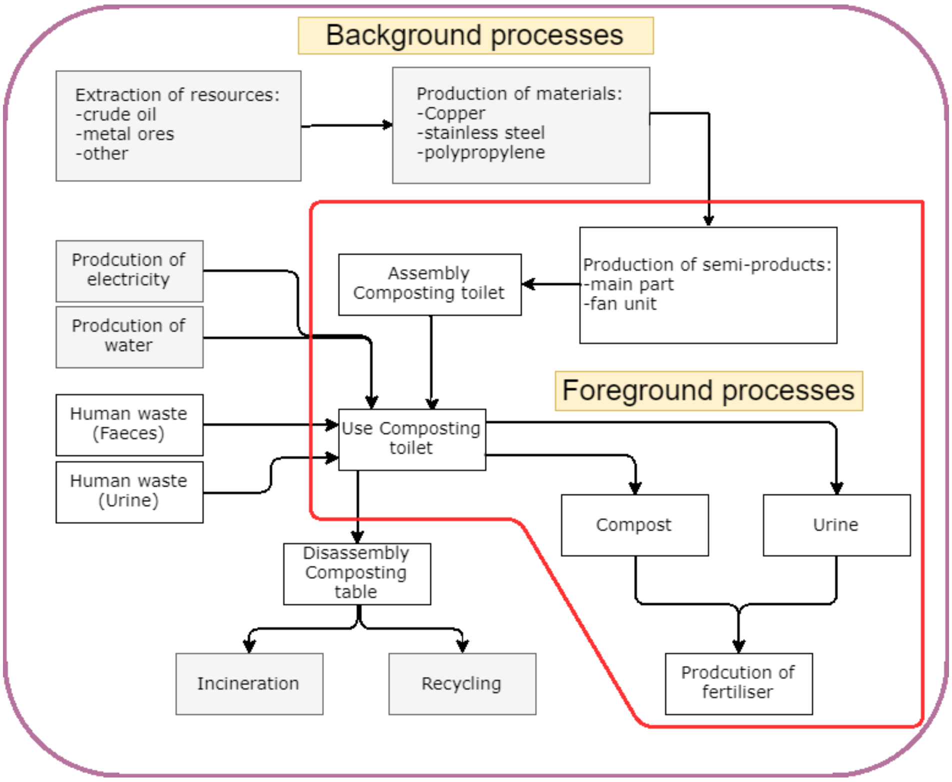


Figure 3.3: System boundaries scheme of the composting toilet.

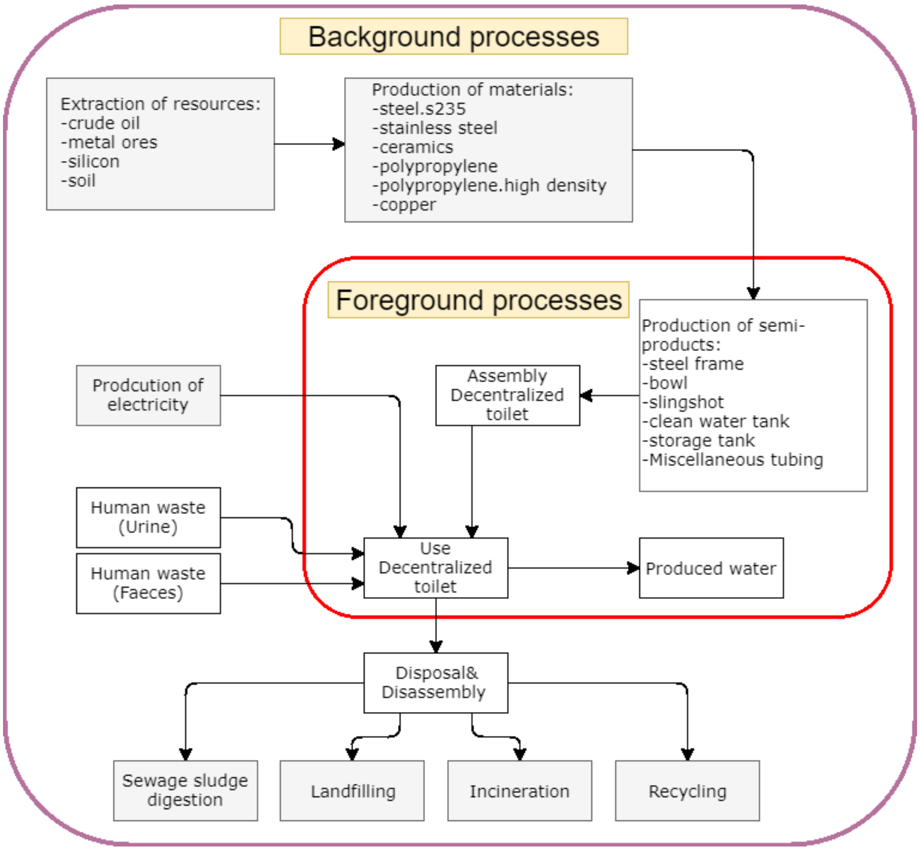


Figure 3.4: System boundaries scheme of the decentralized toilet.

3.5 Representativeness of LCI Data

It is the aim of the LCA to reflect reality. This means that the models should represent what actually happens or will happen to the greatest extent possible. So, the decentralised toilet is based on the current design concept provided by Jacob Hvidtved Lawaetz (DTU Diplom). The composting toilet is based on data collected from the Swedish toilet producer-*Separett*. The data used for the flushing toilet is based on the general, widely-available design. The data for all three toilets can be understood in three interrelated dimensions which are geographical, time-related and technological, see Sections 3.5.1, 3.5.2 and 3.5.3, respectively.

3.5.1 Geographical Representativeness

The geographical representativeness reflects how well the inventory data represents the actual processes regarding location-specific parameters. The three toilets geographical coverage are similar. Ceramics for the three toilets were made in China, crude oil was made from Norway, Russia or Middle east, iron was made in Belgium and copper was made in China as well. Most producing stage of the toilets are processed in China, however the composting toilet was assembled in Sweden. The toilets are mainly used in Nordic countries and disposal stage is the same as using stage. Table 3.3 shows the geographical scope for the life cycle stages and system processes in the flushing, composting and decentralised toilets.

Table 3.3: Geographical scope for life cycle stages and system processes in three toilets

Toilets	Flushing toilet	Composting toilet	Decentralized toilet
Materials	**-Ceramics:** China **-Crude oil:** Norway, Russia, Middle east **-Iron:** Belgium	**-Crude oil:** Norway, Russia, Middle east **-Iron:** Belgium **-Copper:** China	**-Crude oil:** Norway, Russia, Middle east **-Iron:** Belgium **-Copper:** China **-Ceramics:** China
Manufacturing of different stage	**-Bowl:** China **-Seat and cover:** China **-Water storage tank:** China **-Metal fixtures:** China **-Assembly:** Denmark	**-Main part:** China **-Fan part:** China **-Assembly:** Sweden	**-Steel frame**: China **-Bowl:** China **-Slingshot:** Denmark **-Clean water tank:** Denmark **-Storage tank:** China **-Miscellaneous tubing:** China **-Assembly:** Denmark
Use	Mainly Scandinavia		
Disposal	The same as the use stage		

3.5.2 Time-Related Representativeness

The time-related representativeness reflects how well the inventory data represents the actual processes regarding the time they occur. In line with the requirements to define the geographical scope of processes, the time frame of the processes in the different stages of the life cycle must be defined. For the functional unit considered, a decentralised toilet is expected to be used for 35/1.5=23.5 years approximately, a traditional flushing toilet can be used for 35 years and the composting toilet is expected to be used 35/2=17.5 years. Figure 3.5 illustrates the time frames of the different product life cycle stages of the flushing, composting and decentralised toilets respectively. The time frames are mainly influenced by the expected lifetime of these products.

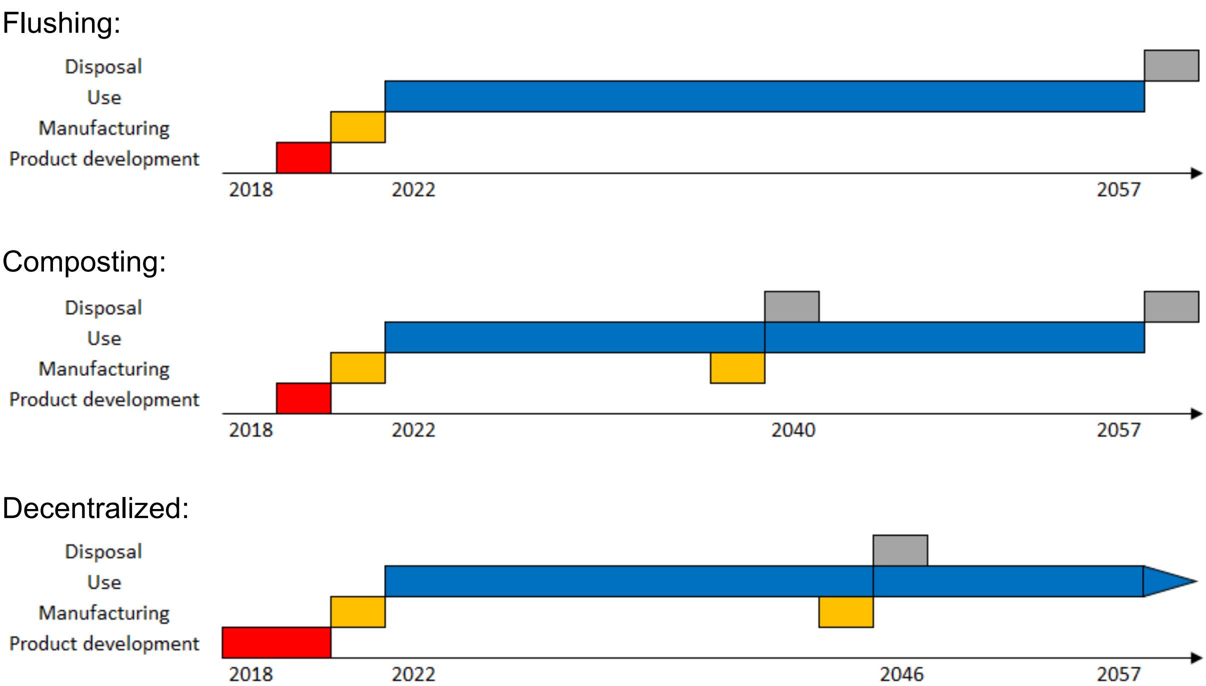


Figure 3.5: Time frames expressed for all toilets in different stages

3.5.3 Technological representativeness

Technological representativeness reflects how well the inventory data represents the actual technologies involved in the studied products system, and is interlinked with geographical and time-related representativeness. However, the utilisation of technology is more related to what materials are the toilets made of. For flushing and decentralised toilets, ceramics is the main component of the bowl. And both high temperature for moulding and chemical solutions are needed to produce good quality ceramics. For composting toilet, it is assumed that the polypropylene injection moulding is the main process to produce the bowl. Table 3.4 lists the main technologies and processes included in the respective product systems of the three toilets.

Table 3.4: List of technologies utilization for the three toilets

Toilet	Flushing toilet	Composting toilet	Decentralized toilet
Technologies utilization	-heating of ceramics -high-purity chemical solutions for ceramics -injection moulding -basic oxygen furnace (BOF) for steel	-injection moulding for polypropylene -basic oxygen furnace (BOF) for steel	-casting, basic oxygen furnace (BOF) for steel -action of heat for ceramics -high-purity chemical solutions for ceramics -injection moulding -refining of copper, to remove impurities

3.6 Preparing the Basis for the Impact Assessment

For the realisation of the impact assessment, the software Simapro is used in order to perform the assessment. According to the criteria given by the ISO regulation, the ReCiPe 2008 (H) method is used. The ReCiPe 2008 (H) method has been established by RIVM, Radboud University, Norwegian University of Science and Technology and PRe Consultants. The ReCiPe 2008 (H) method is used for both midpoint and endpoint impact assessments. As mentioned in the goal definition - section 2.2 Limitations Due to Methodological Choices - a newer version of ReCiPe (2016) method is available in Simapro, but this version does not provide external normalized results.

3.7 Requirements for System Comparisons

In our case, the study comparison has been processed with the same functional unit and system boundaries for all three toilets. However, the data quality between the three toilets is not exactly equivalent, since the decentralised toilet design is in the concept stage. The data for the decentralised toilet has been assumed, based on available data for other product, as best as possible. Therefore the comparison of the three toilets is considered as fair as possibly achievable, and the requirements of comparative research are satisfied.

3.8 Critical Review Needs

This report aims to indicate clearly what is and what is not included in the study, provided with a conclusion and recommendations. However, the report is not intended to be released to the public, it is intended to give an environmental approach to NP Flint and to DTU Diplom on their project. Therefore there is no obligation to make a critical review by a third-party panel.

4. Life Cycle Inventory Analysis

4.1 LCI Model at System Level

The life cycle inventory models at system level, for the three different toilets (flushing, composting and decentralised), are presented in this section. The model of the flushing toilet is given below in Figure 4.1. The composting and decentralised toilet models are given in Appendix A. The models of the flushing toilet and the decentralised toilet are quite comparable, except that the decentralised model requires more materials for assembly, thus the product system becomes more complex. In the LCI models, the grey boxes are background processes and the white boxes foreground processes.

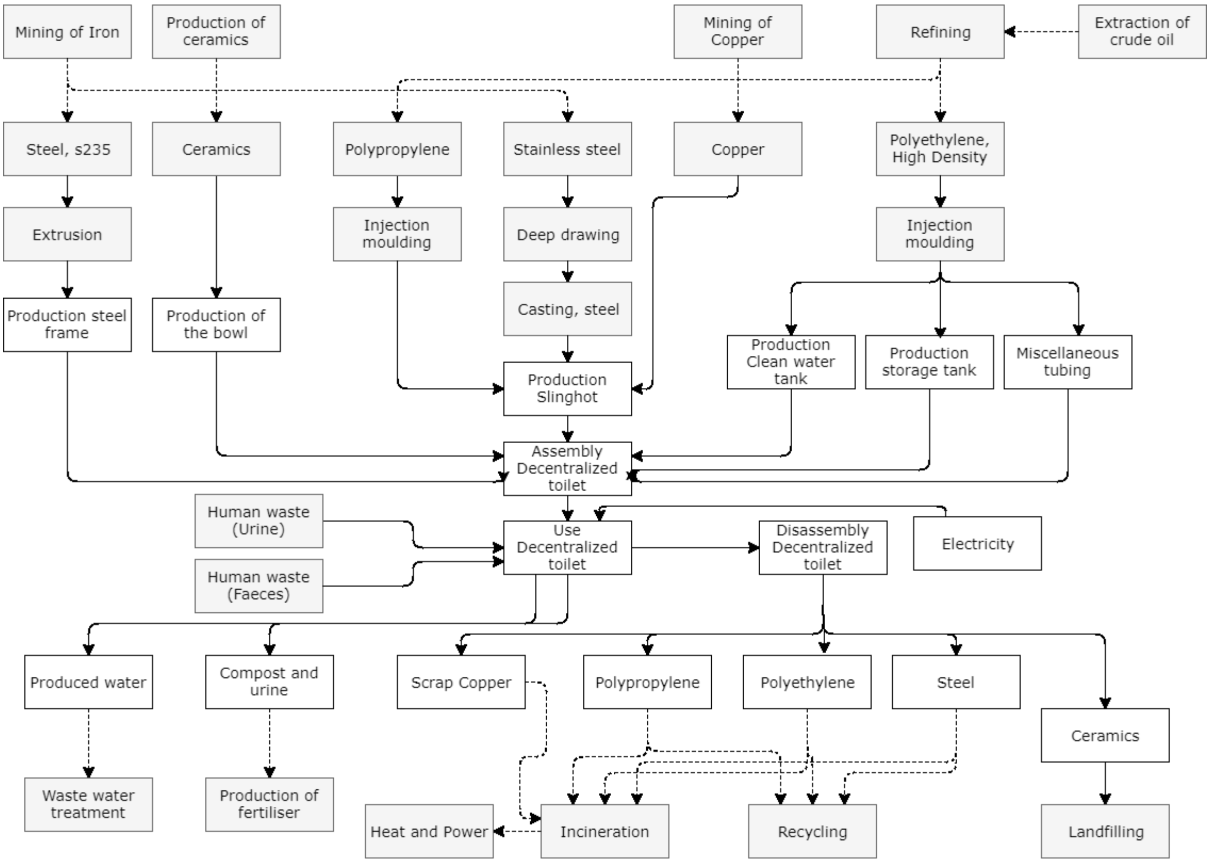


Figure 4.1: LCI model at system level of the decentralised toilet, whereby the grey boxes with dashed lines are of the background process.

4.2 Data Collection

General data for all three systems is mainly collected by research on scientific statistics about human excrement, e.g. the average faeces and urine produced, nutrient value. The data for both the flushing and the composting toilet are quite accurate, since these products are already on the market and enough data is available. However, some small estimations had to be made, e.g. metal fixtures, amount of rubber. Design of the decentralised toilet is still ongoing therefore there is no decentralised toilet data available yet. All of the data used for the decentralised toilet is therefore based on assumptions and estimations, which have been made either as requested by Jacob Lawaetz (DTU diplom), or by ourselves. Moreover, the assumed decentralised toilet design could be changed (using other materials, adaption of the process etc) based on the outcome of this assessment. The LCA would need to be revised in this case.

Table 4.1: General data

General Data for all 3 Systems								
	Specificity							
Process or single data point	Very High	High	Medium	Low	Very Low	Type	Source	Access
usage period flushing toilet			X			years	standard for renting	online search
usage period composting toilet					X	years	estimation	practitioner
usage period decentralised toilet					X	years	estimation	practitioner
Feces per day		X				g/day	scientific article	online search
solid content of feces		X				g/day	scientific article	online search
Urine per day		X				L/day	scientific article	online search
Kalium content of urine			X			g/L	scientific article	online search
Phosphorus content of urine			X			g/L	scientific article	online search
Nitrogen content of urine			X			g/L	scientific article	online search

For the flushing toilet, material usage data is collected by benchmarking the product information of different models from different manufacturers to determine average values.

Table 4.2: Data for flushing toilet

Flushing Toilet								
	Specificity							
Process or single data point	Very High	High	Medium	Low	Very Low	Type	Source	Access
Materials and Manufacture								
Ceramics				X		kg	product information	online search
Polypropylene				X		kg	product information	online search
Rubber				X		kg	product information	online search
Stainless steel				X		kg	product information	online search
Electricity for Assembly					X	MJ	estimation	practitioner
Injection Moulding				X		kg	ecoinvent	Database process
Use and Treatment/Disposal								
Flushing Water					X	L/day	estimation	comissioner
Waste Water			X			m³	calculation	practitioner
Sewage Sludge			X			m³	calculation	practitioner
Transport					X	tkm	estimation	practitioner

Table 4.3: Data for composting toilet

Composting Toilet								
Process or single data point	Specificity					Type	Source	Access
	Very High	High	Medium	Low	Very Low			
Materials and Manufacture								
Polypropylene				X		kg	product information	online search
Copper				X		kg	product information	online search
Steel				X		kg	product information	online search
Electricity for Assembly					X	MJ	estimation	practitioner
Extrusion				X		kg	ecoinvent	Database process
Injection Moulding				X		kg	ecoinvent	Database process
Use and Treatment/Disposal								
Electricity for Fan			X			MJ	product information	online search
Saw Dust				X		kg	calculation	practitioner
Compost			X			kg	calculation	practitioner
Urine			X			L	calculation	practitioner
Methane and CO2 Emissions						m³	average data	online search
Transport					X	tkm	estimation	practitioner

As a reference for composting toilets, the "Villa 9010" from "Separett" is chosen. Material and usage data for the decentralised toilet using the slingshot device is provided by the commissioner of the study. Due to the early stage of development, the data is mostly estimated based on geometrical and functional requirements.

Table 4.4: Data for decentralised toilet

Decentralised Toilet								
Process or single data point	Specificity					Type	Source	Access
	Very High	High	Medium	Low	Very Low			
Materials and Manufacture								
Ceramics				X		kg	product information	comissioner
Polyethylene (High Density)					X	kg	estimation	comissioner
Polypropylene					X	kg	estimation	comissioner
Copper					X	kg	estimation	comissioner
Steel					X	kg	estimation	comissioner
Stainless Steel					X	kg	estimation	comissioner
Electricity for Assembly					X	MJ	estimation	practitioner
Injection Moulding				X		kg	ecoinvent	Database process
Extrusion				X		kg	ecoinvent	Database process
Deep Drawing				X		kg	ecoinvent	Database process
Casting				X		kg	ecoinvent	Database process
Use and Treatment/Disposal								
Electricity (for Slingshot Device)					X	MJ	estimation	comissioner
Flushing Water					X	L	estimation	comissioner
Clean Water (produced)			X			kg	calculation	practitioner
Compost			X			kg	calculation	practitioner
Urine			X			L	calculation	practitioner
Transport					X	tkm	estimation	practitioner

4.3 System Modelling per Life Cycle Stage

In this section the details of the system modelling are described, subdivided into the different stages. The major assumptions are also considered. An overview of all the minor and major assumptions is given in Appendix B.

4.3.1 Materials and Manufacturing stage

The detailed models of the three toilets, including all the activities and materials, and an overview of the details of the materials are shown in Appendix A.

SimaPro processes chosen for all three systems are based on the ecoinvent database. If the manufacturing process is unknown, the most likely process or a combination of several ones is chosen. The energy used for assembling the toilets is a rough estimation, based on the number of components needing to be assembled. Another assumption that has been made is that material losses were not taken into account.

4.3.2 Use stage

It has been assumed that both the faeces and urine have the same density as water. The amount of faeces and urine produced per person and day vary significantly within certain boundaries depending for example on the nutrition. As a broad average, the following data is selected: 0.128 kg/day/person of faeces and 1.42 L/day/person of urine. These assumptions are applicable to all toilets. Assumptions made regarding the decentralised toilet are as follows:

1. The electricity usage for the evaporation of liquid (urine) is estimated to be 11500 kWh (i), the calculation can be found in Appendix B.
2. Crediting of internal heating of the room is assumed to be 2/3rds, i.e. 8 out of 12 months, of the power supplied to the slingshot boiler.

Furthermore, the flushing volume for the flushing and decentralised toilet is both set to 1 litre. Since the decentralised toilet is still in development and will be probably available in the near future, it is more realistic (equal) to compare this system with the nowadays new available technology for the flushing toilet. This new technology is called micro-flushing and reduces the volume of water needed to flush.

4.3.3 Disposal stage

Regarding the human waste (faeces and urine), it has been assumed that both the compost and the urine can be used as fertiliser. The following assumptions have been made about disassembling the toilets:

1. The metal fixtures and plastics (polypropylene and polyethylene) will be incinerated and recycled with a weight ratio of 50:50.
2. The ceramics used for the flushing and decentralized toilet will be disposed by landfilling totally.

Crediting for the nutrients recovered from the urine and faeces has been applied in Simapro consistently for the composting and decentralised toilet, by assuming that all nutrients are recovered. Additionally, for the composting toilet, the faeces will be heated to 60 ℃ and kept for one hour and the urine will be stored in for one year according to Danish legislation. The electricity consumed during heating and production of steel storage tank are included in the model. Diluting fertiliser process is disregarded since it will perform the significant secondary function, e.g. irrigating the plants.

It is assumed that no transport of the produced fertiliser is required since it is envisaged that the fertiliser will be used on site. Another assumption which has been made is that the energy for disassembling the toilets is neglected.

4.4 Calculated LCI Results

A summary of the decentralised toilet life cycle inventory is presented, following the structure of the product life cycle “from cradle to grave”, is presented in Table 4.5. The table is divided into materials and manufacture, use, disposal and transport stages. For each process, the details, e.g. unit, amount, number, SimaPro process are included. Life cycle inventory summaries for the flushing and composting toilets are presented in Appendix E.

Table 4.5: Input data overview of the decentralised toilet

Materials and Manufacture					
Component	**No.**	**Material/R**	**Unit**	**Amount/FU**	**SimaPro Process**
Bowl	1,5	Ceramics	kg	42,75	Sanitary ceramics {GLO}| market for | Conseq, U
Steel Frame	1,5	Steel, s235	kg	38,25	Steel, unalloyed {GLO}| market for | Conseq, U
		Extrusion	kg	38,25	Impact extrusion of steel, hot, 3 strokes {GLO}| market for | Conseq, U
Storage tank	1,5	PE-HD	kg	11,4	Polyethylene, high density, granulate {GLO}| market for | Conseq, U
		Moulding	kg	11,4	Injection moulding {GLO}| market for | Conseq, U
Clean water tank	1,5	PE-HD	kg	7,125	Polyethylene, high density, granulate {GLO}| market for | Conseq, U
		Moulding	kg	7,125	Injection moulding {GLO}| market for | Conseq, U
Miscellaneous tubing	1,5	PE-HD	kg	2,85	Polyethylene, high density, granulate {GLO}| market for | Conseq, U
		Moulding	kg	2,85	Injection moulding {GLO}| market for | Conseq, U
Slingshot	1,5	Stainless	kg	22,5	Iron-nickel-chromium alloy {GLO}| market for | Conseq, U
		Deep	kg	15	Deep drawing, steel, 3500 kN press, single stroke {GLO}| market for | Conseq, U
		PP	kg	6	Polypropylene, granulate {GLO}| market for | Conseq, U
		Moulding	kg	6	Injection moulding {GLO}| market for | Conseq, U
		Copper	kg	0,75	Copper {GLO}| market for | Conseq, U
		Electronic	kg	0	Not modelled
		Casting	kg	7,5	Casting, steel, lost-wax {GLO}| market for | Conseq, U
General	1,5	Electricity	MJ	7,5	Electricity, medium voltage {RER}| market group for | Conseq, U
Use					
Material / Component		**Process**			**SimaPro Process**
		Name	**Unit**	**Amount/FU**	
Human waste (faeces)			kg	6540,8	Not modelled
Human waste (urine)			L	72562	Not modelled
Electricity		Disposing of	kWh	11710	Electricity, low voltage {DK}| market for | Conseq, U
Heat		Indirect	kWh	-7800	Heat, district or industrial, other than natural gas {RoW}| market for | Conseq, U
Disposal					
Material / Component		**Process**			**SimaPro Process**
		Name	**Unit**	**Amount/FU**	
Ceramics		Landfilling	kg	42,75	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Conseq, U
Steel		Recycling	kg	37,875	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Conseq, U
		Incineration	kg	37,875	Scrap steel {Europe without Switzerland}| treatment of scrap steel, municipal incineration | Conseq, U
Polypropylene		Recycling	kg	3	PP (waste treatment) {GLO}| recycling of PP | Conseq, U
		Incineration	kg	3	Waste polypropylene {RoW}| treatment of waste polypropylene, municipal incineration | Conseq, U
Polyethylene		Recycling	kg	106,875	PE (waste treatment) {GLO}| recycling of PE | Conseq, U
		Incineration	kg	106,875	Waste polyethylene {Europe without Switzerland}| treatment of waste polyethylene,municipal incineration
Scrap copper		Incineration	kg	0,75	Scrap copper {Europe without Switzerland}| treatment of scrap copper,municipal incineration | Conseq, U
Produced water		Waste water	kg	-71700	Tap water {Europe without Switzerland}| market for | Conseq, U
Compost		Fertiliser	kg	-2960	Compost {GLO}| nutrient supply from compost | Conseq, U
Urine		Fertiliser	L	-72562	Urine {GLO}| nutrient supply from urine | Conseq, U
Transport					
Material / Component		**Process**			
		Name	**Unit**	**Amount/FU**	**SimaPro Process**
		Transport	tkm	90	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight,lorry 16-32 metric ton, EURO4

4.5 Basis for Sensitivity and Uncertainty Analysis

Sensitivity analyses will be conducted to investigate the influence of key parameters on the environmental impact outcomes.

1. Electricity consumption for heating the faeces (Composting toilet) and of the slingshot boiler (Decentralized toilet). The magnitude and generation technology will be tested respectively.
2. Water use for flushing. In the base case, both flushing and decentralised toilets are assumed micro-flushing, which is emerging and not common. Therefore, 3 and 6 times of the base value are tested.
3. Emission during composting, mainly carbon dioxide and methane, which is supplemented into SimaPro compost process.

In order to identify most influential parameters and to provide a basis for uncertainty analysis, the index "normalised sensitivity coefficients ($X_{IS,k}$)" is applied. The mathematical formula is as shown below.

$$X_{IS,k} = \frac{\Delta IS/IS}{\Delta_{ak}/ak}$$

where $X_{IS,k}$ is the normalised sensitivity coefficient of impact score (IS) for perturbation of a parameter k.

Uncertainty analysis will be conducted using different methodologies, e.g. ReCiPe Midpoint 2008 (H), ILCD 2011 Midpoint+, ReCiPe Endpoint 2008 (H), ReCiPe Endpoint 2016（H), IMPACT 2002+. The influence of different methods chosen for calculating midpoint and endpoint impacts are tested to verify the robustness.

5. Life Cycle Impact Assessment

5.1 Midpoint Impact Categories

The ReCiPe 2008 hierarchist method has been used to assess the midpoint environmental impacts for all three of the toilets considered in this study. The total characterised impact results for each impact category are presented in table 5.1 for each of the toilets. For each category in table 5.1, the highest value is highlighted red and the lowest value is highlighted green. The intermediate value is highlighted amber. Green highlight therefore indicates the most preferred option, and red highlight indicates the least preferred option. It should be noted that, this "traffic light" methodology does not indicate whether the impact scores are negative or positive, it only ranks the options from best to worst for each impact category. The "traffic light" methodology also doesn't indicate the magnitude of differences between the options.

Table 5.1 shows that the flushing toilet is the least preferable toilet in 12 out of 18 characterised midpoint impact results, while it is also the most preferable in 6 out of 18 categories. It can be observed that the flushing toilet attained the lowest score in the metal depletion category, which is expected since the flushing toilet has the lowest metal usage in its inventory. The flushing toilet is also observed to perform the worst in the water depletion category, which is again expected as it relies on the water supply network background system.

The composting toilet appeared to achieve the highest score in 4, and the lowest in 4, of the characterised midpoint categories. The composting toilet is observed to perform particularly well in the land use categories, as it is the preferred option in both the “agricultural land occupation” and “natural land transformation” categories, and the intermediate option in the urban land occupation category.

Finally, the decentralised toilet obtained the highest score in 8 of the characterised midpoint impact categories, and the lowest in 2 categories. Although the decentralised toilet is the preferred option in the greatest number of categories, Table 5.1 does not however inherently indicate that the decentralised toilet is the preferred option overall. External normalisation and weighting must first be applied to the characterised scores before comparisons across impact categories can be made. Externally normalised results are presented in Figures 5.1, 5.2 and 5.3. Weighted results, i.e. conversion to endpoint categories, are presented in Section 5.2. Further discussion regarding the ranking of the toilets, including discussion of unexpected results, is provided in Section 6.

Table 5.1. Characterised impact results for each toilet alternative. green coloured boxed indicate the best score in that category, while amber coloured boxes indicate the intermediate value and the red coloured boxes indicate the least preferable options.

Impact category	Unit	Flushing toilet	Composting toilet	Decentralised toilet
Climate change	kg CO_2 eq	1.73E+03	-8.35E+03	-1.17E+04
Ozone depletion	kg CFC-11 eq	1.89E-04	-4.34E-04	-4.90E-04
Terrestrial acidification	kg SO_2 eq	8.88E+00	5.46E-01	-4.34E+01
Freshwater eutrophication	kg P eq	-9.43E+00	-5.32E-01	-3.18E+00
Marine eutrophication	kg N eq	2.27E+01	-1.81E+00	-2.78E+00
Human toxicity	kg 1,4-DB eq	2.69E+02	-4.46E+03	-6.70E+03
Photochemical oxidant formation	kg NMVOC	-2.38E+00	-1.35E+01	-2.30E+01
Particulate matter formation	kg PM_{10} eq	8.78E+00	-2.29E+00	-3.53E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	-7.00E-02	-5.77E-01	-6.27E-01
Freshwater ecotoxicity	kg 1,4-DB eq	-4.74E+02	1.24E+02	4.56E+02
Marine ecotoxicity	kg 1,4-DB eq	-4.02E+02	9.89E+01	3.72E+02
Ionising radiation	kBq U235 eq	2.92E+02	3.08E+01	7.16E+02

Impact category	Unit	Flushing toilet	Composting toilet	Decentralised toilet
Agricultural land occupation	m2a	4.69E+03	-9.74E+03	-7.59E+03
Urban land occupation	m2a	1.04E+01	-1.08E+02	-7.93E+01
Natural land transformation	m2	4.37E-01	-1.07E+00	-1.00E+00
Water depletion	m3	1.29E+02	-9.62E+01	-3.08E+02
Metal depletion	kg Fe eq	-8.13E+00	1.86E+02	-6.99E+01
Fossil depletion	kg oil eq	7.63E+02	-1.16E+03	-1.97E+03

To convert the midpoint category results to a common scale external normalisation is applied to the results presented in Table 5.1 (above). Externally normalised midpoint results are obtained from the characterised results by applying an external factor, in this case a reference value of the average impact of one person over a year (person-equivalent PE). Figures 5.1, 5.2 and 5.3 present these externally normalised results at midpoint level for the flushing, composting, and decentralised toilet, respectively.

In Figures 5.1, 5.2 and 5.3, the process contributions to each midpoint impact category are presented. It should be noted that some processes are aggregated, such as in the case of the "recycling" process, where the impacts of recycling all materials are combined rather than considering materials individually. The processes presented in each figure differ because of the differing product systems of each toilet. The exact values for the process contribution to each impact category are presented in. Since some normalised results are significantly higher/lower than others, Figures 5.1, 5.2 and 5.3 present a 'zoomed-in' version of the graph, below the full scale graph, so that the smaller contributions can be distinguished more easily. It should be noted that the very high/low impact scores in the freshwater and marine ecotoxicity categories are likely a result of an underestimation of the normalisation factors applied to the ReCiPe 2008 method in SimaPro. Underestimation of the normalisation factors in SimaPro is likely a result of performing simplifications when calculating normalisation factors, without correct estimations of what the person equivalent impacts in these categories are [1-page 717].

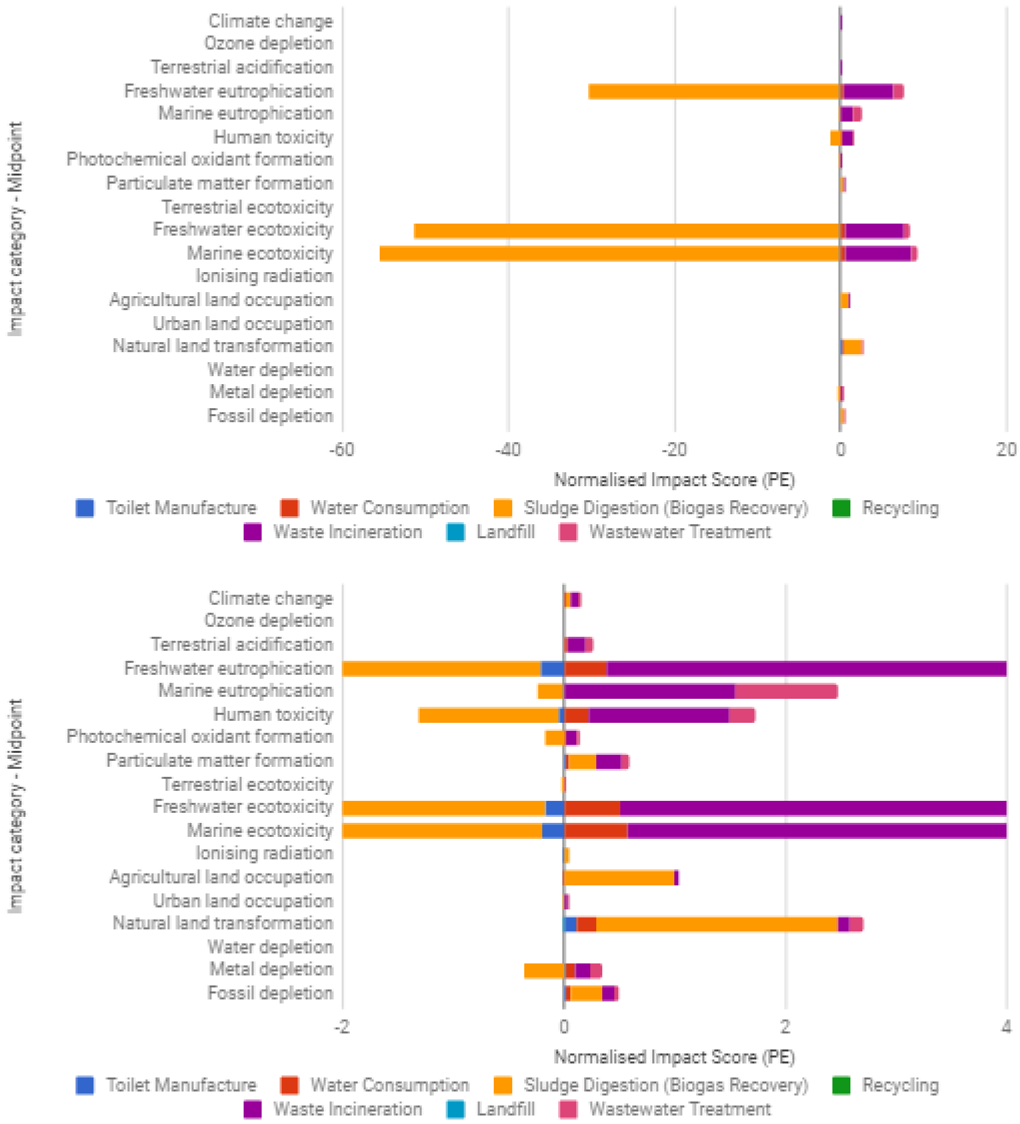


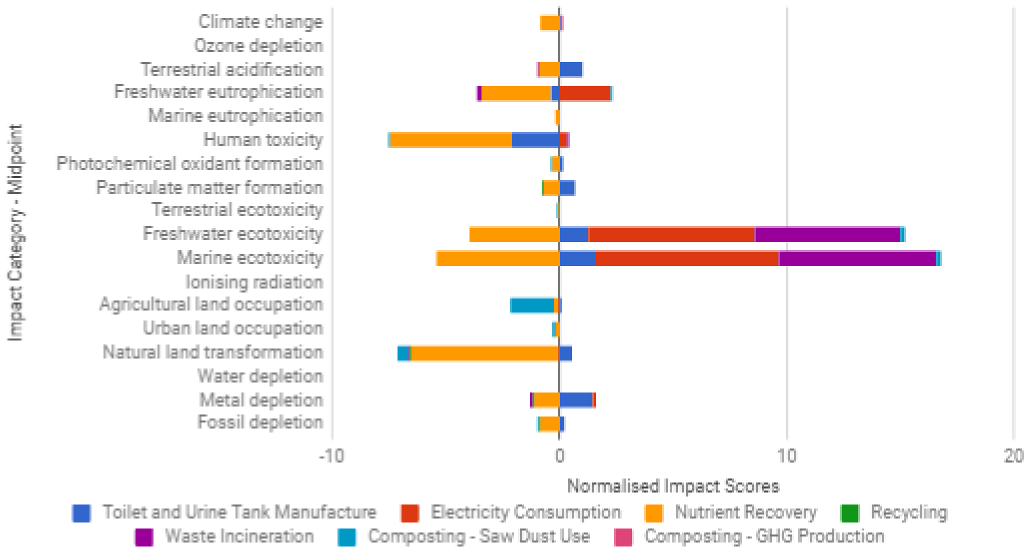
Figure 5.1 Externally Normalised Midpoint Impact Category Results for the flushing toilet.

Besides the impact categories that are overestimated (freshwater ecotoxicity and marine ecotoxicity), the impact categories in which the flushing toilet has (relatively) large net positive environmental impacts are marine eutrophication, natural land transformation and agricultural land occupation. Impacts in both these land impact categories (natural land transformation and agricultural land occupation) depend mainly on the contribution of the sludge digestion - biogas recovery process. The impacts in the marine eutrophication category depend mainly on the waste incineration and wastewater treatment processes. The implementation of the biogas recovery process is discussed further in Section 6.

The impacts of the flushing toilet in the particulate matter formation category are also observed to be large in comparison to other categories. Overall, the largest process contributions to the environmental impacts of the flushing toilet are sludge digestion, waste incineration, waste-water treatment and water consumption. Small contributions are also made by water consumption and toilet manufacturing processes. The impacts from recycling and landfilling waste are negligible in comparison to the other processes.

Besides the impact categories that are overestimated (freshwater ecotoxicity and marine ecotoxicity), the impact categories in which the composting toilet has (relatively) large environmental impacts are natural land transformation and human toxicity. In both these categories the impact score is negative, indicating a positive contribution to the environment. Impacts in both of these categories depend mainly on the nutrient recovery process, which is also the largest contribution group in general, when neglecting the freshwater and marine ecotoxicity impact categories. The nutrient recovery process provides a negative score to almost every impact category, since valuable nutrients are recovered in the composting toilet system substituting the production of fertiliser.

Additionally, electricity consumption and toilet manufacturing processes add positive scores to several categories. The 'zoomed-in' graph in Figure 5.2 shows that the Toilet and Urine tank manufacturing process contributes significantly to almost every category, as a positive score in most cases and a negative score in some others. Waste incineration and electricity consumption are observed to have the largest impact in the freshwater and marine ecotoxicity impact categories.



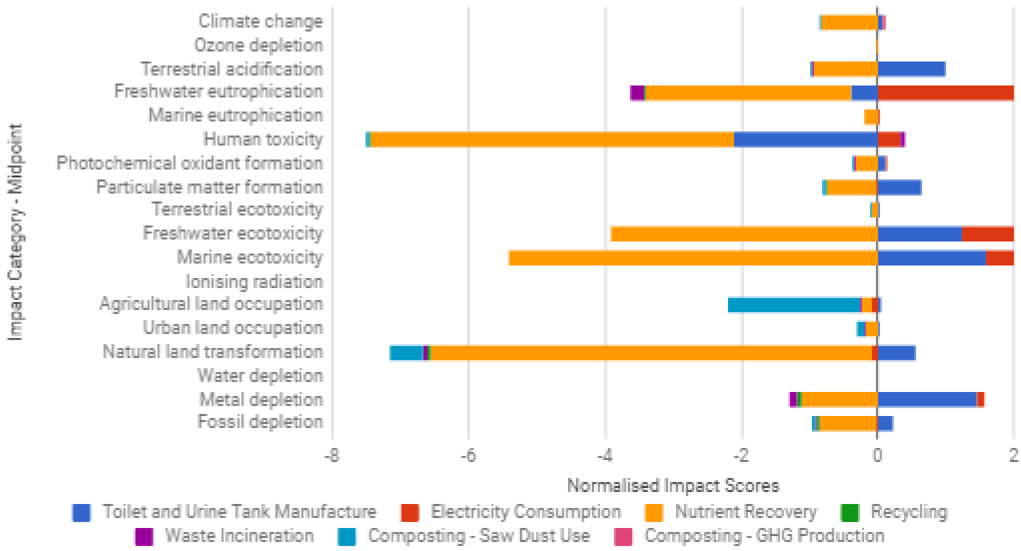
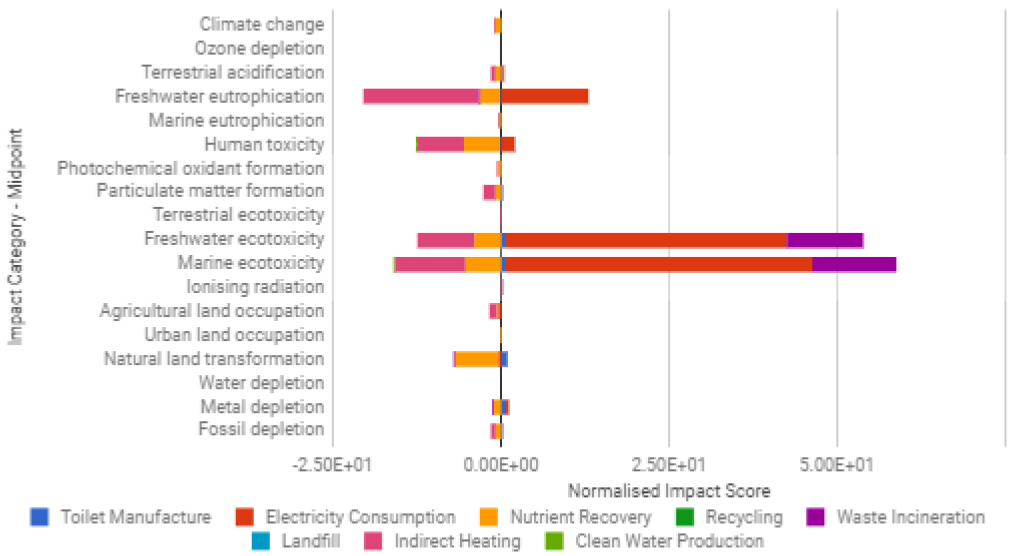


Figure 5.2 Externally Normalised Midpoint Impact Category Results for the composting toilet

Besides the freshwater and marine ecotoxicity categories, the externally normalised midpoint results of the decentralised toilet are most significant in the freshwater eutrophication, human toxicity and natural land transformation categories. In all three of these categories the net impact is negative, indicating a positive impact on the environment. Indeed, in all categories excepting freshwater and marine eutrophication the net environmental impact score is negative. The electricity consumption and waste incineration processes contribute most significantly to the positive impact scores, while indirect heating and nutrient recovery contribute most significantly to the negative impact scores, when comparing the process contributions. Nutrient recovery again provides negatives to the decentralised toilet impacts, as for the composting toilet described previously, whereby nutrients are recovered and production of fertiliser is substituted.



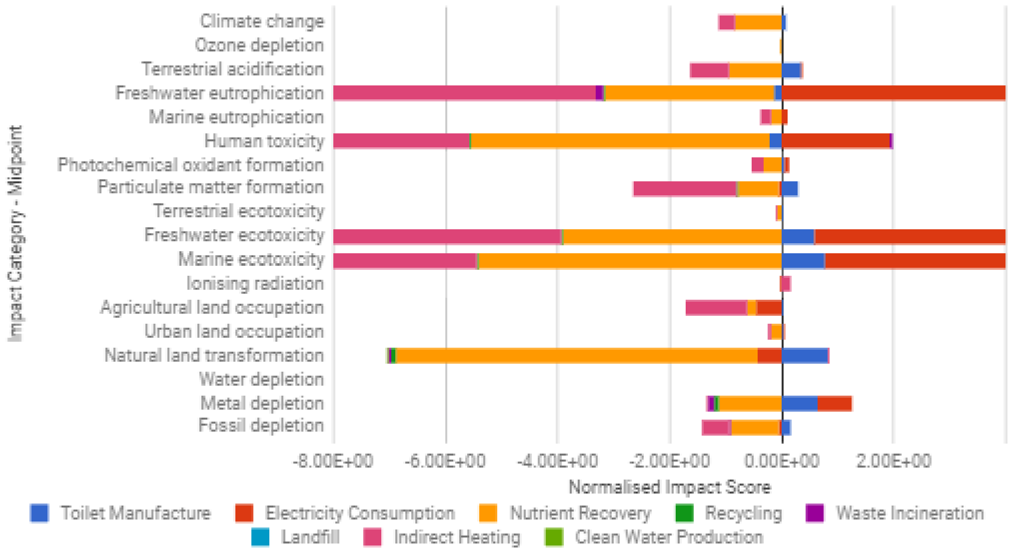


Figure 5.3 Externally Normalised Midpoint Impact Category Results for the decentralised toilet

5.2 Endpoint Impact Categories

The ReCiPe 2008 hierarchist method has also been used to assess the endpoint environmental impacts for all three of the toilets considered in this study. In methodological terms, the midpoint results are converted into endpoint results by applying a weighting factor. The three endpoint impact categories results, human health, ecosystems and resources, for each toilet are shown in Figures 5.4, 5.5 and 5.6, respectively. The corresponding data is shown in Appendix D.

In all of the three endpoint impact categories: human health, ecosystems and resources, the flushing toilet has the highest impact. Both the composting and decentralised toilets have negative scores for all three endpoint impact categories (human health, ecosystems and resources), indicating that impacts are avoided. The composting toilet is shown to avoid more impacts than the decentralising toilet in two of the endpoint categories: human health and resources. In the ecosystems endpoint category, the decentralised and the composted toilet impact scores are approximately equivalent.

The contributions from each midpoint category to the human health, ecosystems and resources categories are indicated in Figures 5.4, 5.5 and 5.6, respectively. Figure 5.4 shows that the three main midpoint categories that contribute to the human health impact endpoint scores are climate change - human health, human toxicity and particulate matter formation categories. Figure 5.5 shows that the main midpoint categories that contribute to the ecosystem endpoint scores are climate change - ecosystems and agricultural land occupation. The resources endpoint score is affected by the respective fossil depletion and metal depletion midpoint impact categories only. For all toilets, the contribution from the fossil depletion midpoint category is much larger than the metal depletion category.

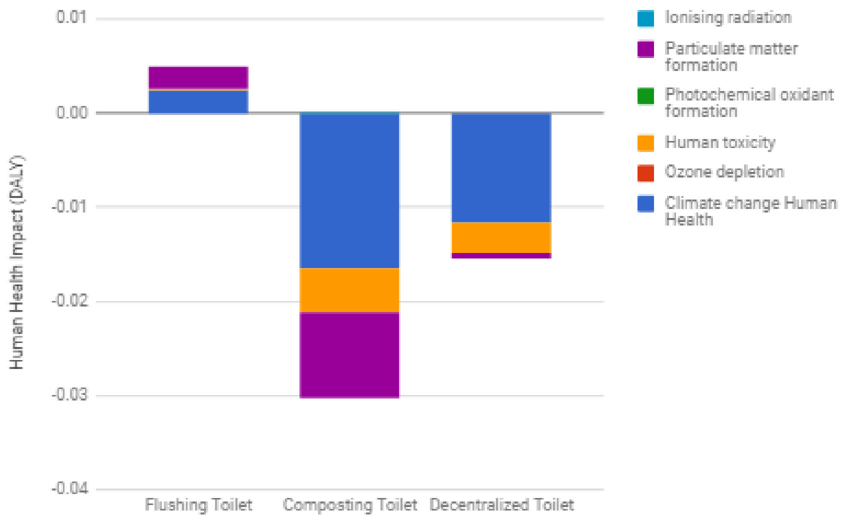


Figure 5.4: Endpoint Impact Category Human Health Results

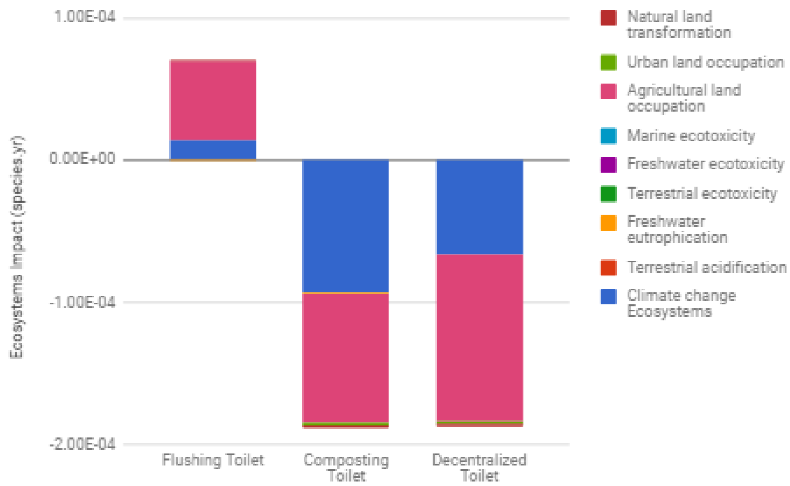


Figure 5.5: Endpoint Impact Category Ecosystems Results.

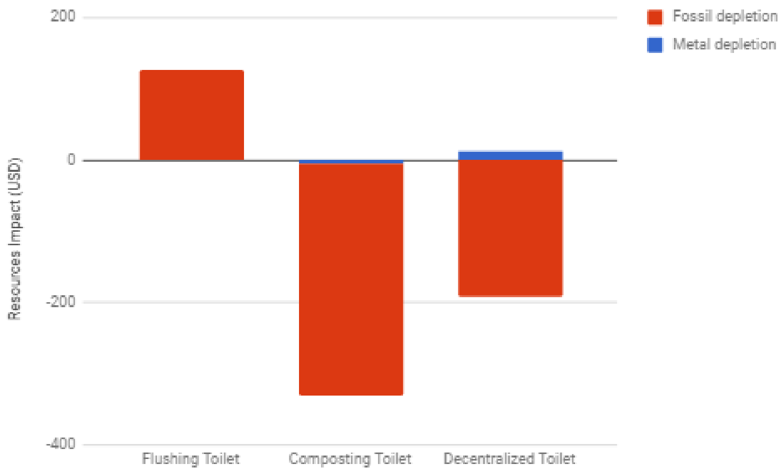


Figure 5.6: Endpoint Impact Category Resources Results

6. Interpretation

6.1 Significant Issues

In order to identify the hotspots that contribute the most to the environmental impact of the toilets, life cycle impact assessments for midpoint (Figures 5.1, 5.2 and 5.3) and endpoint (Figures 5.4, 5.5 and 5.6) impact categories were performed. The contribution to midpoint environmental impacts from each stage of the life cycle (materials and manufacturing, use and disposal) are presented in Figures 6.1 (flushing toilet), 6.2 (composting toilet) and 6.3 (decentralised toilet).

In the midpoint assessment, characteristic values were presented (Table 5.1) and external normalisation of these values was conducted (Figure 5.1, 5.2 and 5.3). By implementing a weighting factor to the externally normalised result the endpoint impact results were also obtained (Figure 5.4, 5.5 and 5.6). For both midpoint and endpoint impact categories the same method was applied: ReCiPe 2008.

Below, first the characterisation impact results are discussed, followed by the discussion of the midpoint process analysis and life cycle stage analysis of each toilet. Subsequently, the endpoint results are interpreted and discussion in general is provided.

*Characterisation impact result*s *(Table 5.1);* Some of the characterised impact results in specific categories are different than initially expected. For example, it was not expected that the impact of the flushing toilet in the freshwater eutrophication category would provide the lowest (most negative) impact score. This may be a result of the consequential database used in this study. It was also not expected that the flushing toilet would perform best in the freshwater and marine ecotoxicity categories. Nevertheless, most of the ranking in the other categories make sense considering the product systems of each toilet. For example, the flushing toilet performs much worse in the water depletion category, than the composting and decentralised toilets. This corresponds with expectations since the composting toilet, which uses no water at all, performs the best in the water depletion category.

Flushing toilet (Figures 5.1 and 6.1); For the flushing toilet, waste incineration is the main driver of positive impact scores, i.e. a negative impacts scores on the environmental (Figure 5.1). Water consumption and wastewater treatment processes are also significant contributors to positive impact scores. However, this negative impact on the environment is largely compensated by the negative score, i.e. positive impact on the environment, of the sludge digestion process, during which biogas is recovered.

Notably, the flushing toilet has a positive impact score in the natural land transformation category. In SimaPro, the production of biogas from anaerobic digestion is a secondary service related to the rearing of livestock. The SimaPro database implements a consequential modelling methodology which subtracts the impact of providing the secondary service from the primary process. In this product system, biogas is produced and therefore the secondary service of the livestock rearing process is avoided. The result is therefore a positive impact score in the land use categories, despite biogas being produced.

The environmental impacts associated with each stage of the flushing toilet product life cycle is presented in Figure 6.1. In Figure 6.1 the externally normalised impact results of each process are grouped into the respective life cycle stage in which they take place: materials and manufacture, use or disposal. Figure 6.1 shows that the use stage is the hotspot in the flushing toilet system. The other two stages (materials and manufacture or disposal) are barely observed from the figure.

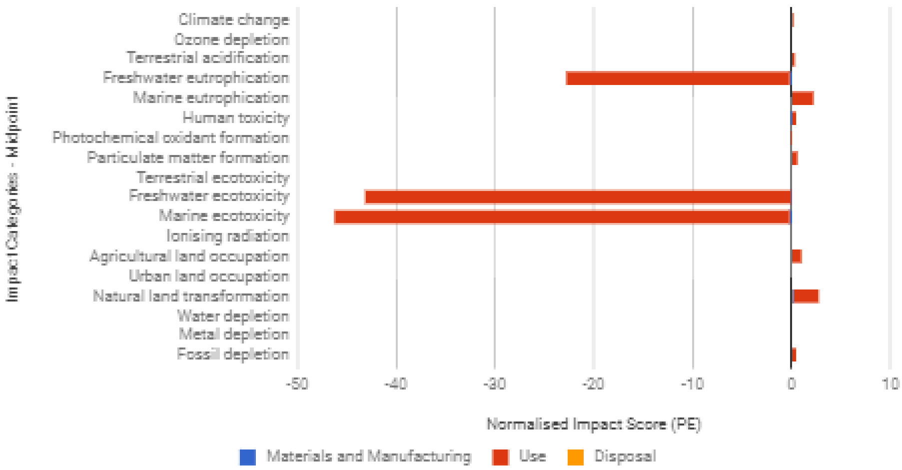


Figure 6.1: Externally Normalised Midpoint Impact Category Results for the flushing toilet, with the individual processes grouped by life cycle stage (materials and manufacturing, use or disposal stage).

Composting toilet (Figures 5.2 and 6.2); For the composting toilet most of the negative impacts on the environment are due to the waste incineration and electricity consumption processes (Figure 5.2), which occur in the disposal and use stages respectively (Figure 6.2). Furthermore, the toilet and urine tank manufacturing process (Figure 5.2) contributes to the positive scores as well, and is included in the materials and manufacturing stage (Figure 6.2). The positive impact scores are compensated for by the negative scores, which arise mostly as a result of the nutrient recovery process. From Figure 6.2 it can be observed that the materials and manufacturing stage has a positive impact score in the majority of categories. Conversely, the use stage has a negative score in the majority of categories, indicating positive impacts. According to the Figure 6.2, the use stage is the hotspot of the flushing toilet life cycle.

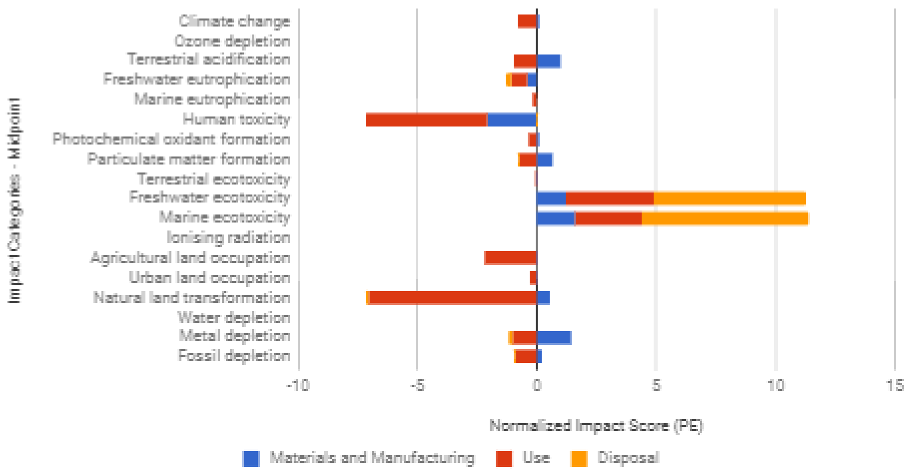


Figure 6.2: Externally Normalised Midpoint Impact Category Results for the composting toilet, with the individual processes grouped by life cycle stage (materials and manufacturing, use or disposal stage).

Decentralised toilet (Figure 5.3 and 6.3); The positives impact scores of the decentralised toilet are attributed to electricity consumption and waste incineration. However, in all categories except freshwater and marine ecotoxicity, these positive impact scores are compensated for by the negative scores resulting from nutrient recovery and indirect heating (Figure 5.3). All these processes are related to the use stage (Figure 6.3), except from waste incineration which is in the disposal stage. The use stage has a non-negligible impact for the freshwater ecotoxicity and marine ecotoxicity categories. These impacts are essentially caused by the electricity consumption to run the Slingshot system (Figure 5.3). In all categories other than the freshwater and marine ecotoxicity categories, the use stage impact scores are negative and contribute to decreasing the overall impact of the toilet. The hotspot for the decentralised toilet is therefore the use stage.

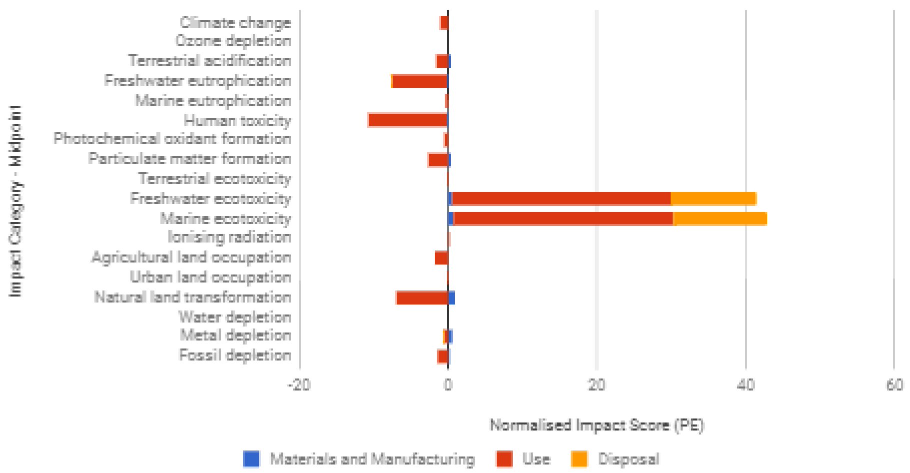


Figure 6.3: Externally Normalised Midpoint Impact Category Results for the decentralised toilet, with the individual processes grouped by life cycle stage (materials and manufacturing, use or disposal stage.

Endpoint impact results; The composting and decentralised toilets both avoid environmental impacts because the nutrient value of the human waste (compost and urine or concentrated waste) is credited to the product system. Additionally, the environmental impact of acquiring urine and faeces have been deemed outside the toilet product system boundaries in this study, also known as the “burden-free approach”. The nutrient value of the flushing toilet waste (sludge) was not credited to the system, since it has been assumed, that the sludge is incinerated after being treated by anaerobic digestion.

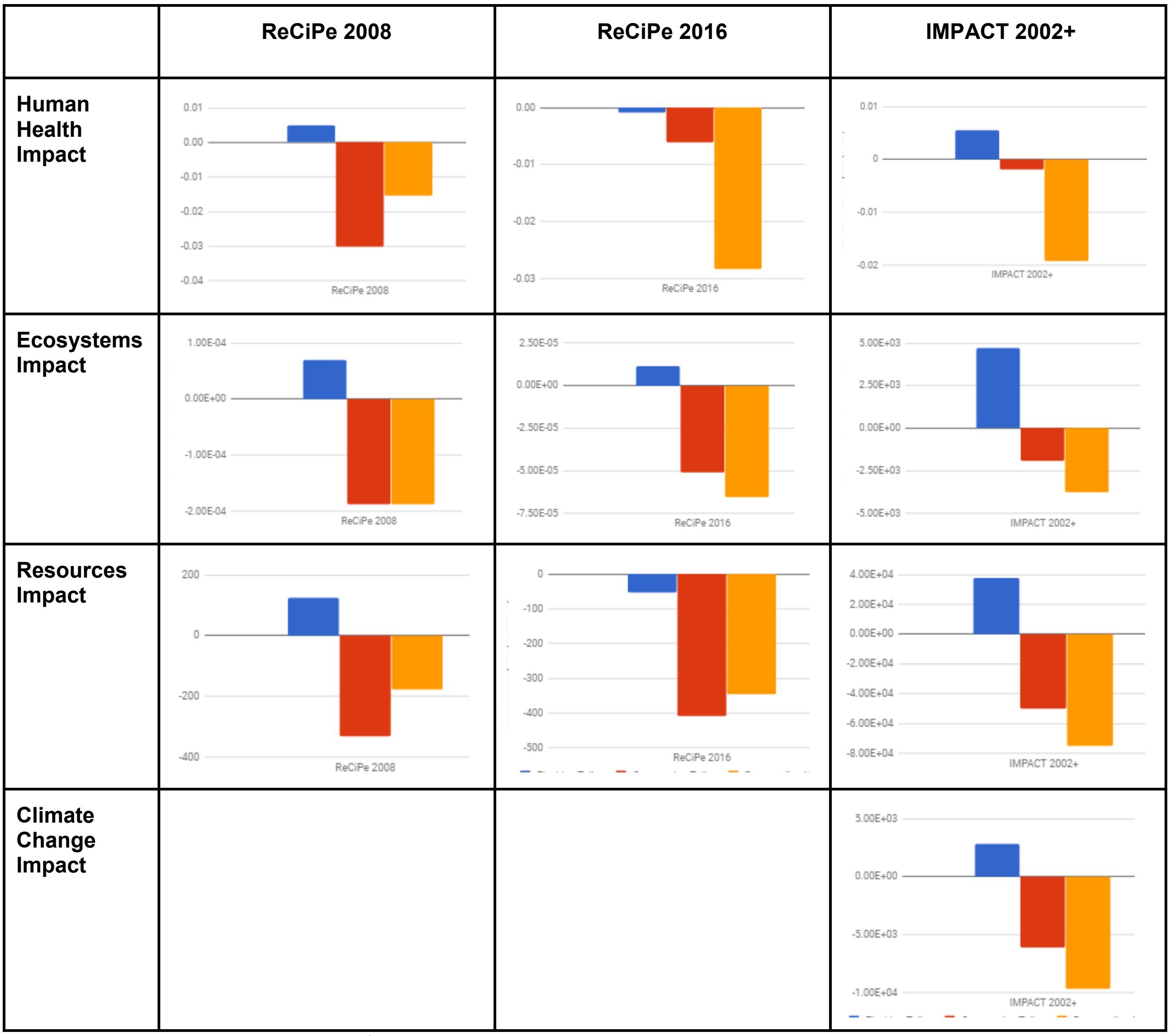
The composting toilet is shown to avoid more impacts, in two endpoint categories, compared to the decentralised toilet, in Figure 5.4-5.6. This can be mostly accredited to the fact that the electricity consumption of the decentralised toilet is considerably higher than the one of the composting toilet. However, the composting toilet uses some electricity, since the regulations in Denmark dictate that the faeces have to be heated up to 60 degrees for an hour if it will be applied as an fertiliser. In the decentralised toilet the faeces have already been heated up to more than 60 degrees in the boiler.

Discussion in general; The process analysis and the life cycle stage analysis are based on the ReCiPe 2008 in Simapro. During the normalization of the results, the coefficients for freshwater ecotoxicity and the marine ecotoxicity seemed to be underestimated and finally contribute to huge normalized scores for these categories. The process contribution in the process analysis differs per toilet system, for both the composting and decentralised toilet the positive impact on the environment is a result of the nutrient recovery, while for the flushing toilet it is the sludge digestion. Despite these somewhat distorted scores of the underestimated categories, the hotspots for all of the three toilets appeared to be the use stage.

6.2 Sensitivity and Uncertainty Analyses Checks

6.2.1 Robustness of modeling method at endpoint level

The comparison of the three toilet systems is complemented with a check of the robustness in regard to the modelling method at endpoint level. Therefore, the initial results from the ReCiPe 2008 method are compared with those of the ReCiPe 2016 and the IMPACT 2002+ methods. Note, that the results from the IMPACT 2002+ method can not be compared directly, as climate change is treated as an endpoint impact category on its own and is therefore not included in the other scores and the units are different. Despite having the same units, the ReCiPe 2008 and ReCiPe 2016 methods should not be compared either, due to significant methodological changes. However, the rankings of each toilet can still be compared because, in the IMPACT 2002+ results, the ranking of the toilets in the climate change is consistent with the other three categories.



***Blue bar: Flushing Toilet; Red bar: Composting Toilet; Yellow bar: Decentralised Toilet**

Figure 6.4: Comparison of endpoint results using ReCiPe 2008, 2016 and IMPACT 2002+

Initially, the results for human health of the different methods are compared. In contrast to the initial results using the ReCiPe 2008 method, both other methods show a more negative impact score for the decentralised toilet than for the composting toilet. Apart from the fact that the flushing toilet has a slightly negative score for human health using the ReCiPe 2016, this method shows quite similar results (regarding the ranking) to that of the IMPACT 2002+ method.

Regarding the impacts on ecosystems, the results of all three methods are quite similar to one another. The decentralised and composting toilet perform almost equally using the ReCiPe 2008 method, while the decentralised toilet performs slightly better while using the ReCiPe 2016 method. The IMPACT 2002+ shows the same ranking, but the differences between the systems are much larger and will further increase if the impact on climate change is taken into account.

Whereas the decentralised toilet performs better for human health and ecosystems according to the ReCiPe 2016 and IMPACT 2002+ methods, and slightly worse/equally according to ReCiPe 2008, the composting toilet performs better in terms of resources according to both ReCiPe methods. The IMPACT 2002+ method in contrast shows the same ranking as for the other categories, indicating that the decentralised toilet performs best.

To conclude, the biggest difference between the endpoint results, when comparing ReCiPe 2008, ReCiPe 2016 and IMPACT 2002+, methods are the impacts on human health between the ReCiPe 2008 and 2016 method. To determine where this difference arises, the contribution of the midpoint impact categories to the human health endpoint score are displayed in Figure 6.5 for the 2008 method results, and in Figure 6.6 for the 2016 results. The figures for the endpoint impact on ecosystems are presented in Figure 5.5. As they do not differ very much, they are not discussed further in this section.

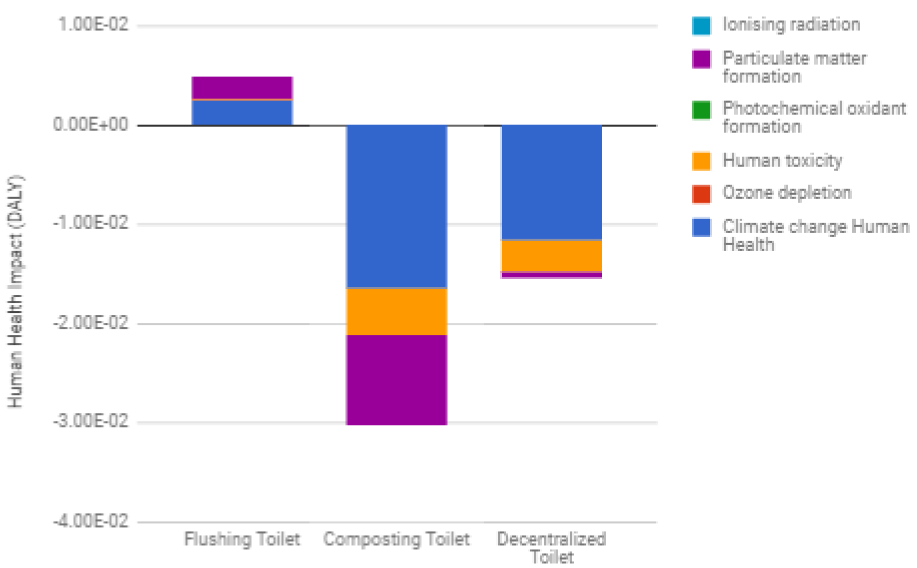


Figure 6.5: Contribution of the midpoint impact categories to the human health endpoint score using ReCiPe 2008

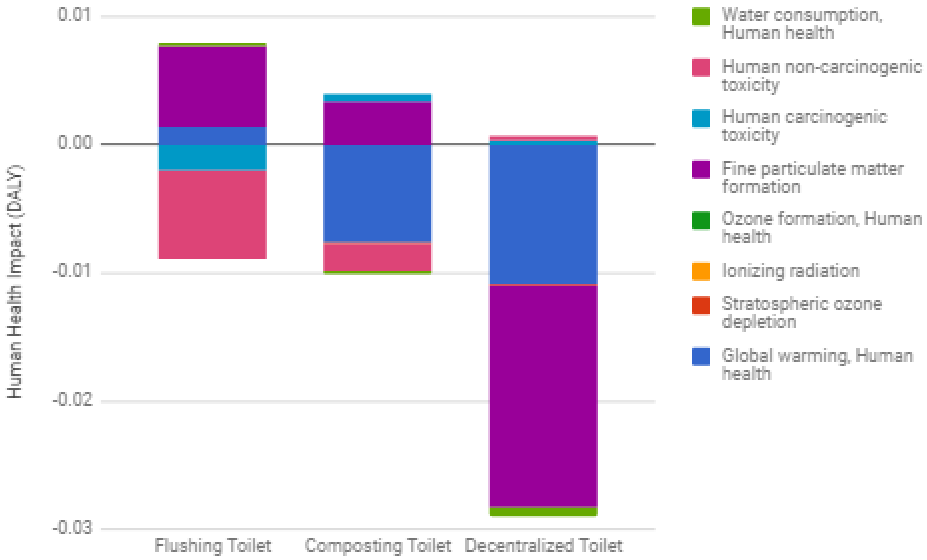


Figure 6.6: Contribution of the midpoint impact categories to the human health endpoint score using ReCiPe 2016

The most striking difference between Figures 6.5 and 6.6 is the impact of particulate matter formation. While the ReCiPe 2008 shows almost no impact of particulate matter formation on human health for the decentralised toilet, there is a markedly negative score for the composting toilet. In contrast, the 2016 method indicates a large, negative score in the particulate matter category for the decentralised toilet but a small positive score for the composting toilet. This observation explains why the ranking of the composting and decentralised toilets change between the two ReCiPe methods.

Additionally, the performance regarding climate change changes between the ReCiPe 2008 to 2016 methods from a better performance of the composting toilet to a better performance of the decentralised toilet. Furthermore, the flushing toilet shows a negative score for human non-carcinogenic toxicity when using the ReCiPe 2016 method is used, which changes the endpoint impact on human health from a positive score to a marginally negative score.

Since the ReCiPe 2016 is more up-to-date than the 2008 version, it can be assumed that the latest version is closer to reality. Furthermore, the results of the ReCiPe 2016 method are better supported by those of the IMPACT 2002+ method.

6.2.2 Sensitivity to input parameters

Some of the data within the report has a low specificity. Therefore, it is very important to check the influence of changes in these parameters on the results. For continuous function parameters such as the electricity consumption or the flushing volume the relative sensitivity coefficient is calculated to characterise the sensitivity to the input parameter. If this approach is not applicable, the relative change is calculated instead.

Flushing Toilet: Flushing Volume

Figure 6.7 compares the impact scores at midpoint level of the flushing toilet if the flushing volume is increased from 1 L to 3 L or 6 L. These sensitivity cases serve to investigate the consequence on the life cycle impact assessment if the flushing toilet were to be a common modern toilet, rather than a micro-flushing toilet. Figure 6.7 shows that the impacts increase noticeably in most of the categories.

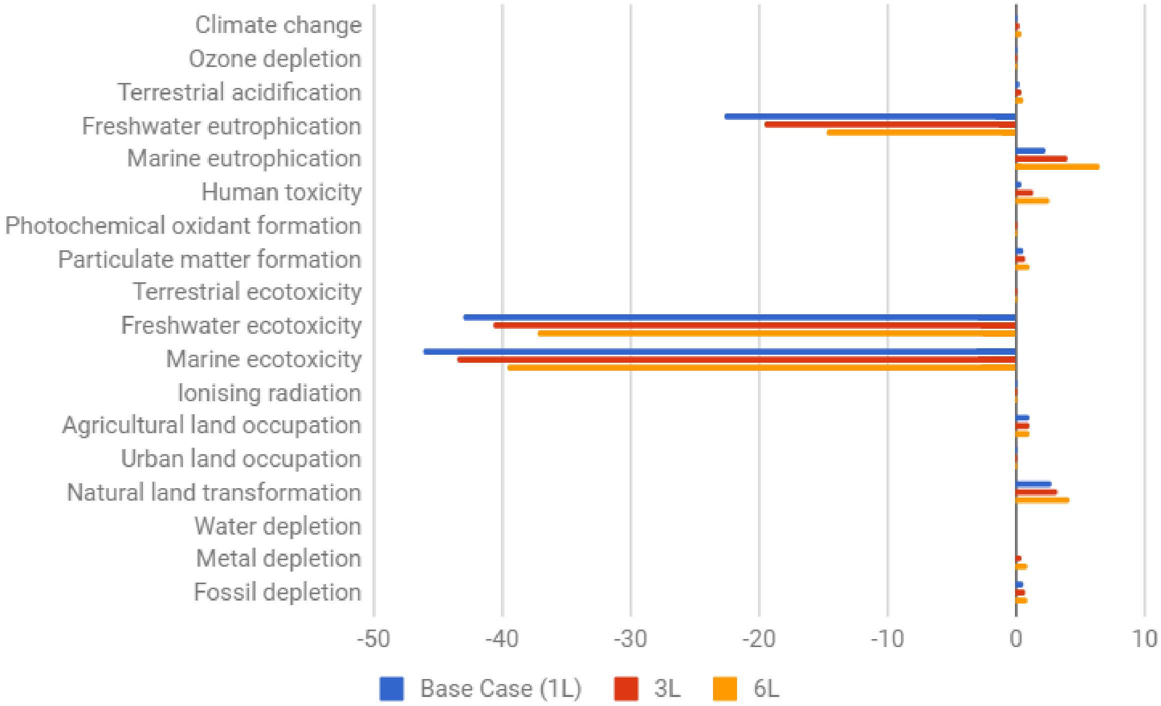


Figure 6.7: Normalised impact scores at midpoint level for different electricity consumptions (PE)

Figure 6.8 presents the sensitivity coefficients calculated in the flushed volume sensitivity analysis. Overall, there are five categories with a high sensitivity (sensitivity coefficient >0.5). Out of those categories, the metal depletion category is by far the most sensitive (>16). The other highly sensitive categories are terrestrial ecotoxicity (1.1), human toxicity (1.0) and photochemical oxidant formation (0.6). Agricultural land occupation, freshwater ecotoxicity and marine ecotoxicity are the least sensitive categories (<0.03). Water depletion is disregarded as the normalised impact score is 0 in all the cases.

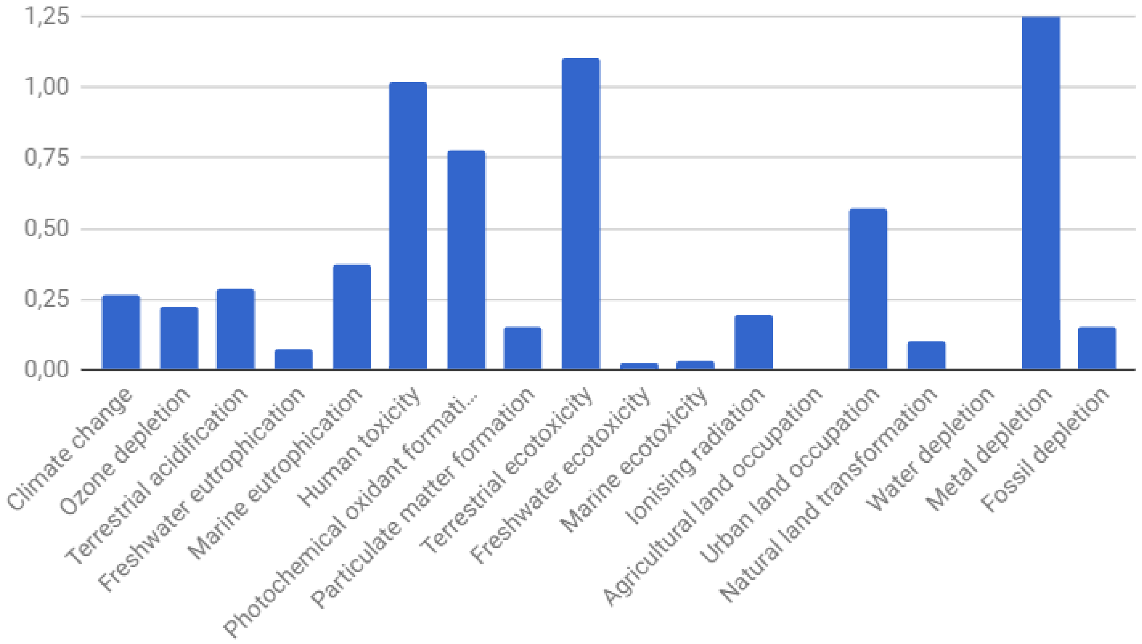


Figure 6.8: Sensitivity to the flushing volume

Composting Toilet: Electricity Consumption

As the specificity of the electricity consumption is low, an analysis of the sensitivity is of special interest. Figure 6.9 shows the changes in impact in each midpoint impact category if the electricity consumption is increased by factors of 2 or 5, compared to the initial consumption.

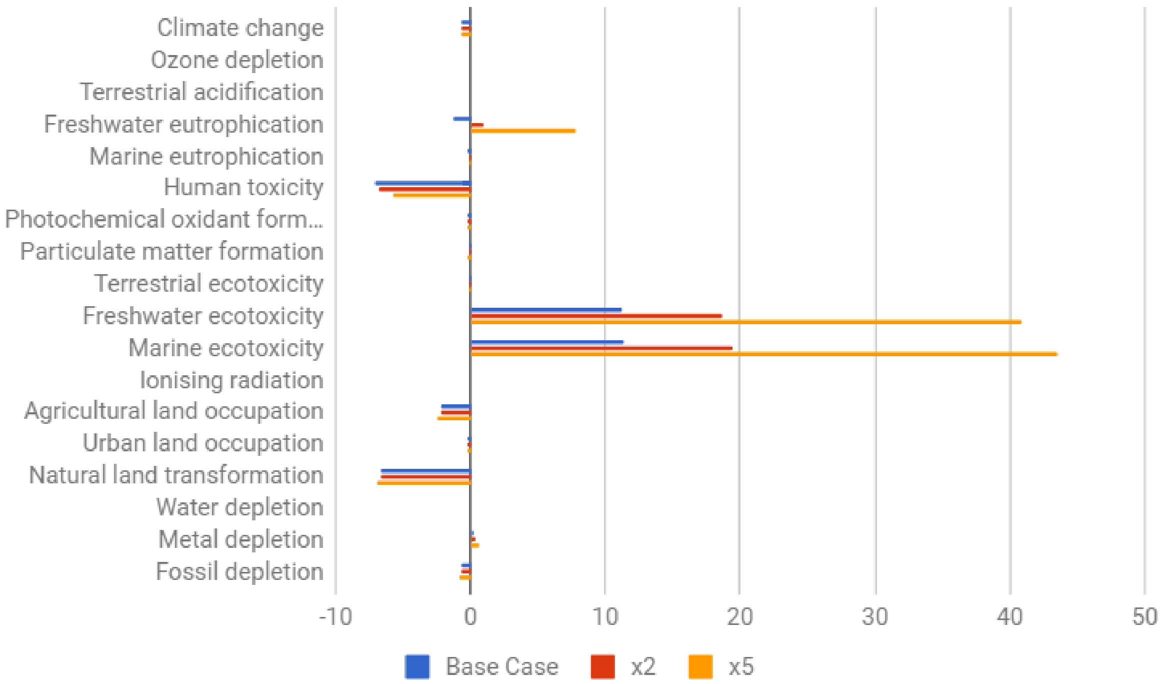


Figure 6.9: Normalised impact scores at midpoint level for different electricity consumptions (PE)

Figure 6.10 presents the sensitivity coefficients calculated in the electricity consumption sensitivity analysis. The impact category with the highest sensitivity to the electricity consumption is freshwater eutrophication (1.8). Three more categories show a high sensitivity, namely freshwater ecotoxicity (0.7), marine ecotoxicity (0.7) and ionising radiation (0.8). Apart from terrestrial acidification and metal depletion, all other impact categories show a very small sensitivity to the electricity consumption.

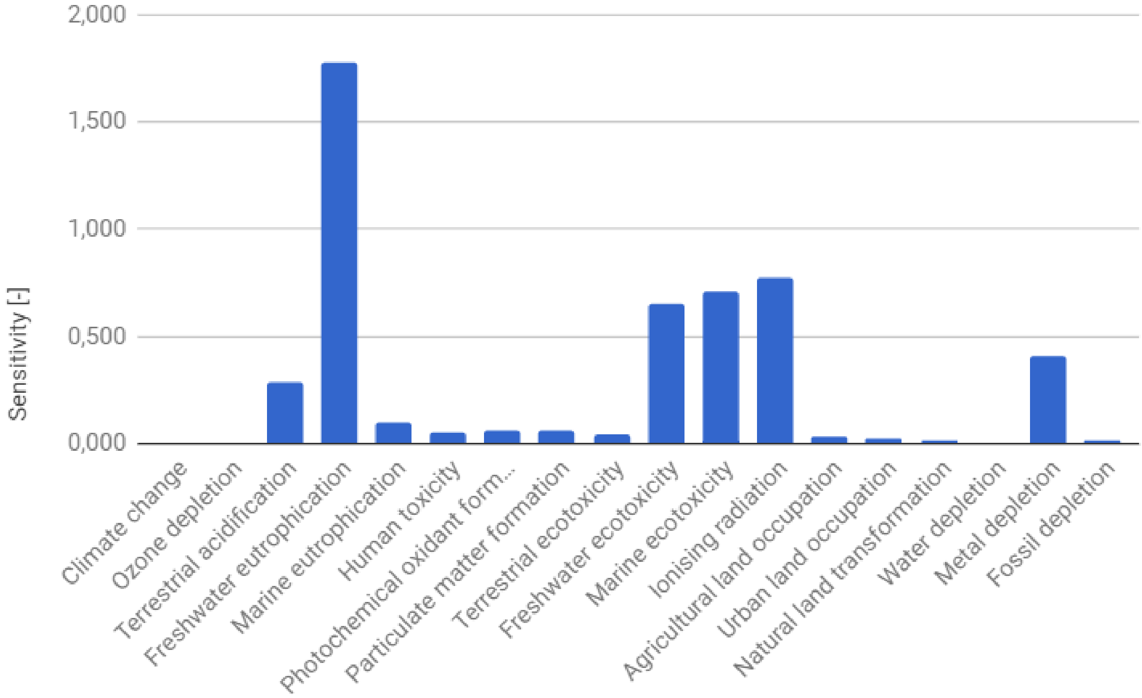


Figure 6.10: Sensitivity to the electricity consumption

Composting Toilet: Emissions from Compost

The amount of emissions emitted from the compost depends on many factors like the air ventilation, temperature or the composition. The impacts of both higher and lower emissions are therefore investigated in this section. Figure 6.11 presents the sensitivity coefficients calculated in the emissions from compost sensitivity analysis. Figure 6.11 shows that the emitted carbon dioxide and methane gases contribute only to the climate change and photochemical oxidant formation categories. However, the sensitivity of these categories to these gas emissions is very low (0.04 and 0.01).

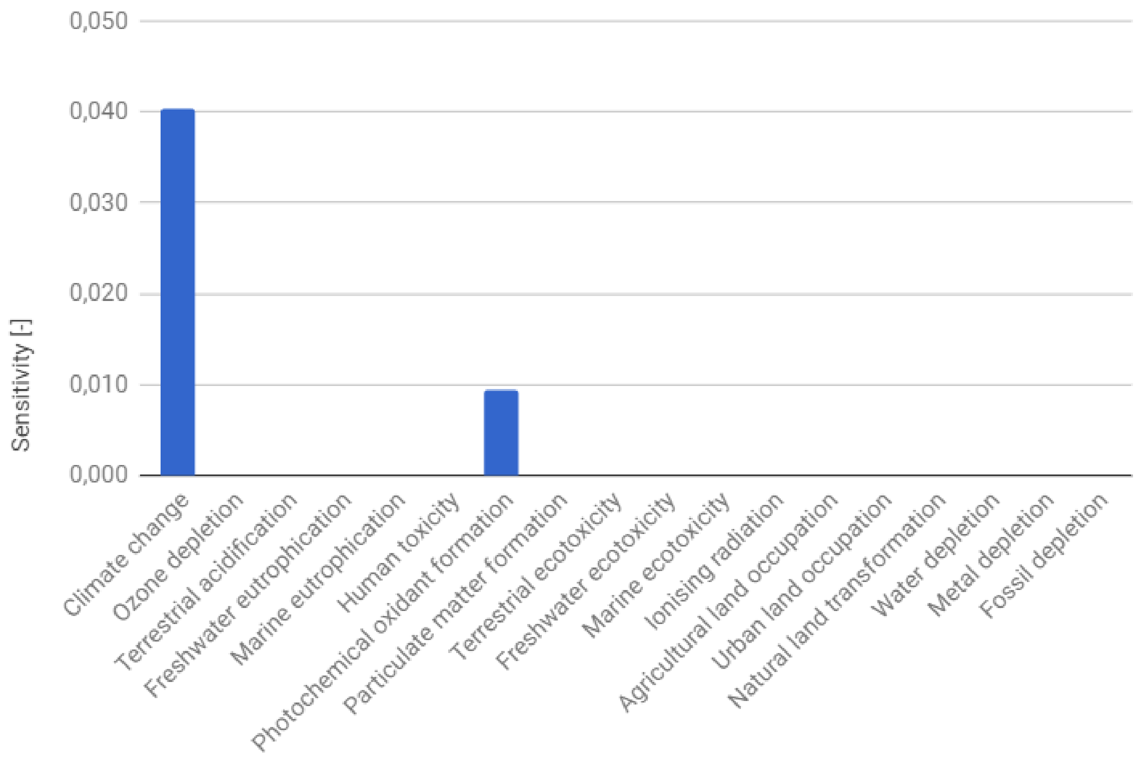


Figure 6.11: Sensitivity to the emitted amount of gases from the compost

Decentralised Toilet: Water and Electricity Consumption

For the decentralised toilet, both water and electricity consumption are analysed concerning their sensitivity. A higher flushing volume only results in a higher electricity consumption, because more water has to be purified before it goes back to the clean water tank and can be used for flushing again. The amount of water entering or leaving the system is not affected. This is why both cases can be handled together. Assuming an efficiency of 50% and 20% of the slingshot purifier the electricity consumption increases by factor 2 and 5, compared to the electricity consumption of the base case.

As Figure 6.12 shows, the two categories with the highest scores, freshwater and marine ecotoxicity, increase further when electricity consumption is increased. In contrast, most of the categories with negative impact scores decrease when the electricity consumption is raised. This is due to the crediting of the heat as a closer analysis of Figure 5.3 shows. Figure 5.3 shows that the impacts of the electricity consumption are lower than the avoided impacts from the credited heat. One possible reason for this how electricity and heat are produced in Denmark. Whereas electricity is partly from renewable sources, heat is mostly provided as district heat from waste incineration and other power plants with much higher impacts on the environment.

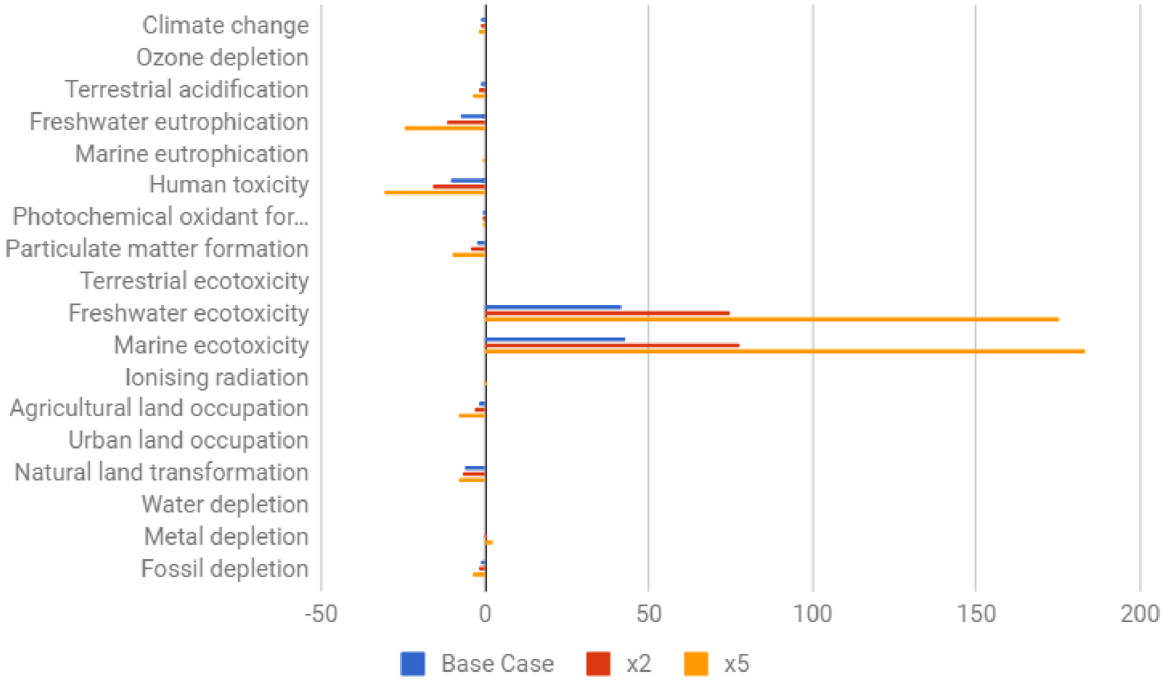


Figure 6.12: Normalised impact scores at midpoint level for different electricity consumptions (PE)

Figure 6.13 indicates that the sensitivity of 8 impact categories is above 0.5. Compared to the composting toilet, the decentralised toilet therefore seems to be more sensitive to changes in electricity consumption. Metal depletion is by far the most sensitive category, with a sensitivity coefficient of 6. Ozone depletion (0.1), terrestrial ecotoxicity (0.1) and natural land transformation (0.07) are the least sensitive. Water depletion is again disregarded as the normalised impact score is 0 in all the cases.

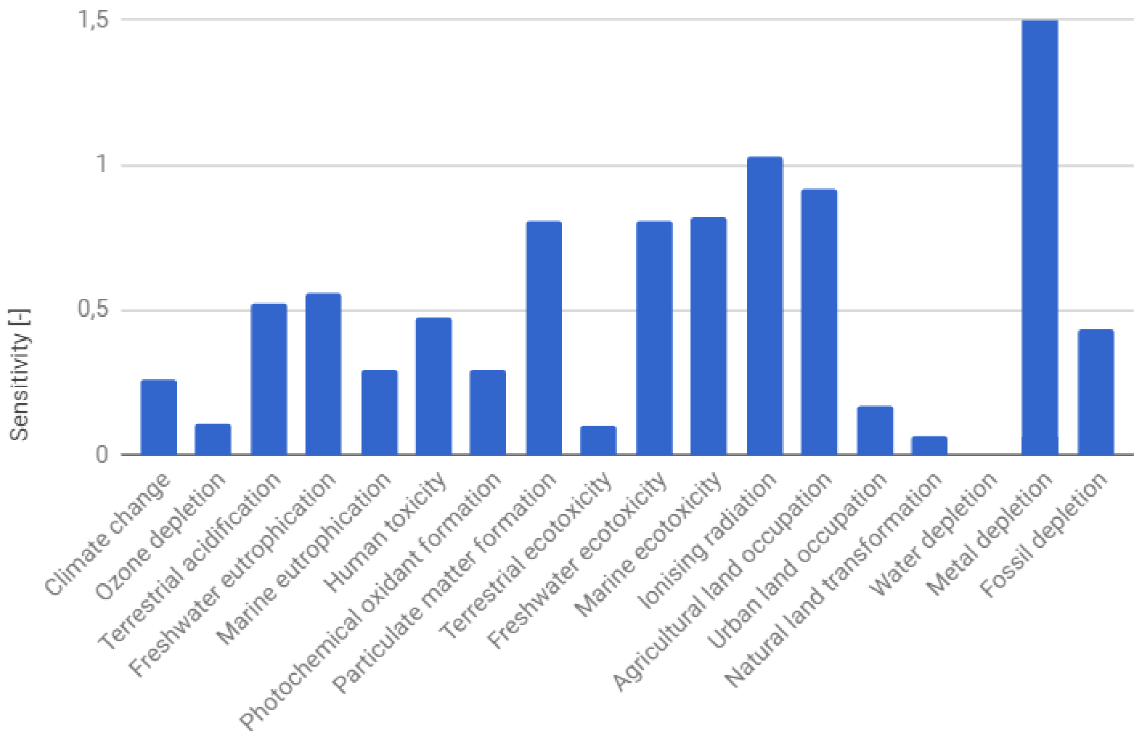


Figure 6.13: Sensitivity to the electricity consumption

Decentralised Toilet: Change of the Electricity Mix to wind energy

As described in Section 3.3, the decentralised toilet could perform water purification during times of the day where there is a surplus of energy, or the consumption is mainly covered by renewable energy sources like wind energy. Hence, the impact of changing the electricity mix to wind energy is assessed in Figure 6.14.

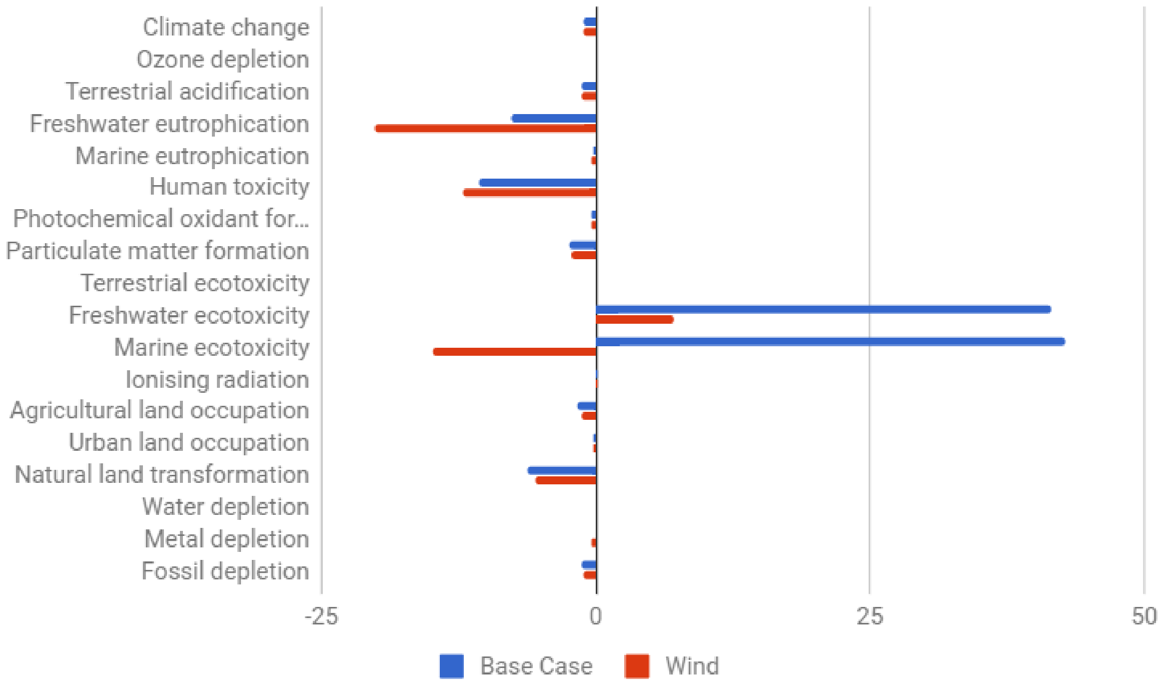


Figure 6.14: Normalised impact scores at midpoint level for different electricity mixes (PE)

Four categories show markedly differences, all reducing the impact in Figure 6.15. It should be noted that it is not relevant to calculate sensitivity coefficients for this case. Instead, relative changes in impact scores discussed. The biggest improvement is achieved for metal depletion (-324%), followed by freshwater eutrophication (-163%) and marine ecotoxicity (-134%). Freshwater ecotoxicity improves by -83%. The other impact categories show a relative change between 0.4% and 35%, and vary in the direction of change (positive or negative). Overall, the usage of wind energy causes an improvement in the environmental impact, compared to the usual energy mix. As the electricity consumption is one of the larger contributors to the environmental impact of the decentralised toilet, the usage of wind energy can lead to a significant improvement in its environmental performance.

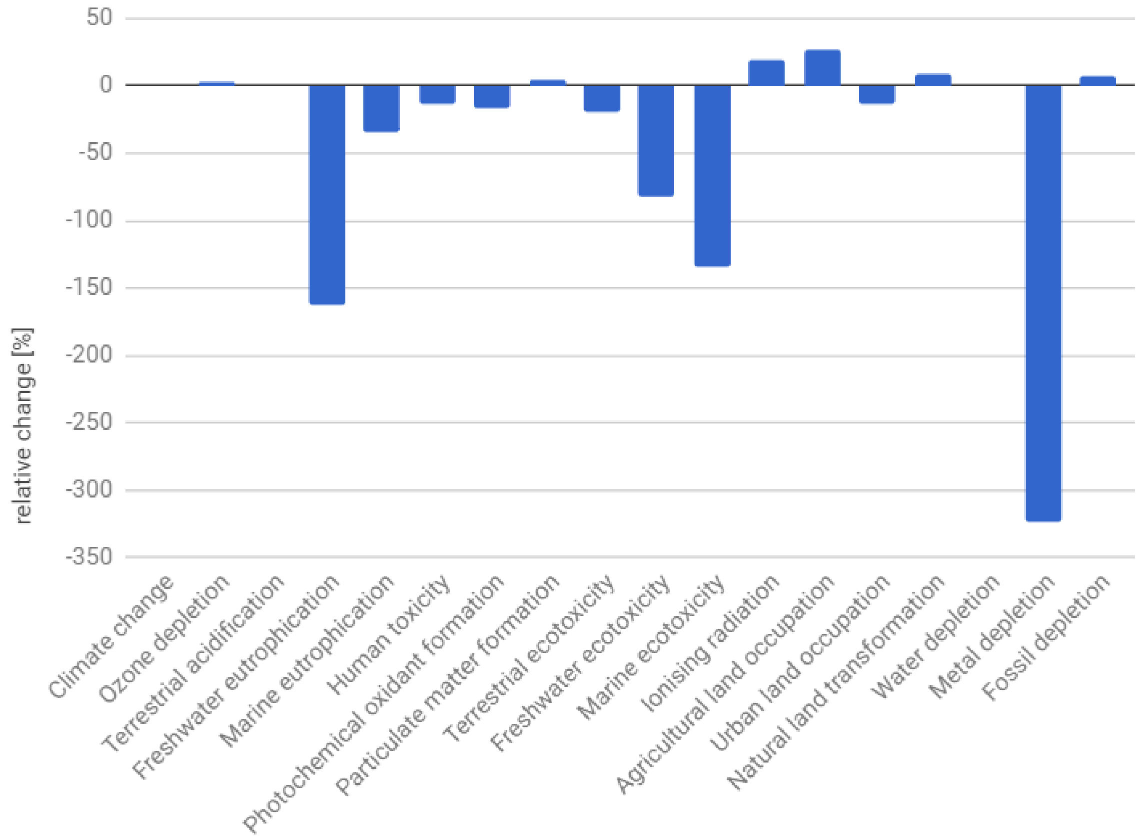


Figure 6.15: Sensitivity to the energy mix

6.3 Completeness and Consistency Checks

6.3.1 Completeness Check

The cut-off rules have been consistently applied across the whole life cycle of the three toilets to ensure the completeness of the study. However, the process of diluting urine before using it as a fertiliser was not included in the model for the composting toilet and the decentralised toilet. The nutrient content of the urine was modelled by substitution of fertiliser production, crediting for the nutrients contained within the urine. In practice, because the nutrient content in urine is so concentrated, it cannot be applied directly as a fertiliser without first being diluted by a factor of ten.

The water used to dilute the urine also serves the function of irrigating the garden. If this water is added to the models of composting and decentralised toilet, system expansion must be performed such that the flushing toilet system also provides this function. Further water volumes would therefore have to be included in the product system of the flushing toilet. To avoid unnecessary system expansion, the diluting water volumes are not included in the system boundaries.

According to the obligatory properties from the goal and scope definition, the three systems perform the primary function of handling human waste. If the use of composting and/or decentralised toilets is implemented on a wider scale the comparison between the three toilets in this study requires review and revision. For example, transport of compost (composting toilet) and/or concentrated waste (decentralised toilet) from the toilet to waste treatment or distribution centres would be required.

6.3.2 Consistency check

The model for the decentralised toilet is based on the design provided by Jacob Lawaetz (DTU Diplom). According to the sensitivity analysis, changing the electricity needed to run the slingshot boiler causes significant changes to the impact scores. If the final design of the decentralised toilet does not correspond to the assumptions made in this study, the study should be revisited.

Concerning the decentralised and the composting toilets, the nutrients contained in the urine and faeces are modelled as substituting fertiliser for use on site. However, depending on the size of the land it may not be possible to effectively use all the fertiliser produced. If the recovery of nutrients were not taking into account, the impact on the composting and decentralised toilet systems would be significant.

If use of decentralised or composting toilets were implementation on a wider scale, it could be envisaged that the nutrients from human waste could be used in industrial agriculture, such as on arable land. However, this would require a collection and transport service for the human waste, which would therefore impact the toilet product systems.

Regarding the externally normalised impact results, some normalised results appeared to be significantly higher in positive/negative scores than others, as shown in Figures 5.1, 5.2 and 5.3. Impact scores in the freshwater and marine ecotoxicity categories were observed to be particularly large in comparison to other categories. The most likely reason for these exceptional results is an underestimation of the normalisation factors applied to the ReCiPe 2008 method in SimaPro. Since the outcome of the underestimated categories were uncertain, and therefore not reliable, those categories were excluded from discussion and interpretation of the results. Instead, more focus was put on the other larger categories.

Underestimation of the normalisation factors in SimaPro is likely a result of performing simplifications when calculating normalisation factors, without correct estimations of what the person equivalent impacts in these categories are [1-page 717]. However, it should be kept in mind that when improving these factors, impacts in the freshwater and marine ecotoxicity categories could still be the largest.

Although it is stated in the scope definition that a method comparison at midpoint level is within the project scope, this comparison is not included in the uncertainty analysis. This is because the variety of impact categories, and some differences in the categories between the two methods (ReCiPe 2008 and ILCD 2011), make drawing a conclusion regarding the preference of one of the systems very difficult. Therefore, the comparison at midpoint level does not provide additional value to the detailed comparison performed at endpoint level.

7. Conclusions, Limitations and Recommendations

7.1 Conclusions

Having analysed the life cycle impacts of flushing, composting and decentralised toilets the following conclusions are made:

1. In general, the decentralised toilet performs better than the composting and flushing toilets based on the endpoint results from the three different methods chosen. The decentralised toilet performs better for human health and ecosystems according to ReCiPe 2016 and IMPACT 2002+ methods, and nearly equally according to ReCiPe 2008. However, the composting toilet has a more positive impact on environment in terms of resources in all three methods.
2. The flushing toilet has the most negative impact on the environment, compared to the other two toilets, based on the endpoint methodology. Both the composting and decentralised toilets have negative impact scores in all endpoint impact categories, indicating that emissions are avoided by the product system. This is due to crediting of the nutrient value of the human waste, while considering the environmental impact of acquiring the human waste as outside of the product system boundaries.
3. From the external normalisation results on midpoint level, the hotspot for all three toilets appears to be in the use stage. Considering process contribution, the positive impact on environment from composting and decentralised toilets is mainly on account of the nutrient recovery, while that of the flushing toilet is the sludge digestion. The negative impact on environment for both the composting and decentralised toilets is attributed to the waste incineration and electricity consumption processes, while the waste incineration is the main contributor for the flushing toilet.

7.2 Limitations

The largest limitation in this analysis is the relatively high uncertainty of the collected data, which has a significant impact on the modelling in SimaPro and, accordingly, the outcome. In order to improve the results, several suggestions are listed below.

1. Include an amount for the losses of materials in the materials and manufacturing stage. However, the impact of this contribution is expected to be small, as the majority of impacts are attributed to the use stage.
2. Accounting for the energy cost of disassembling the toilets. As above, the impact of this contribution is expected to be small.
3. Crediting electricity used for the evaporation of liquid in the slingshot device is most likely very optimistic, so it has to be reviewed.
4. The crediting for the urine and faeces has been applied in SimaPro in the same way for the composting and decentralized toilet, assuming all nutrients are recovered by the toilets. However, this may not be achievable in practice and the assumption could be improved in future work.
5. Taking into account the transport of the compost or concentrated waste (fertiliser products) for the composting and decentralized toilet, respectively.

6. The amount of faeces and urine depends largely on the nutrition and the world region. As the systems are implemented in Denmark, the accuracy and representativeness of the study could be improved by searching for country specific data.

7.3 Recommendation

Having conducted this study, the following recommendations, regarding future work and decentralised toilet design development are made:

1. For future improvements, it would be interesting to investigate why the categories “freshwater ecotoxicity” and “marine ecotoxicity” are overestimated. The results from the study would not change, but interpretations of the impacts for the different categories could be more accurate.
2. Concerning the development of the decentralised toilet, since the hotspot is in the use stage, DTU Diplom, NP Flint and the other participants of this project could focus on reducing the consumption of the electricity for running the slingshot device. This study suggests that further development of the decentralised toilet concept could result in reduced environmental impacts, when substituting use of flushing toilets. However, if the amount of electricity needed is greater than modelled, the conclusions of this assessment must be reconsidered.
3. To reduce the cost of electricity consumed, to smooth the power consumption and therefore to avoid energy sources that have a high impact on the environment, the slingshot device in the decentralised toilet could be run at times of electricity surplus in the grid.

8. References

Literature

[1] Michael Z. Hauschild, Ralph K. Rosenbaum, Stig Irving Olsen, “Life Cycle Assessment, Theory and Practice”, 2017 Chapter 8, pp105.

Online Sources

- Ceramics flushing tank (FT) 26.10.2017 https://pro.villeroy-boch.com/de/de/bw/m/772311.html?tx_mmpdu_profiportal%5Baction%5D=detail&cHash=7c82bc224ab91e8e8a0503aa484433e3
- Ceramics toilet bowl (FT) 26.10.2017 https://pro.villeroy-boch.com/de/de/bw/m/Subway-Tiefspuelklosett-fuer-Kombination--660910.html?_ga=2.98431199.1138291412.1509021894-1948755858.1509021894
- Copper in e-motor 02.11.2017 http://www.isi.fraunhofer.de/isi-wAssets/docs/n/de/publikationen/Schlussbericht_lang_20090515_final.pdf
- Flushing volume per day (FT)02.11.2017 http://www.home-water-works.org/indoor-use/toilets
- Human faeces and urine 02.11.2017 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4500995/
- Metal fixtures (FT) 26.10.2017 https://www.obi.de/zubehoer-fuer-toilettensitze/obi-wc-sitz-scharnier-mit-befestigung/p/3591948
- Plastics main part (CT) 02.11.2017 http://www.separett.com/products/toilets/urine-separating-toilet-villa-9010/
- Plastics seat and cover (FT) 26.10.2017 https://www.obi.de/toilettensitze/wenko-wc-sitz-absenkautomatik-bassano-weiss/p/9020041
- Usage period flushing toilets 28.09.2017 http://www.tfj.ch/mietvertrag-wohnung-kostenlos/lebensdauertabelle.pdf
- Weight fan unit (CT) 02.11.2017 https://www.mouser.de/ProductDetail/ebm-papst/3412NGV/?qs=%2fha2pyFaduimjBAZnK1WQ0YJAtgfwA7OB07E86UciYA%3d
- Separett official site 27.11.2017 http://www.separett.com/products/toilets/urine-separating-toilet-villa-9010/

9. Appendix

A. LCI model at system level & Calculated LCI results

Flushing toilet:

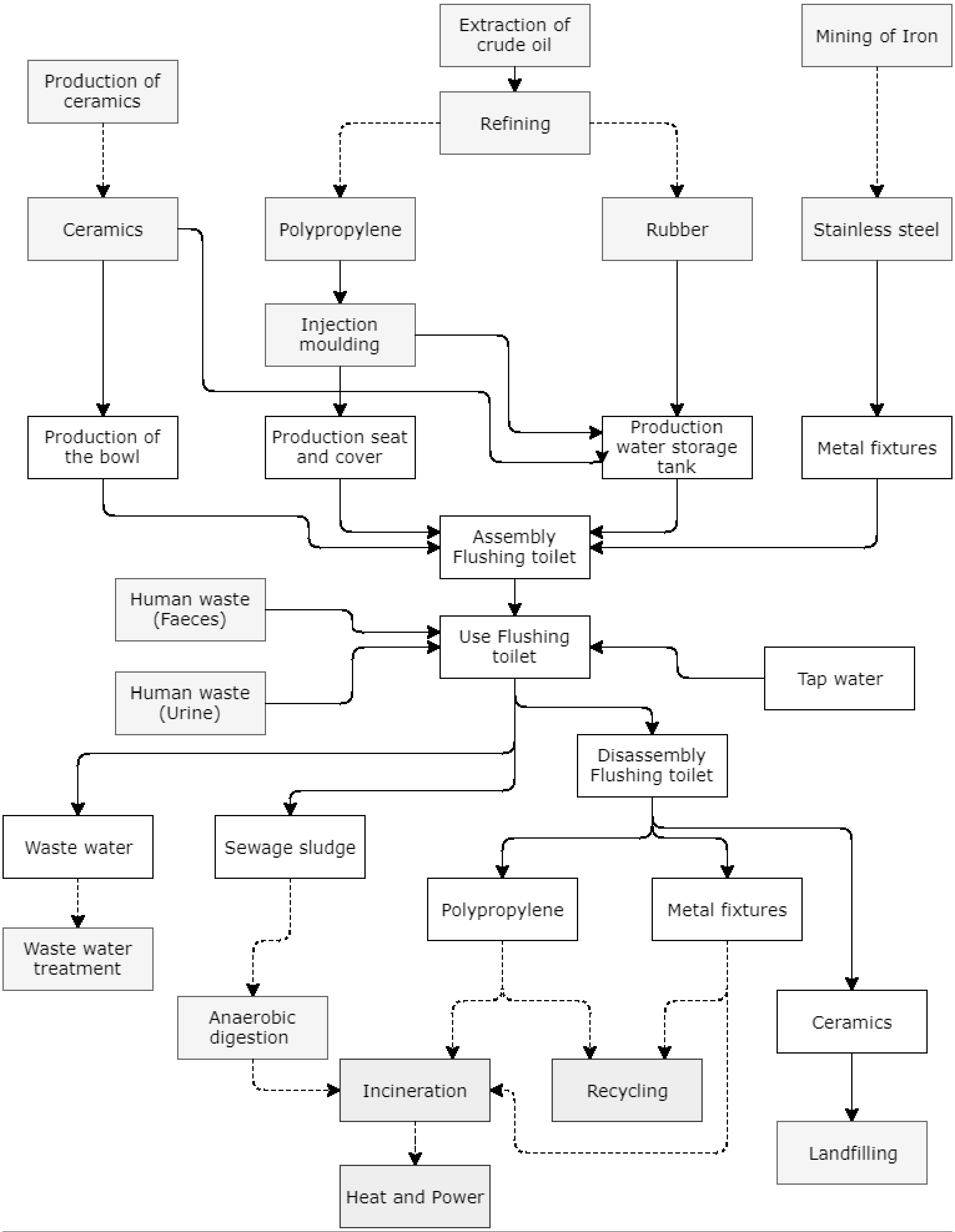


Figure A.1: LCI model at system level of the flushing toilet, whereby the grey boxes with dashed lines are of the background process.

Materials and Manufacture					
Component	**No.**	**Material /Resource**	**Unit**	**Amountper**	**SimaPro Process**
Bowl	1	Ceramics	kg	15	Sanitary ceramics {GLO}| market for | Conseq, U
		Polypropylene	kg	1.5	Polypropylene, granulate {GLO}| market for | Conseq, U
Seat and cover	1	Injection moulding	kg	1.5	Injection moulding {GLO}| market for | Conseq, U
		Ceramics	kg	13	Sanitary ceramics {GLO}| market for | Conseq, U
		Polypropylene	kg	0.3	Polypropylene, granulate {GLO}| market for | Conseq, U
		Injection moulding	kg	0.3	Injection moulding {GLO}| market for | Conseq, U
Water storage	1	Rubber	kg	0.05	Synthetic rubber {GLO}| market for | Conseq, U
Metal fixtures	1	Stainless steel	kg	0.5	Iron-nickel-chromium alloy {GLO}| market for | Conseq, U
General	1	Electricity	MJ	1	Electricity, medium voltage {RER}| market group for | Conseq, U
Use					
		Process			
Material /Componen		**Name**	**Unit**	**Amount/FU**	**SimaPro Process**
Tap water		Use	kg	408800	Tap water {Europe without Switzerland}| market for | Conseq, U
Human waste (faeces)		Not modelled	kg	6540.8	Not modelled
Human waste (urine)		Not modelled	L	72562	Not modelled
Disposal					
		Process			
Material /Componen		**Name**	**Unit**	**Amount/FU**	**SimaPro Process**
Ceramics		Landfilling	kg	28	Inert waste, for final disposal {RoW}| treatment of inert waste,inert material la
		Recycling	kg	0.25	Steel and iron (waste treatment) {GLO}| recycling of steel and iron |Conseq,
Metal fixtures		Incineration	kg	0.25	Scrap steel {Europe without Switzerland}| treatment of scrap steel,municipal
		Recycling	kg	0.9	PP (waste treatment) {GLO}| recycling of PP | Conseq, U
Polypropylene		Incineration	kg	0.9	Waste polypropylene {RoW}| treatment of waste polypropylene,municipal inc
Rubber		Incineration	kg	0.05	Waste rubber, unspecified {Europe without Switzerland}|treatment of waste r
		Anaerobic digestion	m3	-29.5	Sewage sludge {RoW}| treatment of by anaerobic digestion | Conseq, U
Sewage sludge		Incineration	kg	29500	Digester sludge (waste treatment) {RoW}| treatment of,to municipal incinerat
Waste water		Waste water treatment	m3	458	Digester sludge (waste treatment) {RoW}| treatment of,to municipal incinerat
Transport					
		Process			
Material /Componen		**Name**	**Unit**	**Amount/FU**	**SimaPro Process**
		Transport	tkm	30	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport,freight, lo

Figure A.2: Input data overview of the flushing toilet

Composting toilet

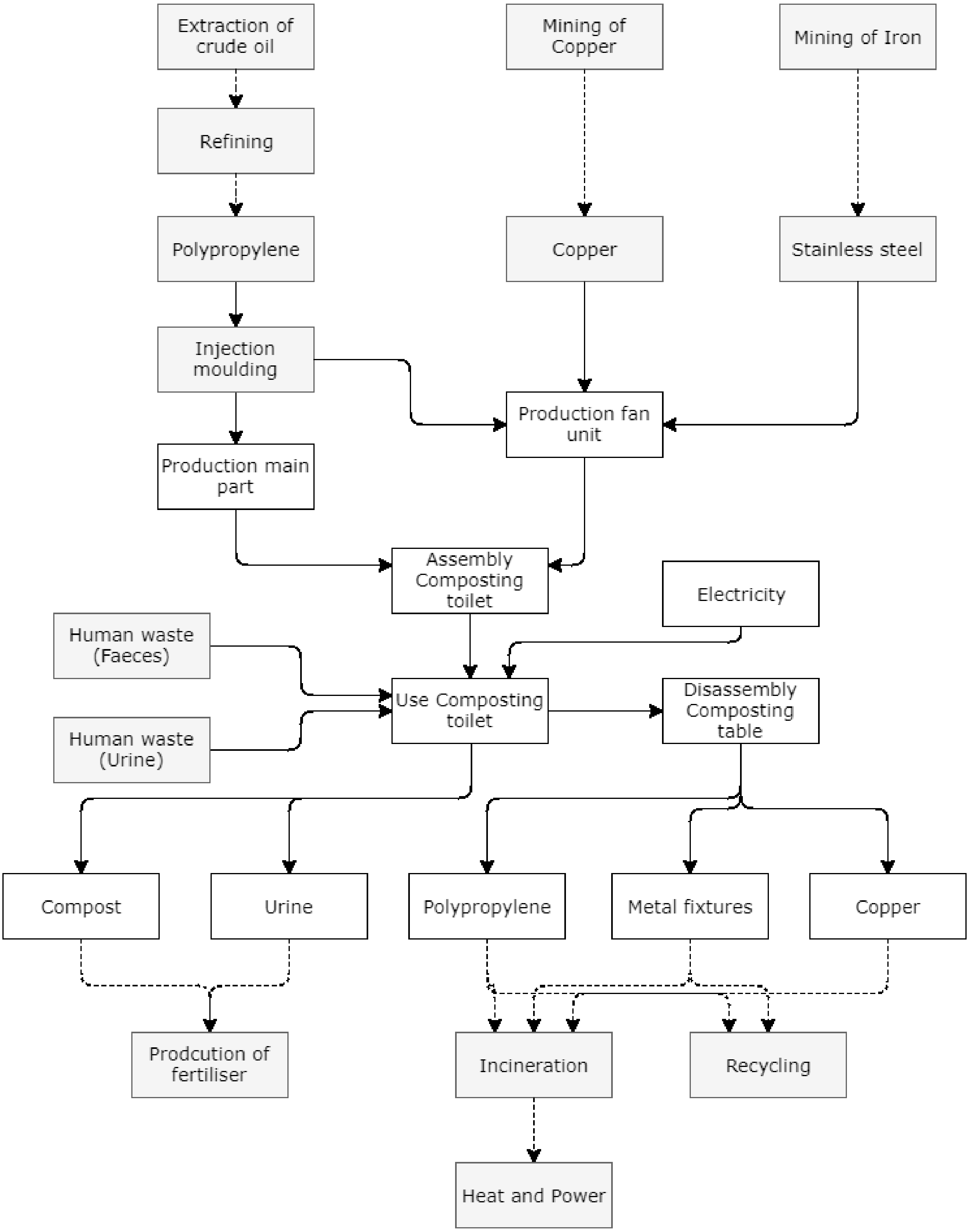


Figure A.3: LCI model at system level of the composting toilet, whereby the grey boxes with dashed lines are of the background process.

Materials and Manufacture					
Component	**No.**	**Material/Re**	**Unit**	**Amount/**	**SimaPro Process**
Main part	2	Polypropylene	kg	36	Polypropylene, granulate {GLO}| market for | Conseq, U
		Injection	kg	36	Injection moulding {GLO}| market for | Conseq, U
Fan unit	2	Polypropylene	kg	0,5	Polypropylene, granulate {GLO}| market for | Conseq, U
		Injection	kg	0,5	Injection moulding {GLO}| market for | Conseq, U
		Copper	kg	0,05	Copper {GLO}| market for | Conseq, U
		Steel	kg	0,05	Iron-nickel-chromium alloy {GLO}| market for | Conseq, U
General	2	Electricity	MJ	2	Electricity, medium voltage {RER}| market group for | Conseq, U
Urine Storage Tank	3	Steel	kg	72	Iron-nickel-chromium alloy {GLO}| market for | Conseq, U
		Extrusion	kg	72	Impact extrusion of steel, hot, 3 strokes {GLO}| market for | Conseq, U
		HDPE	kg	72	Polyethylene, high density, granulate {GLO}| market for | Conseq, U
		Injection	kg	72	Injection moulding {GLO}| market for | Conseq, U

Use				
Material / Component	**Process**			**SimaPro Process**
	Name	**Unit**	**Amount/FU**	
Human waste (faeces)		kg	6540,8	Not modelled
Human waste (urine)		L	72562	Not modelled
Fan	Electricity	kWh	766,5	Electricity, low voltage {DK}| market for | Conseq, U
Saw dust	waste	kg	3200	Saw dust, loose, wet, measured as dry mass {RoW}| suction, sawdust |
Electricity	Heating	MJ	4670	Electricity, low voltage {DK}| market for | Conseq, U
Methane	Digestion	kg	11.7	Methane
Carbon Dioxide	Digestion	kg	21.4	Carbon dioxide

Disposal				
Material / Component	**Process**			**SimaPro Process**
	Name	**Unit**	**Amount/FU**	
Metal fixtures	Recycling	kg	36,025	Steel and iron (waste treatment) {GLO}| recycling of steel and iron |
	Incineration	kg	36,025	Scrap steel {Europe without Switzerland}| treatment of scrap steel,
Polypropylene	Recycling	kg	18,25	PP (waste treatment) {GLO}| recycling of PP | Conseq, U
	Incineration	kg	18,25	Waste polypropylene {RoW}| treatment of waste polypropylene,
Copper	Reuse	kg	0,05	Scrap copper {Europe without Switzerland}| treatment of scrap copper,
	Fertiliser	kg	-2960	Compost {GLO}| nutrient supply from compost | Conseq, U
Urine	Fertiliser	L	-72562	Urine {GLO}| nutrient supply from urine | Conseq, U
Polyethylene	Recycling	kg	36	PE (waste treatment) {GLO}| recycling of PE | Conseq, U
	Incineration	kg	36	Waste polyethylene {Europe without Switzerland}| treatment of waste

Transport				
Material / Component	**Process**			
	Name	**Unit**	**Amount/FU**	**Amount/per toilet**
	Transport	tkm	40	Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport,

Figure A.4: Input data overview of the composting toilet

B. List of assumptions

Table B1: List of assumptions

Assumptions	Flushing toilet	Composting toilet	Decentralized toilet
Materials and Manufacture			
The energy for assembling the toilets are respectively assumed to be 1 MJ, 2 MJ and 7.5 MJ per FU	x	x	x
The transport for each toilet is assumed to be 30, 40 and 90 tkm based.	x	x	x

Use			
Approximately 34.4 L [a] of water flushes through the toilet each day/person, related to the FU gives an amount of 1757840 L	x	-	-
Human waste (faeces) is assumed to be 0.128 kg/day/person [b], related to the FU gives 6540.8 kg	x	x	x
Human waste (urine) is assumed to be 1.42 kg/day/person, related to the FU gives 72562 kg	x	x	x
The electricity assumed to be 766.5 kWh based on a reference model which uses 2 W [d].	-	x	-
It has been assumed that in total 3200 kg of sawdust will be made, based on providing 1 L of sawdust each day.	-	x	-
11500 kWh electricity is used for the evaporation liquid (urine), see table (b1) below for calculation.	-	-	x
Faeces and urine are assumed to have the same density as water	x	x	x
The density of the sawdust is 0.25 kg/L	-	x	x
Disposal			
The whole amount of ceramics will be sent to landfill	x	-	x
Metal fixtures (steel) will be recycled and incinerated in a 50:50 weight ratio.	x	x	x
Plastics (Polypropylene and Polyethylene) will be recycled and incinerated in a 50:50 weight ratio.	x	x	x
Rubber will be incinerated	x	-	-
Copper will be incinerated	-	x	x
Compost and urine will be converted into fertiliser	-	x	x

** add that the volume of flushing water is 1 L, new technology → microflushing.

Table B2. Calculation of clean water production and electricity consumption.

	short name	Calculation	Amount	Unit
Urine per FU	U	= urine/person/day*4*365*35	72562	L
Feces per FU	F	= feces/person/day*4*365*35	6540,8	kg

Flushing Water per FU	Wfl	= 1L*8(times a day)/person/day*4*365*35	408800	L
Dry mass content of sludge going to the storage tank			20	%
Dry mass per FU	dm	= dry mass/person/day*4*365*35	1482	kg
Water in Feces per FU	Wf	= water in feces/person/day*4*365*35	5110	L
Water going to the storage tank (to achieve 20% dry mass)	Wst	= 0,8*dry mass/0,2	5927,6	L
Water to be added (additional to the water included in the feces)	Wadd	= Wst-Wf	817,6	L
Total Volume going to the storage tank		= F+Wadd	7358,4	L
Clean Water	Wc	= U+Wfl-Wadd	480544	L
Electricity consumption		= Energy/liter*Wc	11533	kWh

C. Midpoint Impact Results

Table C1: External midpoint Impact Results for each category for the flushing toilet.

Impact category	Toilet Manufacture	Water Consumption	Sludge Digestion	Recycling	Waste Incineration	Landfill	Wastewater Treatment
Climate change	4.31E-03	2.02E-02	3.88E-02	-2.06E-04	6.81E-02	1.38E-05	2.31E-02
Ozone depletion	5.09E-04	9.40E-04	2.62E-03	-1.64E-06	3.45E-03	2.50E-06	1.06E-03
Terrestrial acidification	8.03E-03	2.16E-02	5.56E-03	-1.05E-04	1.64E-01	3.48E-05	5.88E-02
Freshwater eutrophication	-2.09E-01	3.89E-01	-3.02E+01	1.80E-04	5.94E+00	1.26E-04	1.35E+00
Marine eutrophication	-1.79E-03	5.51E-03	-2.34E-01	-1.18E-05	1.54E+00	6.03E-06	9.34E-01
Human toxicity	-4.92E-02	2.25E-01	-1.26E+00	-1.38E-04	1.27E+00	6.84E-05	2.36E-01
Photochemical oxidant formation	1.38E-03	1.23E-02	-1.77E-01	-1.32E-04	9.85E-02	2.74E-05	2.27E-02
Particulate matter formation	1.31E-02	2.93E-02	2.52E-01	-2.12E-04	2.28E-01	4.43E-05	6.72E-02
Terrestrial ecotoxicity	8.52E-04	1.98E-03	-2.38E-02	-1.10E-06	4.29E-03	1.80E-06	8.26E-03
Freshwater ecotoxicity	-1.66E-01	5.02E-01	-5.12E+01	8.78E-04	7.06E+00	8.90E-05	7.20E-01
Marine ecotoxicity	-1.98E-01	5.75E-01	-5.53E+01	9.34E-04	7.87E+00	1.13E-04	8.48E-01
Ionising radiation	-4.45E-03	6.69E-03	4.01E-02	-4.15E-06	1.77E-03	2.43E-06	2.72E-03
Agricultural land occupation	4.20E-03	-2.28E-03	9.90E-01	-2.61E-05	4.30E-02	1.07E-05	1.15E-03
Urban land occupation	1.46E-03	4.00E-03	-1.38E-02	-3.39E-06	2.19E-02	7.08E-05	1.19E-02
Natural land transformation	1.14E-01	1.74E-01	2.19E+00	-5.12E-04	1.12E-01	-6.88E-03	1.23E-01
Water depletion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Metal depletion	1.29E-02	8.58E-02	-3.57E-01	-4.28E-04	1.34E-01	1.48E-05	1.13E-01
Fossil depletion	1.81E-02	3.92E-02	2.84E-01	-9.78E-04	1.11E-01	7.27E-05	3.93E-02

Table C2: External midpoint Impact Results for each category for the composting toilet.

Impact category	Toilet and Urine Tank Manufacture	Electricity Consumption	Nutrient Recovery	Recycling	Waste Incineration	Composting - Saw Dust Use	Composting - GHG Production
Climate change	7.69E-02	2.56E-03	-8.24E-01	-1.39E-02	3.06E-04	-1.45E-02	2.80E-02
Ozone depletion	5.69E-03	2.00E-05	-2.32E-02	-2.20E-04	-3.54E-04	-1.64E-03	0.00E+00
Terrestrial acidification	9.91E-01	4.55E-03	-9.49E-01	3.18E-04	-1.24E-02	-1.89E-02	0.00E+00
Freshwater eutrophication	-3.87E-01	2.27E+00	-3.03E+00	-1.16E-02	-2.01E-01	7.34E-02	0.00E+00
Marine eutrophication	7.09E-03	1.80E-02	-1.97E-01	-5.37E-04	-2.53E-03	-3.75E-03	0.00E+00
Human toxicity	-2.11E+00	3.41E-01	-5.33E+00	-1.67E-02	6.18E-02	-4.60E-02	0.00E+00
Photochemical oxidant formation	1.12E-01	1.42E-02	-3.30E-01	-8.13E-03	-4.54E-03	-2.29E-02	2.08E-03
Particulate matter formation	6.48E-01	-8.93E-03	-7.31E-01	-1.74E-02	-2.02E-02	-2.39E-02	0.00E+00
Terrestrial ecotoxicity	2.57E-02	3.03E-03	-8.07E-02	-1.59E-04	1.46E-03	-1.92E-02	0.00E+00
Freshwater ecotoxicity	1.24E+00	7.38E+00	-3.92E+00	1.58E-03	6.35E+00	1.95E-01	0.00E+00
Marine ecotoxicity	1.59E+00	8.04E+00	-5.42E+00	1.10E-04	6.98E+00	1.77E-01	0.00E+00
Ionising radiation	1.27E-03	-3.82E-03	9.19E-03	-4.45E-04	-1.14E-03	-1.24E-04	0.00E+00
Agricultural land occupation	4.26E-02	-7.93E-02	-1.61E-01	-1.05E-03	-2.67E-02	-1.93E+00	0.00E+00
Urban land occupation	2.44E-02	5.63E-03	-1.81E-01	-4.95E-04	-3.66E-03	-1.10E-01	0.00E+00
Natural land transformation	5.49E-01	-7.48E-02	-6.48E+00	-6.22E-02	-5.76E-02	-4.80E-01	0.00E+00
Water depletion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Metal depletion	1.46E+00	1.06E-01	-1.13E+00	-6.41E-02	-1.01E-01	-1.23E-02	0.00E+00
Fossil depletion	2.20E-01	-1.07E-02	-8.41E-01	-5.38E-02	-1.92E-02	-4.25E-02	0.00E+00

Table C3: External midpoint Impact Results for each category for the decentralised toilet.

Impact category	Toilet and Manufacture	Electricity Consumption	Nutrient Recovery	Recycling	Waste Incineration	Landfill	Indirect Heating	Clean Water Production
Climate change	6.45E-02	1.45E-02	-8.23E-01	-9.47E-03	-2.29E-03	2.11E-05	-2.88E-01	-3.54E-03
Ozone depletion	3.90E-03	1.14E-04	-2.32E-02	-2.44E-04	-1.85E-04	3.81E-06	-2.53E-03	-1.65E-04
Terrestrial acidification	3.44E-01	2.58E-02	-9.48E-01	4.80E-03	-3.78E-03	5.32E-05	-6.83E-01	-3.80E-03
Freshwater eutrophication	-1.24E-01	1.29E+01	-3.02E+00	-2.68E-02	-1.37E-01	1.92E-04	-1.72E+01	-6.83E-02
Marine eutrophication	6.59E-03	1.02E-01	-1.97E-01	-3.20E-04	-1.42E-03	9.21E-06	-1.84E-01	-9.67E-04
Human toxicity	-2.30E-01	1.94E+00	-5.33E+00	-2.24E-02	3.26E-02	1.04E-04	-7.00E+00	-3.95E-02
Photochemical oxidant formation	5.23E-02	8.07E-02	-3.29E-01	-3.96E-03	-2.47E-03	4.18E-05	-2.01E-01	-2.16E-03
Particulate matter formation	3.01E-01	-5.07E-02	-7.31E-01	-1.54E-02	-1.39E-02	6.77E-05	-1.85E+00	-5.13E-03
Terrestrial ecotoxicity	1.24E-02	1.72E-02	-8.06E-02	-1.61E-04	5.07E-04	2.75E-06	-2.48E-02	-3.47E-04
Freshwater ecotoxicity	5.96E-01	4.19E+01	-3.92E+00	-1.17E-02	1.15E+01	1.36E-04	-8.48E+00	-8.80E-02
Marine ecotoxicity	7.64E-01	4.56E+01	-5.41E+00	-1.56E-02	1.25E+01	1.72E-04	-1.05E+01	-1.01E-01
Ionising radiation	-1.05E-02	-2.17E-02	9.18E-03	-4.83E-04	-2.68E-04	3.71E-06	1.39E-01	-1.17E-03
Agricultural land occupation	3.52E-02	-4.50E-01	-1.60E-01	-9.49E-04	-9.45E-03	1.63E-05	-1.09E+00	3.99E-04
Urban land occupation	2.11E-02	3.19E-02	-1.81E-01	-6.11E-04	-1.76E-03	1.08E-04	-6.45E-02	-7.01E-04
Natural land transformation	8.33E-01	-4.25E-01	-6.47E+00	-7.26E-02	-4.43E-02	-1.05E-02	1.74E-02	-3.05E-02
Water depletion	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Metal depletion	6.46E-01	6.02E-01	-1.13E+00	-6.77E-02	-1.18E-01	2.26E-05	-1.78E-02	-1.50E-02
Fossil depletion	1.65E-01	-6.09E-02	-8.40E-01	-2.34E-02	-8.78E-03	1.11E-04	-4.92E-01	-6.87E-03

D. Endpoint Results

Table D1: Endpoint results of each category giving an overall human health impact for each of the toilet.

Impact category (DALY)	Flushing Toilet	Composting Toilet	Decentralized Toilet
Climate change Human Health	2.42E-03	-1.64E-02	-1.17E-02
Ozone depletion	3.08E-07	-1.22E-06	-1.24E-06
Human toxicity	1.89E-04	-4.69E-03	-3.13E-03
Photochemical oxidant formation	-9.28E-08	-8.99E-07	-5.25E-07
Particulate matter formation	2.28E-03	-9.17E-03	-5.95E-04
Ionising radiation	4.80E-06	1.17E-05	5.05E-07
Total Human Health Impact	4.90E-03	-3.03E-02	-1.54E-02

Table D2: Endpoint results of each category giving an overall Ecosystems impact for each of the toilet.

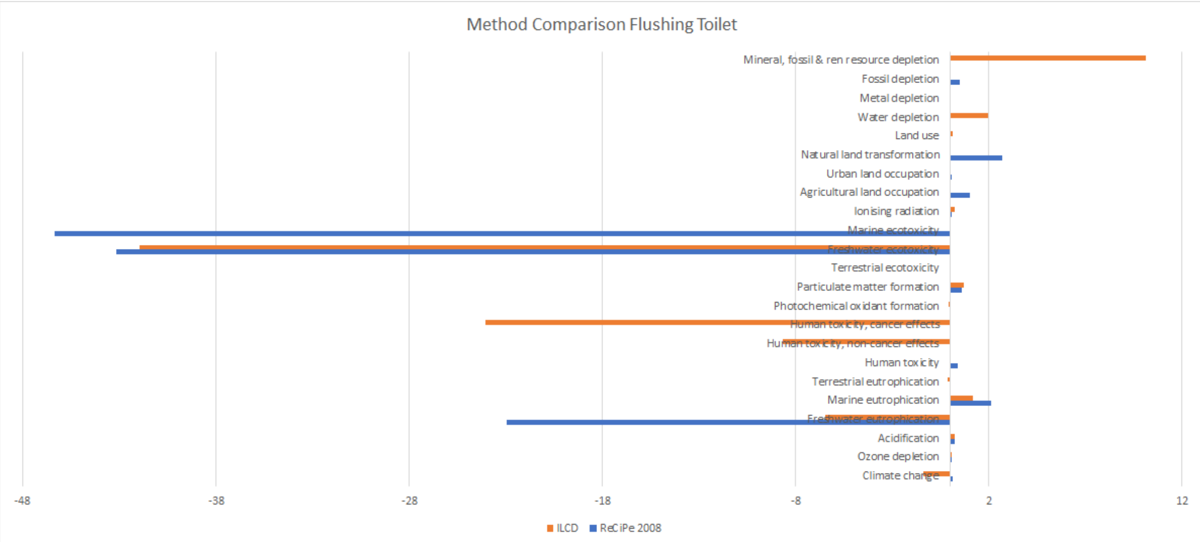
Impact category (species.yr)	Flushing Toilet	Composting Toilet	Decentralized Toilet
Climate change Ecosystems	1.38E-05	-9.30E-05	-6.61E-05
Terrestrial acidification	5.15E-08	-2.52E-07	3.20E-09
Freshwater eutrophication	-4.20E-07	-1.42E-07	-2.37E-08
Terrestrial ecotoxicity	-1.05E-08	-9.44E-08	-8.69E-08

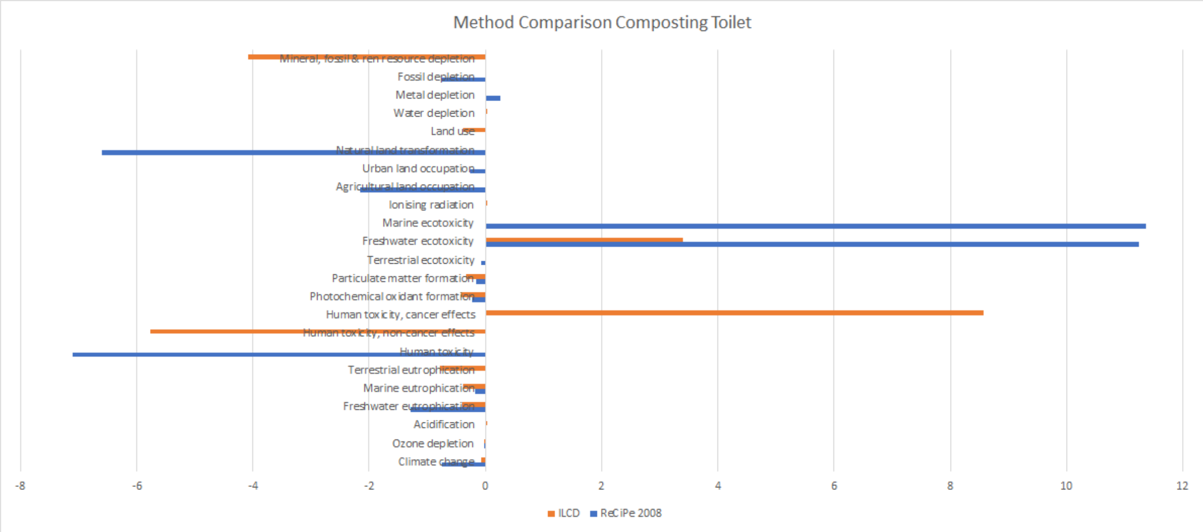
Freshwater ecotoxicity	-4.05E-07	3.90E-07	1.06E-07
Marine ecotoxicity	-7.08E-08	6.56E-08	1.74E-08
Agricultural land occupation	5.56E-05	-9.08E-05	-1.17E-04
Urban land occupation	2.15E-07	-1.64E-06	-2.23E-06
Natural land transformation	9.18E-07	-1.63E-06	-1.66E-06
Total Ecosystems Impact	6.97E-05	-1.87E-04	-1.87E-04

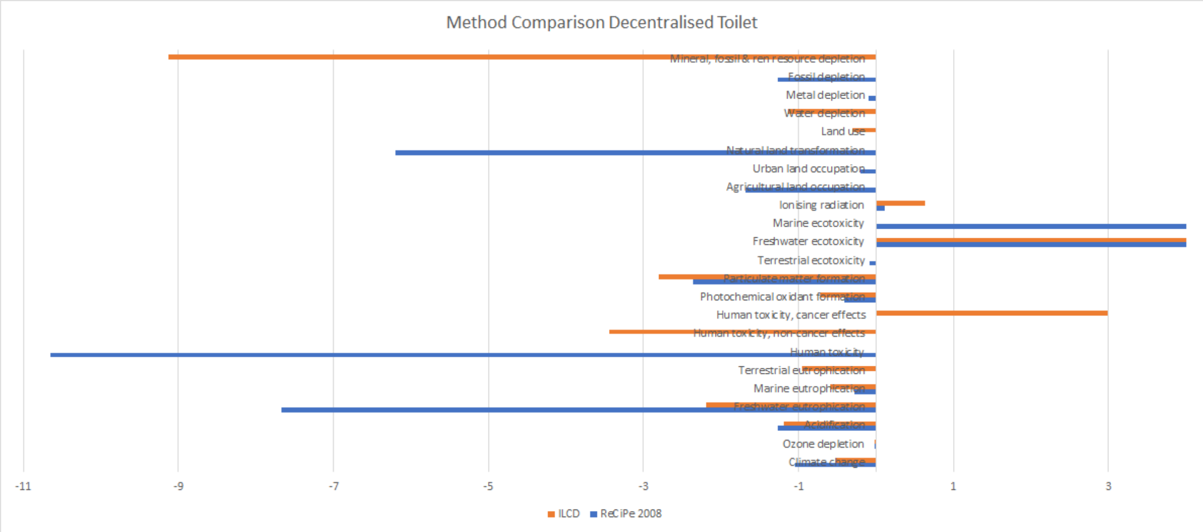
Table D3: Endpoint results of each category giving an overall Resources impact for each of the toilet.

Impact category ($)	**Flushing Toilet**	**Composting Toilet**	**Decentralized Toilet**
Metal depletion	-5.82E-01	-5.00E+00	1.33E+01
Fossil depletion	1.26E+02	-3.26E+02	-1.92E+02
Total Resources Impact	1.25E+02	-3.31E+02	-1.79E+02

E. Robustness check at midpoint level




Method Comparison Composting Toilet
Mineral, fossil & ren resource depletion
Fossil depletion
Metal depletion
Water depletion
Land use
Natural land transformation
Urban land occupation
Agricultural land occupation
Ionising radiation
Marine ecotoxicity
Freshwater ecotoxicity
Terrestrial ecotoxicity
Particulate matter formation
Photochemical oxidant formation
Human toxicity, cancer effects
Human toxicity, non-cancer effects
Human toxicity
Terrestrial eutrophication
Marine eutrophication
Freshwater eutrophication
Acidification
Ozone depletion
Climate change
-8 -6 -4 -2 0 2 4 6 8 10 12
ILCD
ReCiPe 2008


Method Comparison Decentralised Toilet
Mineral, fossil & ren resource depletion
Fossil depletion
Metal depletion
Water depletion
Land use
Natural land transformation
Urban land occupation
Agricultural land occupation
Ionising radiation
Marine ecotoxicity
Freshwater ecotoxicity
Terrestrial ecotoxicity
Particulate matter formation
Photochemical oxidant formation
Human toxicity, cancer effects
Human toxicity, non-cancer effects
Human toxicity
Terrestrial eutrophication
Marine eutrophication
Freshwater eutrophication
Acidification
Ozone depletion
Climate change
-11 -9 -7 -5 -3 -1 1 3
ILCD
ReCiPe 2008