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Master's in chemical engineering-Smart Chemical Factories

WASTE MANAGEMENT OPTIMIZATION IN A SMALL/MEDIUM HOSPITAL FACILITIES

REPORT AND ANNEXES

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ABSTRACT

Generation of waste affects in negative ways to the environment and thus its management should be done properly. Hospital activities produce great amount of waste due to the provision of healthcare leads to the society. The current situation of the waste management process of Granollers hospital will be study and compared it to when the organic fraction is selectively separated from the rest of the waste. Using the LCA methodology the environmental impact was analysed at midpoint and endpoint levels. The functional unit was the average service received from the hospital by one inhabitant in the area of influence. The analysis shows that performing the selective separation reduces the environmental impact in 0,045 (Pt/year)/FU and saves 0,82 (€/year)/FU. Furthermore, the analysis of two other scenarios determined that the selective separation of glass would allow to additionally save 1,18 (€/year)/FU. Also, it was analysed a fourth scenario in which the construction and demolition waste also is selectively separated saving 0,35 (€/year)/FU but with a higher environmental impact than in the two previous scenarios studied.

RESUMEN

La generación de residuos afecta de forma muy negativa al medio ambiente, por lo que su gestión debe realizarse de forma adecuada. La actividad hospitalaria produce gran cantidad de residuos debido a la prestación de servicios sanitarios a la sociedad. Se estudiará la situación actual del proceso de gestión de residuos del hospital de Granollers y se comparará con cuando se separa selectivamente la fracción orgánica del resto de residuos. El impacto ambiental se analizó, mediante la metodología del ACV, a nivel de punto medio y punto final. La unidad funcional fue el servicio medio recibido del hospital por un habitante del área de influencia. El análisis muestra que la realización de la separación selectiva reduce el impacto ambiental en 0,045 (Pt/año)/FU y ahorra 0,82 (€/año)/FU. Además, el análisis de otros dos escenarios determinó que la separación selectiva del vidrio permitiría ahorrar adicionalmente 1,18 (€/año)/FU. Asimismo, se analizó un cuarto escenario en el que los residuos de construcción y demolición también se separan selectivamente ahorrando 0,35 (€/año)/FU, pero con un mayor impacto ambiental que en los dos escenarios anteriores estudiados.

RESUM

La generació de residus afecta de manera molt negativa el medi ambient, per la qual cosa la seva gestió s'ha de fer de manera adequada. L'activitat hospitalària produeix una gran quantitat de residus a causa de la prestació de serveis sanitaris a la societat. S'estudiarà la situació actual del procés de gestió de residus de l'Hospital de Granollers i es compararà amb quan se separa selectivament la fracció orgànica de la resta de residus. L'impacte ambiental es va analitzar mitjançant la metodologia de l'ACV a nivell de punt mitjà i punt final. La unitat funcional va ser el servei mitjà rebut de l'hospital per un habitant de l'àrea d'influència. L'anàlisi mostra que la realització de la separació selectiva redueix l'impacte ambiental a 0,045 (Pt/any)/FU i estalvia 0,82 (€/any)/FU. A més, l'anàlisi de dos escenaris més va determinar que la separació selectiva del vidre permetria estalviar addicionalment 1,18 (€/any)/FU. Així mateix, es va analitzar un quart escenari on els residus de construcció i demolició també se separen selectivament estalviant 0,35 (€/any)/FU però amb un major impacte ambiental que en els dos escenaris anteriors estudiats.

ACKNOWLEDGMENTS

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Content

1. INTRODUCTION

1.1. WASTE MANAGEMENT

The globalization and rapid growth of urbanization over the last decades has led to better quality of life. This increase in prosperity has brough a higher waste generation per capita, 0,74 kg per day in 2018 [1]. As waste generation increases with economic development and population growth, it is expected that by 2030 the world produced 2,59 billion of tonnes of waste, compared to 2,01 billion generated in 2016 [2].

Waste can be defined in many ways, the Europe Union (EU) defines it as any substance or object which the holder discards or intends to discard or is required to discard. The holder is the producer of the natural or legal person who is in possession of the waste [3].

As the population grows more material and energy is produced and consumed, and within this cycle waste is generated as a by-product. This one must be managed, which includes its collection, treatment (if necessary), and disposal. Poor waste management is linked to climate change and environmental pollution. Inappropriate collection can produce a toxic liquid runoff, called leachate, which pollutes rivers, groundwater, and soil. On the other hand, inadequate treatments, as open burning, emits toxins and particulate matter into the air that can cause important health problems [2].

Furthermore, solid waste contributes to climate change by the emission of greenhouse gases, mainly methane, due to the decomposition of organic waste. The emission can be mitigated by improving waste management process (collection and treatment) and raising public awareness about the risks associated with inadequate waste management [2]. Following this line of work, the EU have implemented several policies in the las decades that have reduced the waste environmental footprint.

The EU has defined waste management as the collection, transport, recovery, and disposal of waste, including the supervision of such operations and the aftercare of disposal sites, and including actions taken as a dealer or broker [3]. Nowadays every industry has legislation regulating waste disposal, treatment, and post-processing. This way a common framework was introduced for all industries to have a starting point to build its waste management plant [4].

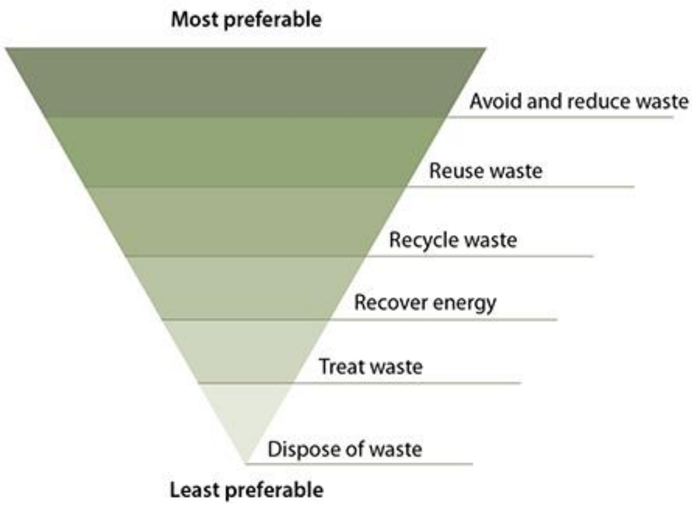


Figure 1. *Waste hierarchy scheme* [5]

The scheme of Figure 1 represents the framework in which governments and companies of all type should follow in the waste management. The highest priority is to avoid and reduce the generation of waste by maximising the efficiency of the processes and avoiding the unnecessary consumption of resources [5].

The second priority, if the first one cannot be achieved, is to reuse and recycle the waste generated or if not, try to recover energy from it. Reuse and recycle concepts are the same, both imply to introduce back the waste itself in the economy, but their difference is that in the re-use process there is no processing of the waste and in the recycled process the waste first goes through a processing process in which some of its characteristics are changed [5].

On the other hand, there are some types of waste that cannot be treated, due to being radioactive or that its intrinsic characteristic does not allow it to perform such processes. This waste are managed following the third priority that is being treated or disposed of [5].

This framework shows that reuse and recycle are being integrated in the new circular economy concept that is being tried to be implemented in the industry during the last decades. Following this approach, what organisations and governments are trying to do is to achieve sustainable development by reducing reliance on natural resources.

For being able to implement this waste framework directive the EU developed the European list of Waste (LoW) to provide a common terminology in waste classification [6]. This list disaggregates the several types of waste and classifies them in relation to their hazardousness and their activity.

This means that waste can be hazardous or non-hazard to the environment, public health, etc. Moreover, the activities to which the waste is classified in are [7]:

- Waste from primary sector: Agricultural, forestry and fishing
- Mining and quarrying waste
- Municipal solid waste (MSW)
- Industrial waste (manufacturing)
- Wastewater sludges
- Sanitary waste (SW)
- Energy

The type of waste that will be treated in this work is related to the sanitary activity.

1.2. HEALTHCARE WASTE (HCW) MANAGEMENT

The healthcare industry is a fast-growing industry which continuously is generating waste. Moreover, this waste is not the same type as the municipal waste which is generated by communities because healthcare facilities provide goods and services to control diseases and treat patients [8].

Part of the waste produced by this industry is infectious or radioactive waste which needs special treatment processes. Poor practices in the management of this waste creates significant health problems and harms the environment [8].

To avoid poor practices in HCW management, the World Health Organization (WHO) and the Atomic Energy Agency had elaborated policy documents and guidelines to support countries when developing policies of HCW management [8].

Also, these guidelines are in accordance with the international agreements signed by many countries, Basel Convention on Hazardous Waste, Stockholm Convention on Persistent Organic Pollutants, and Minamata Convention on Mercury [8]. A structure of various levels on what countries and local communities base their HCW systems is shown in Figure 2.

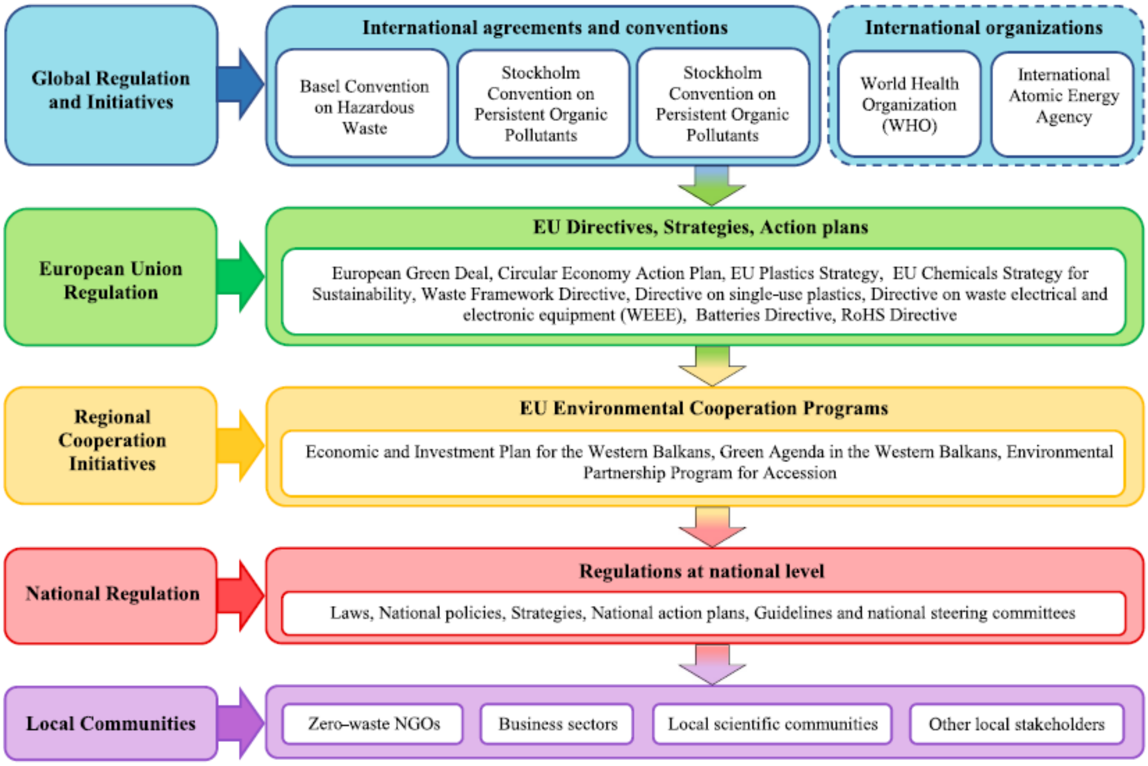


***Figure 2**. Structural levels of the bases of national and local HCW systems, focused on European countries* [8]

Spain's national HCW system has been constructed following the framework of Figure 2, using as basis the guidelines of the WHO and the Atomic Energy Agency, but also, the own directives of the EU including the objectives of their cooperative programs.

Many countries struggle to implement all the management guidelines proposed in the WHO documents. HCW is usually treated by incineration processes which can produce odours, atmospheric contamination, etc, and countries with emerging economies usually mixed it with municipal waste. There is still the need to find a proper approach in other to improve the waste management process of this type of residues [8].

A possible solution to enhance the HCW management it can be couple with the circular economy approach [8]. This approach aims to redirect the economy's actual model to another more environmentally friendly. The actual economy model is a linear model where a product is produced, then used and finally disposed of. What the circular economy approach tries to do is to transform this linear model into a circular one, in which the final is not directly disposed but that when its utility life ends it follows the framework of Figure 1 [9].

In Europe there has been an attempt to turn to the waste to energy concept of the circular economy approach. Several facilities have been built in some countries that use the energy contained in the waste to generate power. But this point of view has not filled in an effective way in the waste management policies of many countries and has not been developed to an extent. General treatments in Europe are of incineration at high temperatures and when this cannot be done their disposal in sanitary landfills [4].

Despite having guidelines, policies, and restrictions in relation to the HCW, in most of the countries of the world, there are still some concerns that affects all of them [4]:

- Although most of the waste generated in hospital facilities is not infectious or a hazard to the environment, there is still some concern in how part of the waste should be treated. This fraction of the waste corresponds to the latex gloves and other items that do not cause any harm, but when treated they may produce compounds harmful for the environment and the public health.
- Hospitals are aware of the needing to reduce the consumption of resources, but not in the reduction of the waste generated.
- Education of general people, as well as the public sectors of what is hazardous and what is not. This way people can demand their leaders' good practices in the HCW management.
- Developing modern technologies increases the innovation in drugs and treatments which may have infectious and chemical risks. So proper treatments must be developed for this new type of waste.
- Correct classification of waste can reduce the environmental impact as this one will allow to send each type of waste to the correct treatment or recovery process.

1.3. HEALTHCARE WASTE CLASSIFICATION

As it has been mentioned, a correct waste sorting is decisive in order to ensure that it is treated properly. Therefore, HCW is classified following the framework given by higher organisms as the WHO, EU, the United States Environmental Protection Agency (US EPA), etc.

WHO classifies healthcare waste in 9 types [10]:

- Infectious waste: Waste contaminated with blood and body fluids, cultures and stocks infected by dangerous agents in the laboratory, or waste from patients which have infections.
- Pathological waste: human tissues, organs or fluids, body parts and contaminated animal carcasses.
- Sharps waste: syringes, needles, disposable scalpels, and blades.
- Chemical waste: Solvents and reagents used for laboratory solutions, disinfectants, sterilant, heavy metals and batteries.
- Pharmaceutical waste: expired unused and contaminated drugs and vaccines.
- Cytotoxic waste: waste containing substances with genotoxic properties.

- Radioactive waste: Products contaminated by radionuclides including radioactive diagnostic material or radiotherapeutic materials.
- Non-Hazardous or general waste: Fraction of the healthcare waste that does not pose any biological, chemical, radioactive, or physical hazard.

So, the HCW can be divided into two streams, one hazardous fraction which would include all the waste generated in the treatment of the patients and a non-hazardous fraction which can be treated as MSW. The hazardous fraction represents 10-25% of the total HCW generated and the non-hazardous fraction the 75-90% [8].

In Spain, each community has his own legislation in HCW management, but overall, there are all the same and classified the HCW in 2 groups, harmful and non-harmful waste, and each group has 2 subgroups. The following classification presented is with respect to the legislation in force in the Community of Catalonia [11]:

a) Non-harmful or unspecified waste
    - Group I: There is the equivalent to the municipal solid waste and does not require any special treatment or management. They come from the lunchroom, offices, etc.
    - Group II: Municipal solid waste that does not need any special treatment out of the healthcare facility.

b) Hazardous or specified waste
    - Group III: Waste that requires specific measures in and out of the healthcare facility due to being risky for the workers of the facility and the public outside it. This type of waste would be the infectious, pathological, and sharp waste defined previously.
    - Group IV: All the hazardous waste not included in group III (chemical and pharmaceutical waste) and the cytotoxic waste. For it to be manage, they are subjected to specific measures from the health and environmental point of view.

Radioactive waste is kept in the healthcare facility, and they are treated following its typology. Moreover, after the pandemic situation generated by the covid-19 virus, new legislation had to be developed around this issue. For the correct management of the materials used in the treatment of this disease, they were classified inside group III as infectious waste that must be treated by incineration [11].

Each group of waste has to go through a different type of treatment, also following the legislation in force [11]. For example, as group I and II can be considered as municipal solid waste, they can be treated as it and therefore this type of waste can be incinerated, landfilled, recycled, or suffer a composted process after proper separation at the disposal facility.

Group III and IV, except cytotoxic components, must go through a disinfection process inside the own healthcare facility or outside by an authorised company. The disinfection process can be done by autoclave and further grinding posttreatment. Also, this type can be introduced in an incineration treatment to eliminate the infectious agents with heat.

Cytotoxic waste can receive a physicochemical treatment instead of the autoclave treatment, or also, go through an incineration process.

2. LIFE CYCLE ASSESSMENT (LCA)

2.1. METHODOLOGY

To address the impacts for a product, from the extraction of the raw materials until his final disposal, that it is the life cycle of a product, the LCA was developed [12], [13]. This methodology started in the 90's and to this is still an underdeveloped framework that over the years has become more and more important for companies due to consciousness of the environmental damage products can have.

Studying the life cycle of a product allows to asset the environmental impacts or benefits of a good or service, the trade-off of different actions to take [14]. LCA framework can be used for different objectives [12], [13]:

- Identify improvements through the life cycle of a product.
- Improve decision-making and marketing in organisations towards sustainability.
- Select several indicators to assess the environmental performance.

The phases of the life cycle assessment are four. The first one is the scope and definition of the LCA which depends on the subject and the level of detail of the study. Also, in this phase is when the system boundaries are established. The second phase is the inventory analysis phase, related to the collection of the data, inputs and outputs of the system.

The third phase is the impact assessment, which is purpose is to provide a series of tools for a better understanding of the environmental results. And for last is the interpretation phase. In this phase the results are analysed and discussed for the decision-making actions in accordance with the scope of the study. All these phases can be seen in Figure 3.

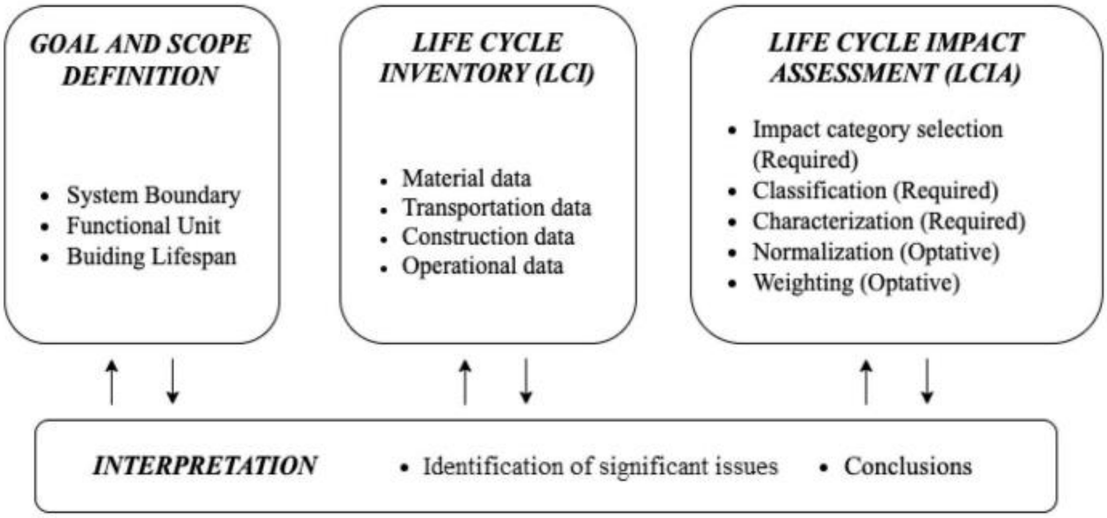


Figure 3. *Life Cycle Assessment scheme* [13]

For a detailed study of the system two other frameworks are being developed. The first one is the life cycle costing (LCC), a methodology that assigns the economic costs, rather than the environmental ones, of a product, project, or system. Its objective is to reduce the production costs [15].

LCC seeks to calculate the costs associated with the entire life cycle of a product, purchase cost, operating cost, and end-of-life costs. By applying this methodology, in the purchase phase of the product, the resource cost, maintenance, and disposal are considered which can lead to situations where a greener and cheaper solution is achieved [16].

The other methodology that completes the life cycle study of a product is the social life cycle assessment (S-LCA). The S-LCA assets the social and socio-economics aspects of a product or system. It provides a framework in which stakeholders can act with social responsibility while performing the life cycle study of their goods and services [15].

While LCA and LCC are well-studied methodologies that have been in use for many years, and are standardised by ISO directives, S-LCA is a relatively new one which still has much development to overcome, and it does not have a normalisation procedure yet [15].

In LCA studies different approaches can be applied. These are defined by the system boundaries which determine which phases of a product or process are included in the study. Many LCA's use the cradle-to-grave approach, that includes all the processes from raw material extraction ("cradle"), going through the use phase, and finally the disposal ("grave") scenario [17].

Cradle-to-grave approach would be the wider approach taken for an LCA study including all the life cycle phases of a product. But if the scope of the study is only to analyse the effect of the extraction and production stage a cradle-to-gate approach can be use. In this approach the limits of the system boundaries would be stablished at the exit of the production process [18].

If the end-life or a product is to be recycled, then the approach is the cradle-to-cradle. This one is similar the cradle-to-grave one, but in this case the end-life or product is not its disposal, but a recycling process. If the objective of the study is to study a specific phase of the process, gate-to-gate approach is the one that should be used. It allows to study the added value of a specific process in the supply chain [18].

An important value of an LCA study is the functional unit (FU). It defines the reference of all the results of the study and only two LCA studies can be compared if both have the same FU [17].

2.2. LIFE CYCLE ASSESSMENT IN HEALTHCARE SECTOR

Many LCA studies have been conducted for the management of the healthcare sector, mainly to improve the decision-making process in hospital management. But the concern of the impact on the environment from hospitals is relatively new, being the first studies of this type in 2010 [17].

These studies focused mainly on countries of Europe being the main one, the United Kingdom, and the rest of the countries which have a search interest in this field are the United States and Australia [17]. In relation to Spain, searching for LCA studies in *ScienceDirect* database there has been found related to hospital building, C. Llatas et al. [19], and to foot industry, C. Lamnatou et al. [20], but neither of them related to the hospitals waste management.

Moreover, the LCA studies focused on three main areas, products used in hospitals, processes (surgeries, water contamination, etc.) and carbon footprint [17]. Between these three areas the one of interest for this work is the process and product ones.

In product area they studied the cradle-to-grave life cycle of tools commonly used in hospitals, comparing between reusable and non-reusable products. The area of process focused on all types of activities that are conducted in a hospital to identify the hotspots which hospital managers can solve and improve such activities.

On Table 1 the studies of the process area that Christin Seifert et al. [17], reviewed, shows mainly waste treatment processes. These are centred on the comparison between technologies used with a cradle-to-grave approach.

Table 1. *Process area activities reviewed* [17].

Reference	Country	Object under study
Thiel et al. (2017)	India	Cataract surgery FU: Removal of cataract in one eye using phacoemulsification
Thiel et al. (2015)	United States	Surgical procedure (hysterectomy) FU: One hysterectomy
Campion et al. (2012)	United States	Birth (caesarean, vaginal) FU: Birth of one baby
de Oliveira Schwaickhardt et al. (2017)	Brazil	Treatment of hospital laundry wastewater FU: 1 m^3 of treated wastewater, considering a treatment time of 3 hours
Ali et al. (2016)	Pakistan	Solid waste treatment FU: 1 ton of disposable solid hospital waste
Igos et al. (2013)	Luxembourg	Wastewater treatment scenarios for reduction of pharmaceuticals FU: Treatment of 1 m^3 of wastewater
Köhler et al. (2012)	Germany	Wastewater treatment scenarios for removal of pharmaceutical residues FU: Treatment of 1 m^3 of membrane bioreactor permeates

In Table 2 some of the processes reviewed by Christin Seifert et al. [17], are presented. It can be observed that in hospitals, not only the activities generates waste (medical operations, services, etc), but also the products used for developing such activities.

Table 2. *Product area reviewed* [17]

Reference	Country	Object under study
Unger & Landis (2016)	United States	Several reprocessed medical devices: A deep vein thrombosis compression sleeve, a pulse oximeter, a ligature, a harmonic scalpel, an endoscopic trocar, an arthroscopic shaver, and a scissor tip. FU: Seven medical devices, which is the number of medical devices needed to fulfil the reprocessed device supply chain requirements of the hospital.

Table 2. *Product area reviewed* [17] *(continuation)*

Reference	Country	Object under study
Ison & Miller (2000)	United Kingdom	Suction receptacle FU: Average kilograms of waste from body fluids produced over 1 year of elective surgeries
Sørensen & Wenzel (2014)	Denmark	Bedpans FU: Use of one bedpan once for urinating and defecating while being hospitalised and in bed (compare effects of four different bedpans)
Sherman et al. (2012)	United States	Anaesthetic drugs FU: 1 minimum alveolar concentration (MAC) or MAC-equivalent for propofol for maintenance anaesthesia for an average 70-kg adult patient for 1 hour (1 MAC-h)
McGain et al. (2010)	Australia	Drug packaging alternatives (glass vs. polymer vials) FU: 1,000 vials Drug trays
Goellner & Sparrow (2014)	United States	Shipping containers (thermally controlled) FU: 22-year clinical trial consisting of 30,000 individual package shipments able to maintain roughly 12 L of payload at a controlled 2–8°C temperature range for approximately 96 hours

Among all the works reviewed the study of the waste generated in hospitals (solid, wastewater) is poor compared to other type of activities conducted. The studies analysing the life cycle of products also includes their final disposal, but few studies are centre in the overall waste management process of a hospital.

3. STATE OF THE ART

Through the introduction of this work, it has been seen that healthcare management is an issue of great interest that has multiple branches of study.

3.1. HEALTHCARE WASTE MANAGEMENT PRACTICES

Many authors have studied mathematical methods for the optimization of the management practices. For example, there have been some studies that have analysed the best route for waste collection, and a disposal network for reducing risk and costs of transportation in Teheran [21].

Other authors had developed a model for optimising the location of storage sites to facilitate the transportation between the waste storage location and the disposal station. Moreover, mathematical formulations to select between different management strategies, or to find the safest route when managing hazardous waste also have been studied [8].

Many of the works have also focused on the treatment technologies and the development of a multicriterial mathematical method. These methods will help decide which type of technology should be use in relation to the type of waste treated, the environmental impact of the technology, etc [8].

Other works outlined the hotspots in which head hospital managers should be focused on. For example, Ali et al. [22], made a review on how HCW was managed in different parts of the world, finding that one of the major problems is the waste segregation at the hospital site. Furthermore, hospital workers, and society in general, are not aware of the environmental problems that bad HCW management can produce. Therefore, a reinforcement of education and employee training should be done to improve managing practices.

Also, in emerging economies the waste transportation to disposal stations is still under development and far behind developing countries, which have greater experience managing this type of waste. About treatments is the same, while developing countries are consequently reducing the use of incineration technologies due to environmental pollution, other countries prefer the use of off-site incineration facilities or landfilling [22].

Barbosa and Mol [23] proposed HCW indicators to improve the risk management of infectious waste, which lead to an increase in good practices in segregation, identification, and disposal of infectious waste in a Brazilian hospital.

As it has been mentioned, countries are putting aside incineration treatments in favour of more environmentally friendly treatments like autoclaving, reverse polymerization, recycling etc. Although Incineration of infectious waste generates toxic emissions (PCDDs and PCDD/Fs) and heavy metals are still widely used, there are technologies under study to remove the toxic pollutants generated in this treatment [8].

Recycling technologies are also being developed, following the trend of Figure 1, but there is still academic discussion about how the waste should be segregated. It has been studied that part of the waste generated in operating rooms is recyclable, but this one is mixed with not recyclable waste, so proper networks in this area should be developed [8].

Many of the studies focused on the proper medical waste, the infectious, and hazardous fractions, but there is still also the pharmaceutical waste. This refers to the medicines that are not used in the hospital facilities, and whose mismanagement can generate water contamination. In this area it has been proposed different methods and treatment systems to enhance its disposal [8].

Although HCW management is an interesting field of study, this must be developed more to reduce the environmental impacts of the waste generated, which generates more environmental pollution than the people is aware of [8].

3.2. LIFE CYCLE ASSESSMENT FOR HEALTHCRE WASTE MANAGEMENT

As it has been explained in section 2.2 the LCA studies conducted in the HWC management haven been focused on products and several processes, mainly medical operations, but few have centred on the managing process of waste. Furthermore, the studies found on LCA waste management are centre in the comparison of treatment technologies [24], [25].

Even fewer studies had been found combining an LCA study in HCW management and mathematical optimization [26]. The studies mainly focused on the hazardous fraction of the hospital waste, Ali et al. [24] studied the effect of good practising in segregation of general and medical waste in Pakistan, but only using one environmental indicator, the GHG emissions.

Regula Lisa Keller et al. [27] studied the environmental hotspots of hospital waste management in Sweden. They used the data of 33 hospitals to model the 3 types of hospital waste, solid waste, medical waste, and chemical waste. Their results showed that solid waste is relevant for two impact categories, while medical and chemical waste for three impact categories. This highlights the fact that the management of the other type of waste, which is not hazardous waste, also has an environmental impact.

The studies found are performed in countries of emerging economies, while few of them are centred in developed countries. More in depth, studies of European countries are very scarce, only having been found in Sweden, Regula Lisa Keller et al. [27], Greece, Zamparas et al. [25], and Italy, Sebastião Roberto Soares et al [28]. No study related to the HCW management in Spain has been found, only to hospital buildings and food management as it has been mentioned before.

4. OBJECTIVE

In this work an analysis of the waste management process of Granollers hospital will be performed. For this study, an LCA and LCC of the current situation, in which no organic fraction selective separation is done, will be performed. Afterwards an analysis (LCA and LCC) of a second scenario, in which the organic fraction is separated, will be conducted. Finally, a mathematical optimization will be proposed in order to find alternative scenarios where the environmental footprint and costs are reduced.

5. METHODOLOGY

5.1. CASE STUDY DESCRIPTION

Spanish legislation classifies the waste in separate groups according to their typology and its dangerousness. But when it comes to the management of the waste legislation only gives different alternatives and therefore, each facility acts in a separate way from each other. Some manage the waste locally while others employ an authorised company to take the waste and do the management duties outside the facility influence. This leads to a situation, where small and medium hospitals have problems with good management practice.

Granollers hospital is a medium size hospital facility of the province of Barcelona with an influence area of 400.000 habitants. Currently the hospital classifies the waste according to the Spanish classification explained in section 1.3. The waste in groups I and II are named in this work as general or solid waste. Currently the hospital only separates selectively the paper fraction.

The hospital wants to separate the organic fraction (FORM) from the solid waste locally and send it to a biomass treatment to improve its environmental footprint. Also, it would like to see the economic aspects of such change.

The hospital conducts the waste management process in collaboration with a private company authorised by public organisms. This company is responsible of the collection procedure of the waste groups I and II, subsequent separation, and treatment. From the information of his website [29], the company performs a selective separation of the fractions of the waste and those that can be recycle (paper, plastic, glass, and metals) goes to the respectively recycling process and the others, goes to landfill.

Waste group III goes through and sterilization process after which can be consider as the type of waste as groups I and II. Then is mixed with these two groups. Group IV, chemical and cytotoxic waste goes to an incineration process plant located in Tarragona.

5.2. GOALS AND SCOPE

The aim of this work is to analyse the environmental footprint of the hospital waste management process in the actual situation, scenario 1, and compared it to a future upgrade of the hospital installations, in which the organic fraction is selectively separated from the rest of the waste of groups I and II, scenario 2. An LCC of both cases will be performed and an optimization model for searching more alternative scenarios will be studied. For the study, the different waste fractions are grouped in two categories:

- General waste: This is the solid fraction of the waste. Includes groups I and II explained in section 1.3 and group III after sterilization process. It can be considered as MSW, so the treatments which will be defined for this category will be recycling and landfill.
- Chemical waste: This is the waste that needs special treatment due to its chemical composition, but it does not include any infectious waste produced in hospitals. It is the waste classifies as group IV in section 1.3. It goes through an incineration process.

The inputs of the process would be the hospital activities that generates waste. The outputs would be the environmental pollution produced by the management of such waste. The system, for scenario 1, can be shown in Figure 4.

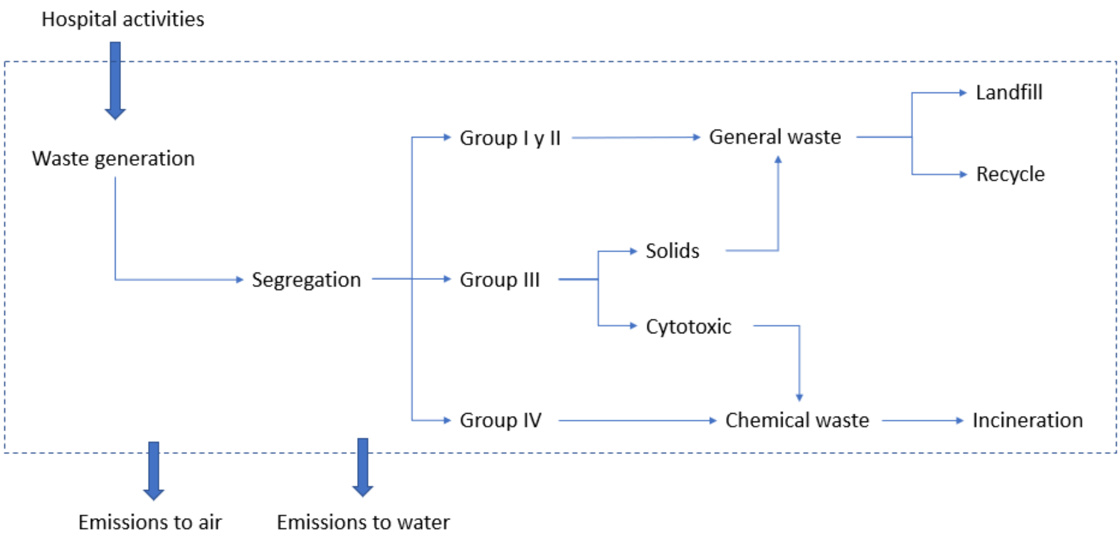


Figure 4. *System boundaries scenario 1*

In the second scenario the organic fraction of the MSW is separated locally from the rest of the waste, so in this case there are two streams coming from the general waste collection process the FORM and the residual solid waste (RSU). This FORM fraction will go through a different treatment, a biological process. The RSU will be the fraction of the waste without the organic fraction that will go through recycling process or landfilling treatments. The scheme of the system studied in scenario 2 can be seen in Figure 5.

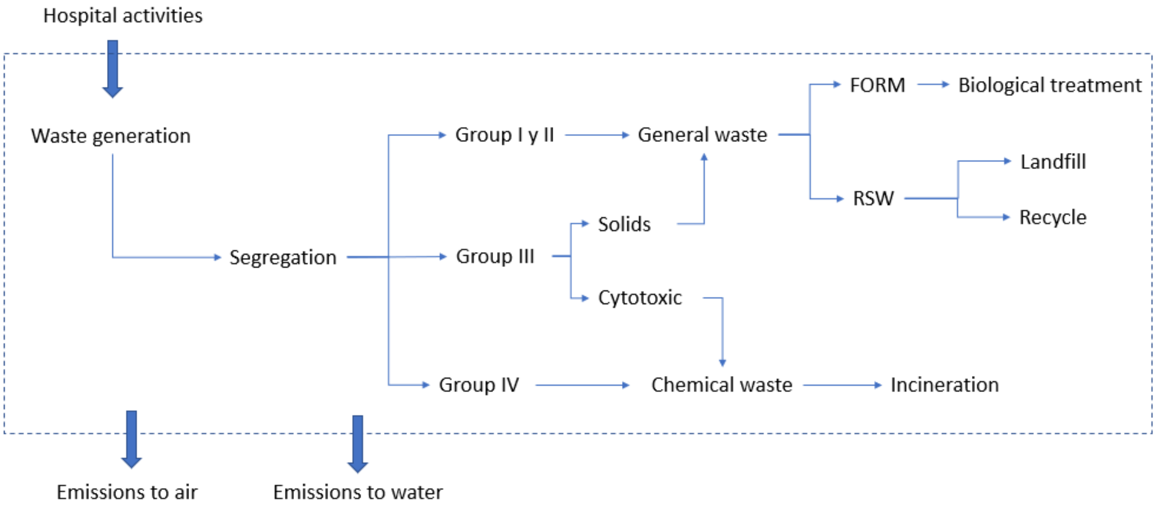


Figure 5. *System boundaries scenario 2*

5.3. DATA COLLECTION

For the composition of the two waste types, general and chemical, data from the hospital was collected as well as the quantity of each of the sub-groups that make up the main groups, Table 3.

Table 3. *Waste composition and quantity*

Group	Subgroup	Quantity (kg/year)
General waste	Ferro metals residues	34.940
	Glass residues	12.500
	Paper and cardboard residues	86.130
	Plastic residues	2.940
	Wood residues	8.901
	Electronic waste	440
	Batteries and accumulators' residues	375
	Food and animal residues	1.070
	Yard residues	34.140
	Household residues	728.356
	Construction and demolition residues	80.159
	Disinfected solid medical	96.212,25

Table 3. *Waste composition and quantity (continuation)*

Group	Subgroup	Quantity (kg/year)
Chemical waste	Non chloride compounds residues	2.135,10
	Aqueous solution residues	1.098,10
	Medicaments residues	3.056,45
	Contaminated containers residues	445,15
	Basic solution residues	15,10
	Acids residues	42,20
	Filter residues	17,10
	Chemical cleaning products residues	18,65
	Solid/Paraffin residues	1.371,57
	Cytotoxic residues	87.687

The composition of the subgroups has been determined by searching in literature, as reference it has been used the EU statics and the data given by the Spain government documents. For the data that could not be found, as well as the background data, the ecoinvent v3.8 has been used. All the background data from ecoinvent that has been used is geographically located in Spain.

5.4. FUNCTIONAL UNIT

The functional unit that has been used in most studies is the quantity of waste produced, Ali et al. [24], that used 1 ton of waste generated in the hospital of Pakistan or Igos et al. [30], that used 1 m^3 of wastewater produced in a hospital as FU. But the FU has to be something that describes the particular function of the system that is under study [17]. For example, this has been done in the work of, Thiel et al. [31]. They used one hysterectomy as FU for the LCA analysis of the hysterectomy surgical operation.

Sebastião Roberto Soares et al. [28] analysed the efficiency of the disinfection processes for the infectious fraction of the HCW and compared several scenarios and its environmental impact. The total amount of waste through an autoclave or microwave machine lifetime was used as FU. Also, it performed an economic analysis, which FU was the cost of treating 1 kg of waste through the disinfection technology. This functional unit is representative of the system as it considers the lifetime of the technology used.

Regula Lisa Keller et al. [27] used the number of hours worked by the hospital staff as FU. This can be considered a good FU as it represents an essential part of the hospital, the workers, which generates waste, but also is a general reference for all the service sectors and is not restricted only to hospital facilities.

On the other hand, each hospital facility has an area of influence. This one is bigger or smaller depending on the size of the hospital, a bigger hospital will have a bigger area of influence than a smaller one. The area of influence is determined by the number of people that are in that area and for which a hospital is assigned. Although it would be logical to assume that with a bigger area of influence the generation of waste increase, this is not true. Due to infrastructure limitation, it is not possible to serve all the potential patients. Moreover, the average age of the people in the area of influence affects the number of patients served by the hospital. It is not the same to have and average age of 50, less care activity, than of 80, more care activity.

A reference value related to the quantity of waste generated would be the number of beds occupied by patients or the number of operation rooms in the hospital. This last one introduces many variables as the number of operations per day, or the type of operation. On the other hand, the number of beds occupied by patients leaves out the waste generated by the patients that go to the hospital due to regular medical consultations. Because of this it has been decided to use a relative functional unit relating the number of inhabitants in the catchment area to the number of hospital beds.

In the case of Granollers hospital the area of influence is of 400.000 habitants, and it has approximately 400 beds. So, the FU chosen for the system studied is the average service received from the hospital by one inhabitant in the area of influence, which would relate to 0,001 beds occupied. The bigger the area of influence is more will be the number of beds occupied by patients, thus more waste will be produced. Also, it is a restricted reference for comparing hospital facilities of the same size or to smaller or bigger ones. The quantity of waste presented in Table 3 is corrected with the functional unit as is shown in Table 4.

Table 4. *Waste composition and quantity per FU.*

Group	Subgroup	Quantity ([kg/year]/FU)
General waste	Ferro metals residues	$8,74 \cdot 10^{-2}$
	Glass residues	$3,13 \cdot 10^{-2}$
	Paper and carboard residues	$2,15 \cdot 10^{-1}$
	Plastic residues	$7,35 \cdot 10^{-3}$
	Wood residues	$2,23 \cdot 10^{-2}$
	Electronic waste	$1,10 \cdot 10^{-3}$
	Batteries and accumulators' residues	$9,38 \cdot 10^{-4}$
	Food and animal residues	$2,68 \cdot 10^{-3}$
	Yard residues	$8,54 \cdot 10^{-2}$
	Household residues	1,82
	Construction and demolition residues	$2,00 \cdot 10^{-1}$
	Disinfected solid medical	$2,40 \cdot 10^{-1}$

Table 4. *Waste composition and quantity per FU (continuation).*

Group	Subgroup	Quantity ([kg/year]/FU)
Chemical waste	Non chloride compounds residues	$5,34\cdot10^{-3}$
	Aqueous solution residues	$2,75\cdot10^{-3}$
	Medicaments residues	$7,64\cdot10^{-3}$
	Contaminated containers residues	$1,11\cdot10^{-3}$
	Basic solution residues	$3,78\cdot10^{-5}$
	Acids residues	$1,06\cdot10^{-4}$
	Filter residues	$4,28\cdot10^{-5}$
	Chemical cleaning products residues	$4,66\cdot10^{-5}$
	Cytotoxic residues	$2,2\cdot10^{-1}$

5.5. IMPACT ASSESSMENT METHODS

For the impact assessment the ReCiPe Endpoint (H) method was used, as is the one used in similar studies to this one, Sebastião Roberto Soares et al. [28], Igos et al. [30], Kok SinWoon et al. [26]. Also in other work Kok SinWoon et al. [32], performed a review of solid waste management an state that researches were using ReCiPe methods more frequently in the studies of solid waste management.

The ReCiPe Endpoint method is a combination of two LCIA methods, CML and Ecoindicator 99. ReCiPe method uses three perspectives to group various sources of uncertainty and assumptions. An individualist perspective is used for a short-term interest, around 20 years, while hierarchist perspective is based on scientific consensus with the period and impact mechanism, it has a time horizon of 100 years. Egalitarian perspective considers the longest period (1000 years) and all the impact pathways. As the hierarchist perspective is the one that provides a balance in the future socio economic developments, neither to optimistic (individualist) or pessimistic (egalitarian), it has been the one chosen for the analysis [33].

It has been analysed 19 mid-point categories to evaluate the damage, Table 5, and 3 end-point categories were study, human health, ecosystems damage and resources. The analysis was performed using the software SimaPro, version 9.0.

Table 5. *Mid-point environmental impact categories.*

Mid-point environmental impact category	Abbreviation
Global warming, Human health	Global warm., Hum. Health
Global warming, Terrestrial ecosystems	Global warm, Terrestrial ecosy.
Global warming, Freshwater ecosystems	Global warm, Freshwater ecosy.
Stratospheric ozone depletion	Stratosp., ozone depl.
Ionizing radiation	Ioniz., rad.,
Ozone formation, Human health	Ozone form., Hum. Health
Fine particulate matter formation	Fine parti., mat. Formation
Ozone formation, Terrestrial ecosystems	Ozone form., Terrestrial ecosy.
Terrestrial acidification	Terrestrial acid.
Freshwater eutrophication	Freswater eut.
Marine eutrophication	Marine eut.
Terrestrial ecotoxicity	Terrestrial ecotoc.
Freshwater ecotoxicity	Freshwater ecotoc.
Marine ecotoxicity	Marine eco.
Human carcinogenic toxicity	Human carc. Toxicity
Human non-carcinogenic toxicity	Human non-carc. Toxicity
Land use	Land use
Mineral resource scarcity	Mineral res. Scarcity
Fossil resource scarcity	Fossil res. Scarcity

Normalisation and weighting steps are optional steps referring to the ISO-standard 14044 [12]. The ReCiPe method has no proper normalisation values, and therefore in SimaPro software they use the values of the Ecoindicator-99 method, which are the normalisation values proposed by the European Union [34].

In the normalisation procedure the relative contribution of the calculated damages to the total damage caused by a reference system. This reference system is usually the sum of all emissions and all resources extraction. This procedure allows us to compare impact categories with different units and see which one contributes most in an overall way [35].

Weighting is the next step to the normalisation procedure and consists in applying weighting factors to the normalised results. These weights are aimed to represent the point of view of the society or a group of stakeholders [35].

5.6. UNCERTAINTY ANALYSIS

An uncertainty analysis was performed in order to analyse the variability of the input data. This was determined with the pedigree methodology that is applied in the ecoinvent database [36]. The uncertainty of the results have been calculated using the Monte Carlo analysis which the most widely used method for this calculation in LCA [37].

5.7. LIFE CYCLE COSTING MODEL

For the LCC there has been consider the cost of each stage of the waste management process, generation of waste, collection, and treatment. Generation cost are not evaluated as it has not been possible to find information, neither the hospital has provided any of it.

The treatment cost would come from the sum of all the treatment process in the industrial plant conducted in each scenario plus the cost of the containers located at the hospital where the rubbish is store. The locations between the plants and the hospital are small, so the transportation costs are neglected. Equations 1 and 2 shows the mathematical formulation of the treatment cost for scenarios 1 and 2, respectively.

$$C_{treatment}^{Scenario\ 1} = C_{GWt} + C_{CWt} + C_{containers} \left[\frac{(€/year)}{FU}\right] \quad (1)$$

$$C_{treatment}^{Scenario\ 2} = C_{GWt} + C_{CWt} + C_{FORMt} + \ C_{containers} \left[\frac{(€/year)}{FU}\right] \quad (2)$$

Where the abbreviation GW_t and CW_t refers to general waste and chemical waste treatment, respectively. About the containers costs these are stablished by the local government. The hospital is located in Granollers, but not information has been found of municipal taxes for waste management. On the other hand, taxes related to Barcelona municipality have been found [38]. As Granollers is near Barcelona it has been assume that these taxes are the same or similar.

The taxes are referred to how many containers of a certain capacity are needed. The capacity is measured in litres, the mass quantities of each waste type have to be converted into volume. Chemical waste are chemical products in dissolution, so the density of water, 1 kg/L, have been used. General waste can be considered as MSW, so the density of this waste type has been used which is of 0,45 kg/L [39].

The taxes price includes the collection price and the afterwards selective separation of the different waste fractions. But it a selective separation is performed by the hospital, the price varies. So, the final containers cost is dependant of performing a selective separation or not. This is shown in Equations 3 to 5.

$$V_i = \frac{M_i}{\rho_i} \cdot 400.000 \ \ [L/year] \tag{3}$$

$$C_{Containers}^{Scenario\ 1} = \left(\frac{V_{GW}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) + \left(\frac{V_{CW}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) + \left(\frac{V_{Paper}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) \left[\frac{(€/year)}{FU}\right] \tag{4}$$

$$C_{Containers}^{Scenario\ 2} = \left(\frac{V_{GW}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) + \left(\frac{V_{CW}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) + \left(\frac{V_{Paper}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) + \left(\frac{V_{FORM}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) \left[\frac{(€/year)}{FU}\right] \tag{5}$$

The term V_i refers to the volume of the waste groups i, general waste group, FORM fraction, etc. Then the value is multiplied by the number of inhabitants in the area of influence in order to see how many litters of waste is produced by the hospital each year. This way the capacity of the container can be selected. Once this has been done, al the volume fraction are sum, divided by the capacity of the containers to see how many of them are needed, and finally multiplied to the price of each container and again referred it to the FU.

Also, in the case of performing a selective separation the municipality gives a reduction. Currently the hospital separates selectively the paper which has a reduction of 0,5%. In the case of separating the organic fraction the reduction is of 0,75%. This value has been used as the value of the discount rate (i). With this interest rate the present value (PV) is calculated by Equation 6. To be able to see the effect of the discount rate given by performing the selective separation the present value is used to evaluate the long-term expenditures in present day.

$$\mathrm{PV}_i = \sum \frac{{C_n}^i}{(1+i)^n} \left[\frac{(€/year)}{FU}\right] \tag{6}$$

Where the C_n variable is the sum of the cost of the treatment process and the cost of the containers in the year n. It is assumed that the reduction factors do not change through the years. To have a reference of how many years should be taken into account when calculating the PV the years of amortization of an industrial plant are obtained from the amortization table [40], 18 years.

For the collection stage cost it has been considered how many workers would need to be recruited. First the salary that would receive an employee performing this task has been search. The BOE states that for a job of this type the wage is of 14.171,71 €/year [41]. This gross salary is not the total cost of a worker for the hospital as it has to be considered that the company has to pay the social security to the employee. So, the total cost of a new recruiter is of 16.630,50

€/year. The values considered for this calculation are shown in Table B5 and Table B6. Afterwards the total cost is divided by the number of inhabitants in the area of influence. It has been considered that when volume treated per day y for a specific fraction is 2000 or below the number of workers needed to manage the waste separation process is 1. Higher number of containers need 2 employees or more. Furthermore, the BOE stated that the salary should increase a 2% each year, so to be able to sum it to the present value of the treatment stage Equation 7 is used.

$$\mathrm{PV}_{collection} = \sum (C_{worker} \times N_{workers}) \times (1 + 0{,}02)^n \left[\frac{(€/year)}{FU}\right] \tag{7}$$

The amortization years are used for both NPVs the one of the treatments and the one of the collection processes. The total cost of the process would be the sum of both NPV as is represented in Equation 8.

$$C_{total} = PV_{treatment} + PV_{collection} \left[\frac{(€/year)}{FU}\right] \tag{8}$$

For the environmental costs, the quantity it will be study the emissions of CO_2, CH_4, and N_2O. The total quantity of the emissions will be taken out of the SimaPro software and multiplied to the price of each emission compound which is given in dollars, so the change from $ to € [42] is used for obtaining the price in euros. This operation can be seen in Equation 9.

$$C_i^{Pollutant} = Q_i^{Pollutant} \left[\frac{kg/year}{FU}\right] \times C_i^{Pollutant} \left[\frac{\$}{kg}\right] \times 0{,}95 \frac{€}{\$} \tag{9}$$

5.8. MATHEMATICAL OPTIMIZATION MODEL

After having collected all the data and having performed the LCIA and LCC an optimization is conducted in order to study two other alternative scenarios to the one proposed of only separating the organic fraction. The objective function of the optimization model performed would be the minimization of Equation 8, that would be represented by Equation 10.

$$Min(C_{total}) = Min(PV_{treatment} + PV_{collection}) \tag{10}$$

As it has been mentioned before, the hospital only separates selectively the paper, so one of the alternative scenarios studied would be the selectively separation of the other two fractions which the local municipality gives reductions for, glass and plastic. With this study the objective is to see if performing extra selective separations would be economically beneficial and, if, other fractions are separated if still separating the hole organic fraction would be profitable.

The reduction coefficient for each fraction would be of 0,5% for paper and plastic residues, while of 0,25% for the glass residues. The mathematical procedure would the same as the one shown in Equations 1 to 8, but in this case Equation 11 would represent the collection cost.

$$\begin{aligned} C_{Containers} = {} & \left(\frac{V_{GW}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) + \left(\frac{V_{CW}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) \\ & + \left(\frac{V_{FORM}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) + \left(\frac{V_{Paper}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) \\ & + \left(\frac{V_{Glass}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) \\ & + \left(\frac{V_{Plastic}}{V_{container}} \cdot C_{container} \cdot \frac{1}{400.000}\right) \quad \left[\frac{(€/year)}{FU}\right] \end{aligned} \tag{11}$$

For the calculation of the environmental costs the same procedure, as the one followed for Equation 9 was performed. The mathematical constrains for this scenario would be the shown in Equations 12 to 19. This constrains assure that the mass balance of the waste management is maintain through the hole process.

$$in = out = \sum M_i \tag{12}$$

$$M_{RW}^{Max} = M_{GW} \tag{13}$$

$$M_{RW}^{Min} = M_{GW} - \left(M_{FORM} + M_{Paper} + M_{Plastic} + M_{Glass}\right) \tag{14}$$

$$M_{RW}^{Min} \leq M_{RW} \leq M_{RW}^{Max} \tag{15}$$

$$0 \leq M_{FORM} \leq M_{FORM}^{Max} \tag{16}$$

$$0 \leq M_{Paper} \leq M_{Paper}^{Max} \tag{17}$$

$$0 \leq M_{Plastic} \leq M_{Plastic}^{Max} \tag{18}$$

$$0 \leq M_{Glass} \leq M_{Glass}^{Max} \tag{19}$$

Where the abbreviation RW refers to the residual fraction left in the general waste group when the organic, paper, plastic, and glass fraction are separated. The mass flow of this fraction are stablished between 0, when no fraction is separated, therefore all of it remains in the general waste group, and the maximum mass flow if all the fraction was separated. This maximum value would be stablished by the quantities shown in Table 4.

The fourth scenario will evaluate the effect of performing a selective separation of the debris waste. As it will be explained later, construction and demolition waste is formed of several residues, most of them recyclable [43], [44] and in the current situation hospital only mix them with the other residues and goes to landfill.

For the evaluation of this scenario, it has been decided to divide the general waste groups in three groups, the residual solid fraction that contains the waste that will go to landfill treatment, the organic fraction, and the recyclable fraction, which contains the residues that goes to the recycling process. This break down of the general waste groups is done in order to evaluate in an efficient way the transfer of mass from one group to another and its corresponding treatment.

The procedure followed for the optimization of this scenario is the same as the previous ones, but in this two more constrains must be add for the debris and recyclable fraction, Equations 20 and 21.

$$0 \leq M_{Recycable\ fraction} \leq M_{Recycable\ fraction}^{Max} \tag{20}$$

$$0 \leq M_{C\&D} \leq M_{C\&D}^{Max} \tag{21}$$

The construction and demolition waste can be separates up to an 80%, so the maximum would be state to the 80% of the quantity of Table 4 while the minimum would be the situation in which no part of the construction and demolition waste is separated. For the recyclable fraction, the maximum would the sum of the fraction that currently goes to this treatment process plus the sum of all the debris that would go to recycling. The minimum would the quantity of the current situation where only, paper, plastic, metal, and glass enters the recycling process.

6. LIFE CYCLE INVENTORY

The quantities of each waste subgroup was given by the hospital, but the composition of this ones were not. For modelling each one of these subgroups' information was taken from similar studies carried in regions near Spain or from official websites.

Ferro metals composition was taken from Catalonia good practice guide about metal waste and recycling [45]. From this document it could be determined that the waste was made from iron and steel. No information has been found if a material is in greater quantity than another, so the quantities were divided equally.

Glass residues come mainly from packaging, which can be recycled or not [46]. As composition is not defined it has been using the different type of package and the quantity was divided equally. Paper and cardboard waste also comes from packaging [47] but it was not specified if part of it was recycled. It was considered all virgin material, without recycling.

Plastic waste is a mix of polyethylene of low and high density (PE), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS) [48] . No information has been found if a material is in greater quantity than another, so the quantities were divided equally.

For the wood waste information was found in a Basque country document for the department of environment and land use planning [49]. In this document, a survey of the typical composition of the wood waste in the Spain community has been performed. From this study it has been determined that the wood waste is composed of particleboard (70%), plywood (24%), and medium density fireboard (MDF) (6%). These products are available in the ecoinvent database, so they were chosen.

Electronic waste was modelled following the approach used by Regula Lisa Keller et al. [27], which used the lifetime service of the equipment. As the type of equipment was not provided by the hospital it was used for literature search, desktop, and laptop computers, printer, and tablet. As no more information was held, electronic medical devices were not counted in this analysis.

In first place, the lifetime of the devices were taken off the amortisation tables [50], being 6 years for computers and tables, and 10 years for printers. Afterwards each type of electronic equipment generates a specific amount of waste, this value was taken from the work of Rohit Panchal et al [51].

From the EU web page of statistics [52], it was seen that in Spain each person generates 7,9 kg of electronic waste per year. Considering all the variables mentioned, it was calculated how much each electronic device contributes to the total amount of electronic waste generated by each habitant, Table 6.

Table 6. *Electronic waste composition*

Device	Quantity generated per device (kg)*	Percentage waste generated per device (%)	Quantity [(kg/EU-habitant)/year]**
Desktop	8,77	40,58	3,21
Laptop	1,26	5,83	0,46
Tablet	1,26	5,83	0,46
Printer	10,32	47,76	3,77
Total	21,61	100	7,9

* Values taken from the work of Rohit Panchal et al. [51].

** The percentage of column 2 has been multiplied by the total quantity of waste generated by inhabitant in Spain, 7,9 kg [52]

For batteries and accumulators, it have been selected those identified by the Spain government [53]. No information about what type of battery or accumulator is presented in more quantity than other so its composition were divided in equal values. The batteries and accumulators chosen where:

- Lead batteries
- Ni-Cd accumulators
- Mercury batteries
- Alkaline batteries

- Li batteries

For the modelling of the food and animal residues the known food pyramid [54] was used to select the foods that are found in the hospital diet. These are vegetables, fruits, fish, and meat. Their quantities have been distributed in equal terms, as there was no information provided by the hospital in which proportion each food is given.

For the yard waste its composition was taken from the work of Marga López et al. [55]. This work examines the composition of MSW yard fraction in Catalonia, which is made from yard trimmings. The concentration of each of the components of the yard waste is shown in Table 7.

Table 7. *Nutrients yard waste composition*

Nutrients	Concentration (g/kg)
P	2,62
K	10,8
Ca	45,99
Mg	3,77
Na	8,34

Household residues were not modelled. This type of waste is the waste that made off the municipal waste, so instead was divided between paper, plastic, glass, food, and garden residues. The composition of the municipal waste in Cataluña, Table 8, was taken from the annual memory of generation and management of municipal residues [56].

Table 8. *Municipal waste composition in Cataluña in 2019* [56].

Type of waste	Quantity (ton)	Fraction (%)
Paper	405.667	31
Glass	203.329	16
Food	447.245	35
Yard residues	53.497	4
Plastic	184.923	14
Total	1.294.661	100

The fraction of each waste was multiplied to the value of household residues on Table 4 and them sum to the corresponding value of the waste type. The final quantities of paper, glass, food, garden residues and plastic are shown in Table 9.

Table 9. *Final quantities of residues*

Type of waste	Quantity ((kg/year)/FU)
Paper	$7{,}86 \cdot 10^{-1}$
Glass	$3{,}17 \cdot 10^{-1}$
Food	$6{,}32 \cdot 10^{-1}$
Yard residues	$1{,}61 \cdot 10^{-1}$
Plastic	$2{,}67 \cdot 10^{-1}$

For the modelling of the construction and demolition residues, information about its composition was obtained from the official web page of the minister of development [57], Table 10. Moreover, some of the types of waste that make up construction residues are in turn composed of varied materials. For the modelling of these one’s literature research has been carried out [58]–[60].

Table 10. *Construction and demolition residues composition* [57]–[60]

Type of waste	Fraction (%)	Quantity for 1 kg of waste (kg)
Ceramic	54	0,54
Concrete	12	0,12
Stone	5	0,05
Gravel	4	0,04
Wood	4	0,04
Glass	0,5	0,01
Plastic	1,5	0,02
Metals	2,5	0,03
Asphalt	5	0,05
Gypsum	0,2	0,00
Paper	0,3	0,00
Waste	7	0,07
Others	4	0,04

As it has been mentioned earlier medical waste is composed of infectious solid medical waste and special cytotoxic residues, chemical residues that come from several types of treatments. The solid medical waste is composed mainly of glass, plastic, and cotton [61]. As no information of its composition has been given, they are supposed to be in equal quantity. The modelling of the cytotoxic waste was done with the ecoinvent dataset “Chemical Organic {GLO}” as was done by Regula Lisa Keller et al. [27].

Chemical waste subgroups were modelled following the information found in literature research [62]. The non-chloride solutions groups were modelled using the ecoinvent datasets that provided information of non-chloride compounds. Again, as no information of composition was given, this one was divided equally between the datasets introduced in the group.

Aqueous, basic solutions, and acids were modelled in the same way as non-chloride groups. For the medicine residues, the ecoinvent data set "Chemical Organic {GLO}" was used. Medicines are also a mixture of organic compounds, so using this dataset is the best approach that can be done with the information provided by the hospital [27]. For the paraffin group ecoinvent has in his database the process of producing such compound, so this one was used to model this subgroup.

For the second scenario of the case study, the one that would be proposed as an improvement of the actual one, the general waste will be divided in two separated fractions as has been explained before. The FORM fraction and the Residual waste fraction. The residues that will be in each of them are shown in Table 11

Table 11. *General waste composition and fraction in scenario 2.*

Group	Subgroup
Residual waste fraction	Ferro metals residues
	Glass residues
	Paper and carboard residues
	Plastic residues
	Electronic waste
	Batteries and accumulators' residues
	Construction and demolition residues
	Disinfected solid medical waste
FORM	Wood residues
	Yard residues
	Food and animal residues

The treatment stage includes the containers where the waste is storage and the transportation from hospital to plant. For the container it has been used the ecoinvent database of "Container, for collection of post-consumer waste plastic for recycling {Europe without Switzerland}| container production, for collection of post-consumer waste" for all the cases. About the transportation the distance has been taken from google maps from the hospital to the Llorens plant, that is located in Granollers and is at $1{,}125 \cdot 10^{-5}$ km/FU from the hospital [63]. For the chemical waste the plant is located in Tarragona and the distance is of $3{,}075 \cdot 10^{-4}$ km/FU from the hospital [64].

For the general waste there are two treatment process in scenario 1, landfill and recycling. Neither the hospital or in the official website of the company specifies the percentage of paper, glass, plastic, or metals that are recycle. Following the data given by official Spain documents

[56] all four materials are 100% recycle. Solid medicals are made of paper, plastic or glass as has been mentioned before, so it is assumed that they go to recycling processes. For each one of them a residue definition was specified for avoiding wrong mismatching of waste. The energy values of the recycling process were obtained from best available techniques European document [65] and is of 0,03 kWh/kg of waste treated.

In the case of landfill all the waste that does not go to recycling process goes to it. No information has been found for the energy values of this process, so the background data inside the ecoinvent database was used in this case and all the energy processes were referred to Spain.

For the second scenario proposed, the municipal solid waste treatment was maintained in the same way. In this case a separated process was constructed for the treatment of the FORM fraction. For this, no information about any specific biomass plant of the Granollers town was found. Following the annual memory of generation and management of municipal residues, organic fraction can go through an anaerobic digestion process or a composting process so the total FORM quantity, 0,81 (kg/year)/FU, is divided in two following the LoW [66], wood waste will go to composting, while yard and food waste to anaerobic treatment.

In the anaerobic digestion process biogas is produced, and part of it is used for the generation of electricity in the biological treatment plant. The quantity of biogas used in the anaerobic digestion and the energy used in these two processes was obtained from the best available techniques document of the Spain government for biological processes [67]. The report stated that the energy comes from the electricity grid, so it was selected the “Electricity, low voltage {ES} market” from the ecoinvent dataset. The electricity demand is of 0,055 kWh/kg of waste introduced into the process.

As it has been mentioned part of the biogas produced in the anaerobic digestion is used to generate electricity for the own plant. The volume of biogas needed to produce electricity for self-consume per kilogram of waste introduced in the process is of 0,029 m^3. It is assumed that the composting process is in the same plant as the digestion unit, so no transportation between both plants is required.

The chemical waste fraction goes through an incineration process, stated by the Spanish legislation, as has been previously mentioned. For the modelling, the datasets of hazardous incineration processes from the ecoinvent database were used. The energy values were obtained from the best available techniques document for incineration processes [68] which reported that an energy demand of 1,56 MJ/kg of waste introduced in the process. In the second scenario, this treatment has no changes as the separation of the FORM fraction do not affect the chemical fraction treatment.

For the LCC analysis, the treatment cost have been obtained from different literature sources. For the biological treatment (anaerobic digestion and composting) there has not been found the cost per kg of waste treated, so it has been used the energy values of the life cycle inventory. For transforming these values to monetary terms, it has been used the price of electricity for industrial facilities in Spain in November 2021 of 0,076 €/kWh [69].

For incineration processes, the prices have been taken from the best available techniques document [68] which gives a value of 350 €/tonne for hazardous waste incineration.

For landfill process, it has been found that the average treatment prices in Europe is of 60 €/tonne [28]. For the recycling process it has also not been possible to fine a price per quantity of waste treated. The price, as for the biological process comes from the energy used in his treatment and the price of electricity for industrial facilities. The prices in function of the quantity of waste treated in this study are shown in Table 12.

Table 12. *Treatment process price per FU*

Process	Price (€/kg)
Hazardous waste incineration	0,3500
Landfill	0,0600
Recycling	0,049
Anaerobic digestion + Composting	0,0016

About the collection costs as it has been said previously, these are stablished by the local government. No information of the hospital has been given about or conditions, so it has been assumed that for the general waste group a container of 1000 L will be used and for chemical waste group they a container of 320 L. In the case of selective separation of the FORM, paper, glass, and metal is also assumed that the container is of 1000 L. These assumptions made plus the information about Barcelona taxes are shown in Table 13.

Table 13. *Waste containers prices* [38]

Nonselective separation		**Selective separation**	
Container (L)	Price (€/day)	Container (L)	Price (€/year)
90	2,15	90	91,69
120	2,9	120	98,95
240	5,71	240	107,37
360	8,68	360	116,44
660	15,94	660	137,54
800	19,3	800	149,61
880	21,25	880	154,43
1000	24,14	1000	159,25

The emission costs are referred to the total emissions of CO_2, CH_4 and N_2O produce during the hole HCW management process. This resembles the environmental impact in monetary of how much society has to pay for polluting. The monetary values of these pollutants are shown in Table 14, and are taken from the work of Meghann Smith et al. [70].

Table 14. *Emissions costs* [70]

Compound	Price (€/kg)
CO_2	0,051
CH_4	1,5
N_2O	18

7. RESULTS AND DISCUSSION

7.1. LIFE CYCLE IMPACT ASSESSMENT

The environmental footprint was analysed for the mid-point impact categories shown in Table 5, and the 3 end-point impact categories, human health, ecosystems, and resources. First the analysis was performed for the initial scenario, and them for the second scenario. In both cases it has been used the same procedure. Finally, a comparison between the two scenarios will be performed.

Figure 6 shows the midpoint impact categories for the actual situation of the hospital. In this plot each group contains the three phases of the waste management process, generation of waste, collection, and treatment.

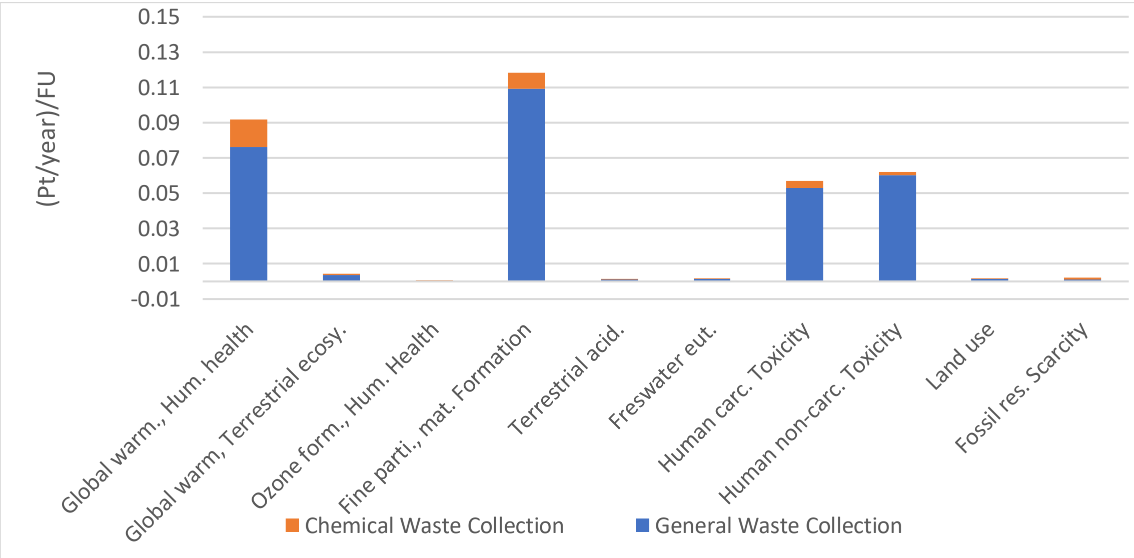


Figure 6. *Weighted impact contribution for midpoint categories of the two groups of waste for scenario 1*

Chemical waste group, which includes cytotoxic, and laboratory chemical products represents 8% of the total waste generated. His environmental impacts comes mainly from his treatment process, incineration. In reference to the impact of the chemical waste group, the treatment hoars at least the 50% of the damage in most of the categories, and in some of them rise up to 80%, for example in human carcinogenic toxicity, due to the emissions of chromium (VI), a very carcinogenic compound [71].

In other categories as fossil resource scarcity and mineral scarcity, the impact comes from the generation of chemical waste that hoars the 43% and 70% of the total impact respectively. This is due to the ecoinvent group “Chemical, organic market {GLO}” which includes numerous organic compounds. So, the damage comes from the use of this products, that included the extraction of resources [27].

Regarding the fine particulate matter formation, the chemical waste group represents the 8% of the total damage, with 50% due to its treatment process, that comes from the emission of sulphur and nitrogen oxides, particles, and ammonia during the incineration process [8].

Global warming impact category also, plays an import role in the environmental damage [27]. The generation and treatment of chemicals represents the 18% of the total impact. This comes from the treatment, with the heat needed for this one that has a weighting score of $5{,}62 \cdot 10^{-3}$ (Pt/year)/FU that represent a 33% of the total score of the chemical group in this category. Also, the incineration treatment accounts for a 12% of the total carbon dioxide emissions, 0,494 (kg/year)/FU of the total 4,09 (kg/year)/FU. This represents how polluting is this process considering that the chemical waste group only has a composition of 8% in the total waste generated.

The general waste group hoar most of the environmental damage. This is logical because the general waste group is the major in composition, 92% of all the waste generated, and also is the one with most variety in his content. Regarding the human toxicity impacts, carcinogenic and non-carcinogenic, more than 65% of both impacts are due to the treatment processes due to the emissions of chromium (VI), arsenic, lead, and zinc.

Fine particulate matter formation comes from the generation of waste, having a score of 0,109 (Pt/year)/FU that represents the 92,1% of the total contribution for the overall impact. This high punctuation comes from the substantial number of different waste types included in this group, paper, plastic, metals, etc. individually none of them hoars a great percentage in the overall impact category, the maximum contribution is around 10%, but due to their amount in combination represent the major impact of the analysis. Looking at the work of Regula Lisa Keller et al. [27] the same impact category was mainly affected by the use of tools and devices within 33 Swedish hospitals.

In the global warming midpoint impact category, the landfill process has a higher contribution, with a 14% of the total impact damage due to the emissions of methane which represent the source of the 95% of the emissions, 0,0222 (kg/year)/FU to the 0,0234 (kg/year)/FU from the total waste management process. However, the environmental impact on this midpoint category comes from the generation of CO_2. Waste generation stage hoars the emission of 3,74 (kg/year)/FU out of the total 4,09 (kg/year)/FU produced, due to the, his quantity and variety.

Figure 7 represents the midpoint impacts for each individual phase of the waste management process, waste generation, collection, and treatment.

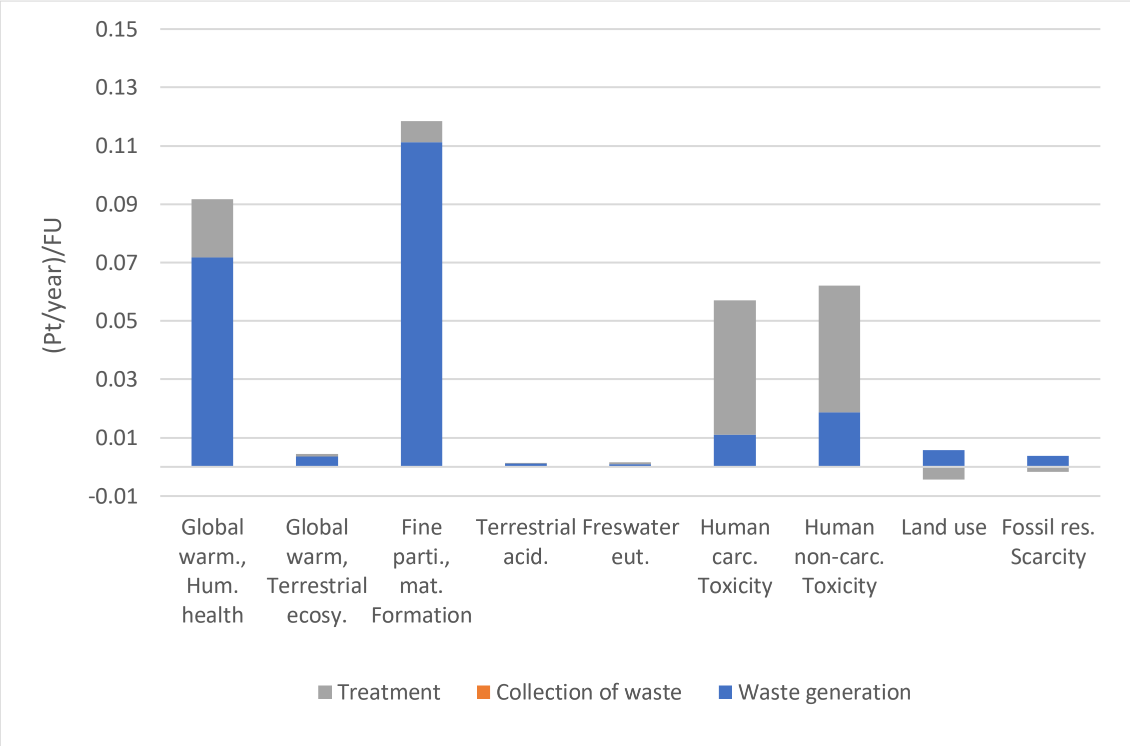


Figure 7. *Weighted impact contribution for midpoint categories of the three phases of the waste management process for scenario 1*

The bar plot of Figure 7 represents what has been explained before. The high scores of global warming and fine particulate matter formation impact categories, 0,092 and 0,118 (Pt/year)/FU respectively, are due to the waste generation, while human toxicity categories environmental impact comes from the treatment processes.

Collection stage has a null impact in all categories, due to lack of information that was not proportioned by the hospital about this stage.

Waste generation also has a contribution to land use due to food waste. This result is in accordance with one of the hotspots found by Regula Lisa Keller et al. [27]. This is compensated with the negative score of the treatment process, specifically the recycling process. This can be seen in Figure 8 that represents the midpoint impact categories of the treatments.

The bar plot shows, as it has been explained previously, how polluting is the incineration process although input waste quantity is exceptionally low. On the other hand, landfill is also a process with great environmental impact, especially for the human non-carcinogenic toxicity due to the emissions of lead. Also, it has a significant effect on the terrestrial and freshwater ecotoxicity hoarding the 75% and 73% respectively of the total damage for these categories.

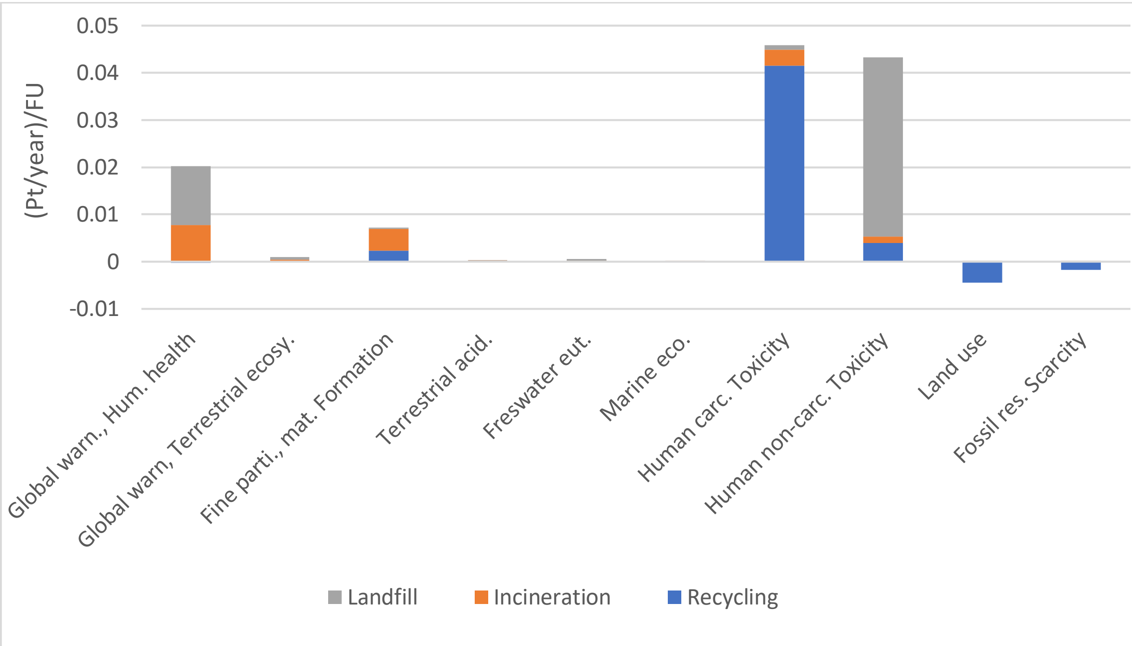


Figure 8. *Weighted impact contribution for midpoint categories of the treatment process for scenario 1*

Recycling process has positive environmental effects in the majority of the impact categories but is the main contributor to the human carcinogenic toxicity due to the emissions of chromium (VI). Recycling process is the source of the 75% of the emissions, it produces 0,0001 (kg/year)/FU of the total 0,000134 (kg/year)/FU of this pollutant substance.

Overall, the most important midpoint categories to address are global warming, fine particulate matter formation, and human toxicity. The rest of the categories have a minor impact, not reaching the 0,01 points, while the other four categories are 6 to 9 times higher. These midpoint categories are related to the endpoint category, human health which is the one that has a mayor weighting value, Figure 9.

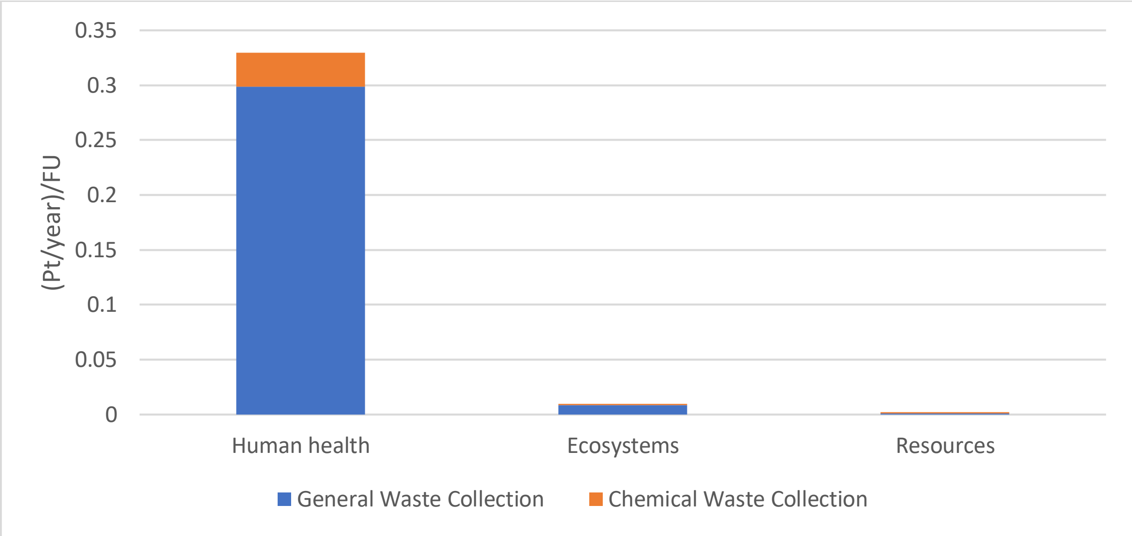


Figure 9. *Weighted impact contribution for endpoint categories of the two groups of waste in scenario 1.*

In Figure 9 it can be represented the weighting values of the endpoint categories. Resources is the least impact category to be affected, which is reasonably, the analysis does not study the impact of the products production, rather, their use and disposal. As it can be seen in the previous bar plots fossil fuel scarcity and mineral scarcity have low scores, midpoint categories relate to this endpoint category, have low scores.

The ecosystems impact category also has a low relevance on the analysis. The analysis of this category follows a similar trend that the resource one, with a more relevance contribution of the general waste group. The effect is due to the landfill process that produces leaches that contaminated the water and ground around the facility [26].

Human health impact category is the one to be aware of with, by far, the greatest impact of all. The major contributor to this impact is the general waste group with an overall weighting of 0,3 (Pt/year)/FU, compared to the 0,03 (Pt/year)/FU of chemical waste group. This situation is due to the fact that general waste group is the major contributor in the four main midpoint impact categories.

Looking at Figure 8, human toxicity midpoint categories scores are because of the treatment process of general waste (recycling and landfill) which the sum of the two represents the 74% and the 68% of the human carcinogenic and non-carcinogenic toxicity, respectively.

Figure 10 show the results of the midpoint impact categories for scenario 2. This second scenario follows the same trend as in the base case scenario with global warming, fine particulate matter formation and human toxicity as the main midpoint impact categories to consider.

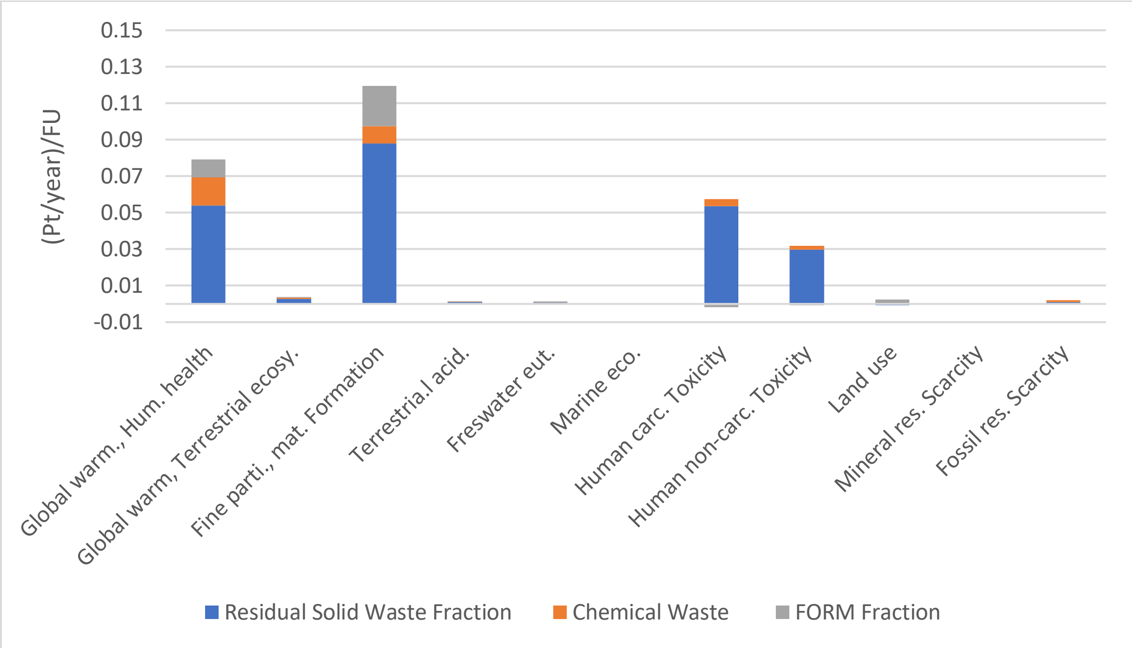


Figure 10. *Weighted impact contribution for midpoint categories of the three groups of waste in scenario 2.*

Chemical waste group does not change his contribution to each impact category, while general waste has been divided into the residual solid waste fraction and the FORM fraction.

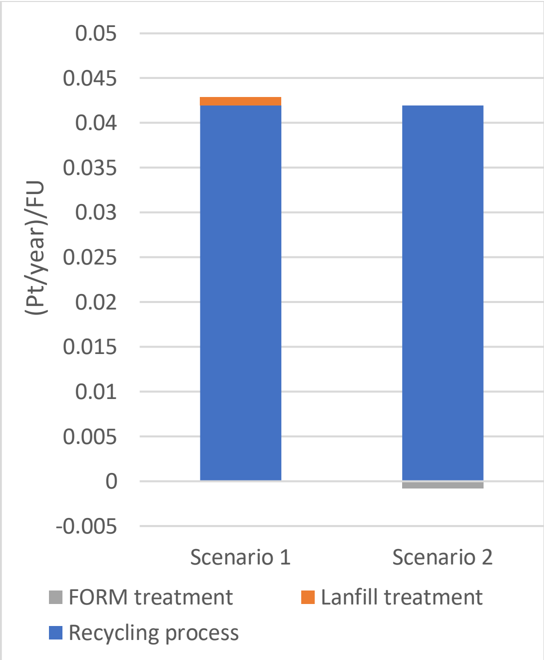
Comparing Figure 10 to Figure 6, it can be seen that the human toxicity impacts have decreased. Human carcinogenic toxicity has decreased a 2% compared to scenario 1, while human non-carcinogenic toxicity have decreased 50% from a score of 0,06 (Pt/year)/FU to 0,03 (Pt/year)/FU. This decrease is due to the separation of the FORM fraction of the rest of the waste.

In the case of human carcinogenic toxicity category, the low decrease is because the major contributor to this category, the recycling process, has not decreased his workload, as it can be seen in Figure 11a. Rather the decrease comes from the less quantity of waste that enters the landfill process. In Figure 11a the contribution of the treatment is negligible. His environmental score has decrease in $6{,}89 \cdot 10^{-4}$ (Pt/year)/FU which means a decrease of 76% of the initial impact.

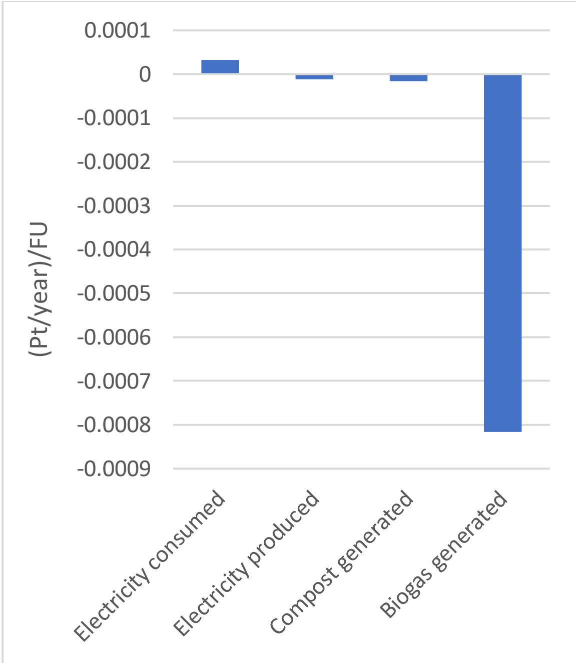
Also, the biological treatment has a negative score, Figure 11b, in this impact category. This means that thanks to this type of treatment $1{,}67 \cdot 10^{-6}$ (kg/year)/FU of chromium (VI) (main pollutant for this category) are saved. In Figure 11b it can be seen that this effect mainly comes from the production of biogas that has negative score of $-8{,}16 \cdot 10^{-4}$ (Pt/year)/FU on the midpoint category. Furthermore, the electricity produce by the excess of biogas that it is not use in the treatment process also has a negative score that contributes to reduce the overall impact in the midpoint category.

The sum to the negative score of the FORM treatment, $-6{,}79 \cdot 10^{-4}$ (Pt/year)/FU, to the reduction in the score of the landfill treatment, it accounts for the difference of score in both scenarios of

1,36·10-3 (Pt/year)/FU. In the work of Kok Sin Woon et al. [26], where different treatment scenarios where studied, those in which the workload of landfill is reduce the overall impact in both human carcinogenic toxicity categories is reduce.



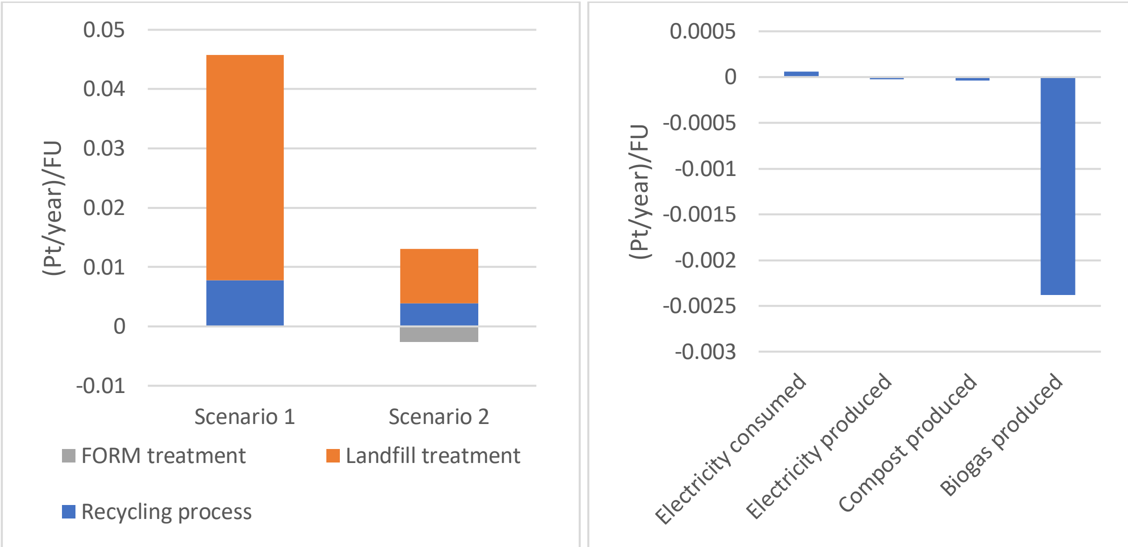
(a)



(b)

Figure 11. *(a) Treatment impacts for the treatment phase to human carcinogenic toxicity of scenarios 1 and 2 with a 1% cut. (b) Main contributors of the FORM treatment process to the same midpoint impact category with a 1% cut*

On the other hand, human non-carcinogenic toxicity has much greater decrease a 50% due to the reduction of the landfill workload. In this case the impact of landfill has decreased a 75,7%, from 0,038 (Pt/year)/FU to 0,00923 (Pt/year)/FU, his contribution has decreased from 61,3% to 29,7%. Figure 12 shows the main treatment contributors to this category. In Figure 12a it can be seen the reduction of the landfill contribution between both scenarios. Also, it can be observed that the recycling process has a lower score in the second scenario, this is because for the 1% cut the FORM treatment contributions have more weight than other recycling treatment contributors that in scenario 1 were. The contribution of the FORM treatment is breakdown in Figure 12b as has the same distribution as in Figure 11b. Biogas has a greater contribution for this midpoint category with a score of -0,0025 (Pt/year)/FU and compost has tiny contribution in this category, $-3{,}6\cdot10^{-5}$ (Pt/year)/FU.



(a) (b)

Figure 12. *(a) Treatment impacts for the treatment phase to human non- carcinogenic toxicity of scenarios 1 and 2 with a 1% cut. (b) Main contributors of the FORM treatment process to the same midpoint impact category with a 1% cut*

Having an extra treatment process does not increase in the fossil fuel scarcity midpoint impact category, rather it has decreased a 15% due to the contribution of the biological treatment. This treatment has a negative score of -3,25·10^{-4} (Pt/year)/FU which contributes in a positive way to the environment in a 16,3%, out of which the biogas production has a weight of 2,3% which suppose -2,98·10^{-3} (Pt/year)/FU. These changes can be seen comparing Figure 13 to Figure 7.

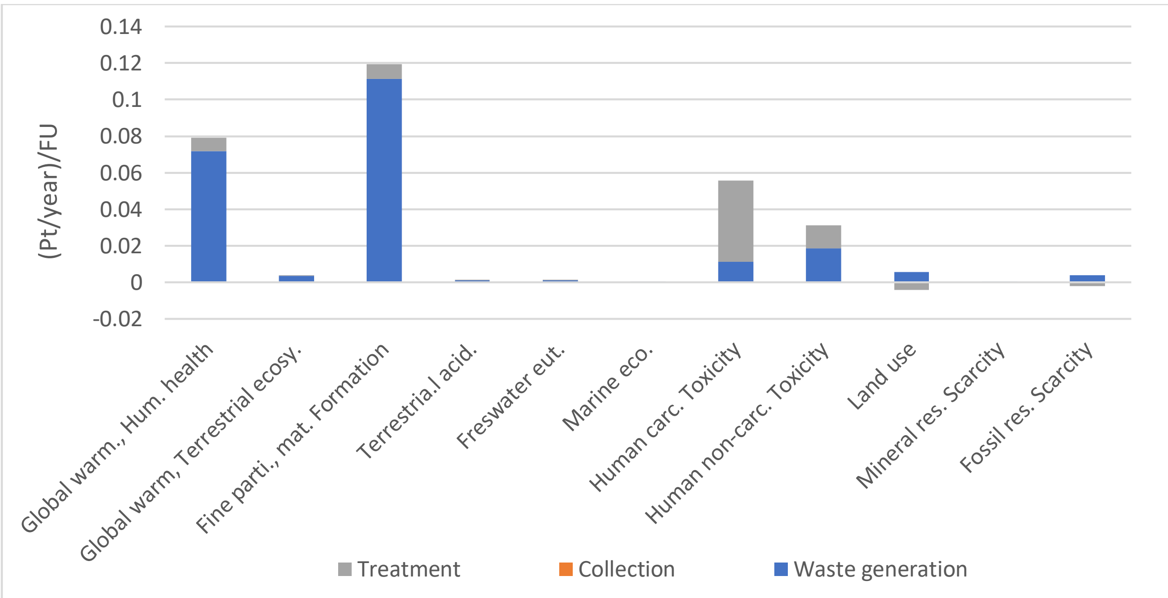


Figure 13. *Weighted impact contribution for midpoint categories of the three phases of the waste management process for scenario 2*

Figure 13 shows the 3 phases of the waste collection treatment. About the waste collection impact again this is 0 as no information has been obtained. On the other hand, the waste generation group does not change his contribution as the production of waste does not increase neither decreases.

The overall treatment group of Figure 13 has also decreased his overall score from 0,0926 to 0,0475 (Pt/year)/FU. This decrease is due to the biological treatment that, overall, is an environmentally friendly process as it has been shown previously. However, the organic fraction also has some negative effects in the environment. One of this is the fine particulate matter formation that has increase in $1{\cdot}10^{-3}$ (Pt/year)/FU. As it can be seen in Figure 14 FORM treatment has a positive score in this midpoint impact category.

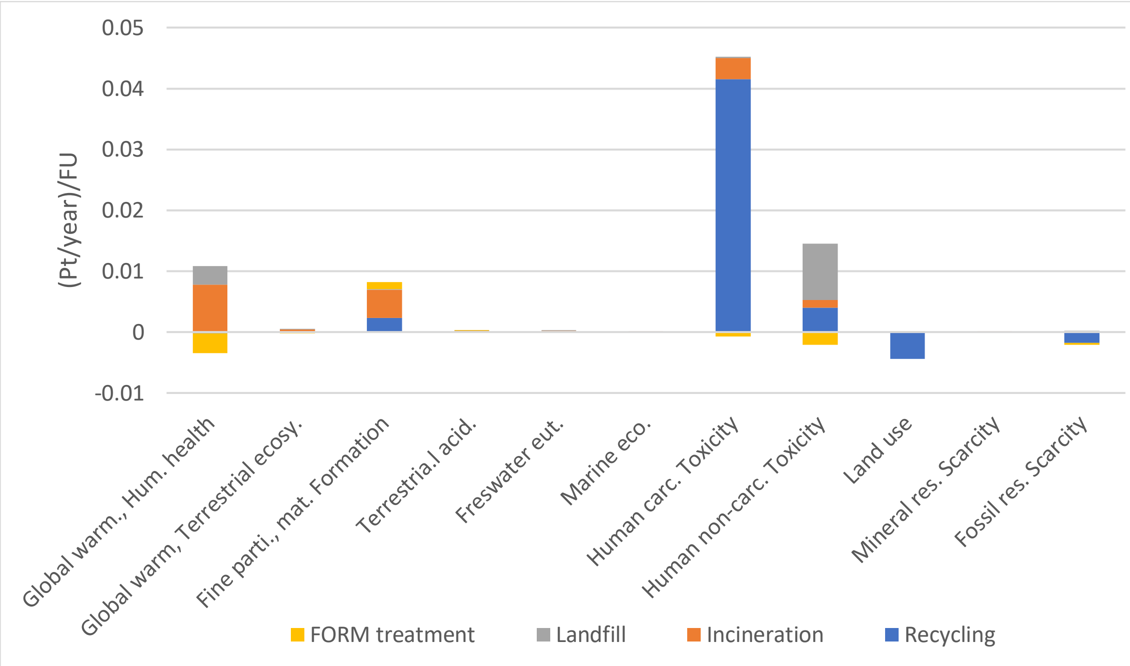


Figure 14. *Weighted impact contribution for midpoint categories of the treatment process for scenario 2*

In this bar plot it can be seen the negative scores mentioned for the midpoint impact categories previously explained before and that the FORM treatment has a score in in fine particulate matter formation category of $1{,}22{\cdot}10^{-3}$ (Pt/year)/FU. This score is partly compensated by the reduction of the impact of landfill process in $1{,}465{\cdot}10^{-4}$ (Pt/year)/FU. In Figure 15a it can be seen how much it contributes the FORM treatment to this category.

In this case biogas production has a positive score of $8{,}37{\cdot}10^{-4}$ (Pt/year)/FU for the midpoint category as it can be seen in Figure 15b. Moreover, composting process has a positive score of $4{,}43{\cdot}10^{-4}$ (Pt/year)/FU, add to the score of the biogas production, both process hoar the 35,8% of total damage related to the treatment category of Figure 13 for the fine particulate matter formation category for the treatment phase. On the other hand, the compost produced has a negative score in this category as it can be used as fertilizer and so reduces the need of producing other fertilizers that contributes to polluting the environment. But his overall treatment has positive score due to its energy needed. This is in accordance with the results obtained by Kok Sin Woon et al. [26].

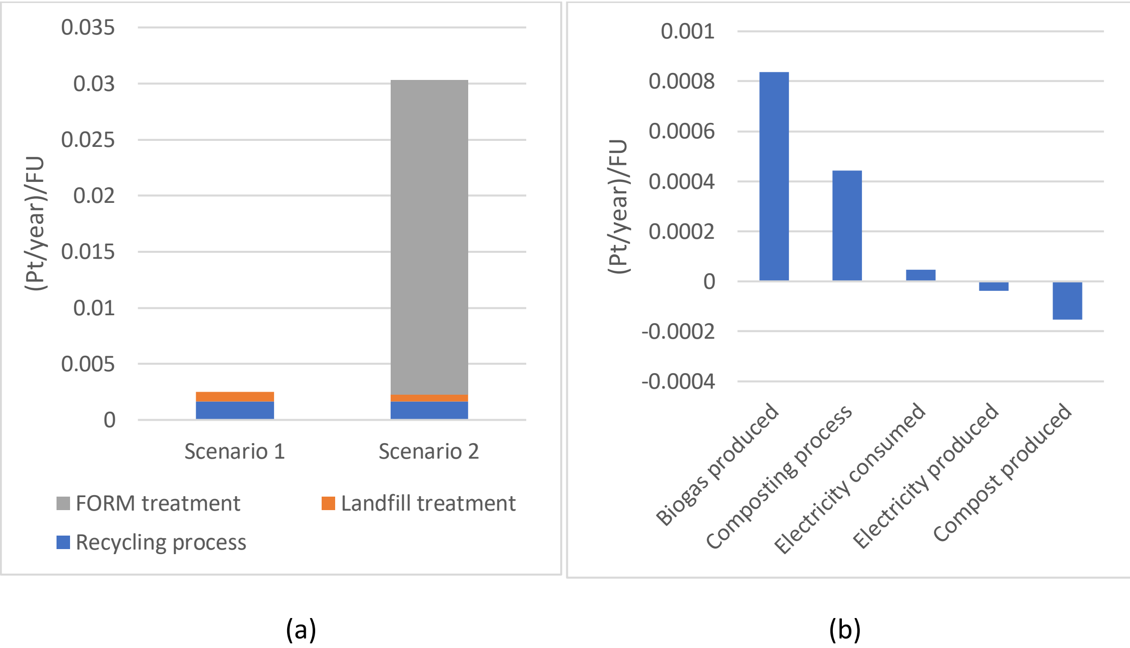


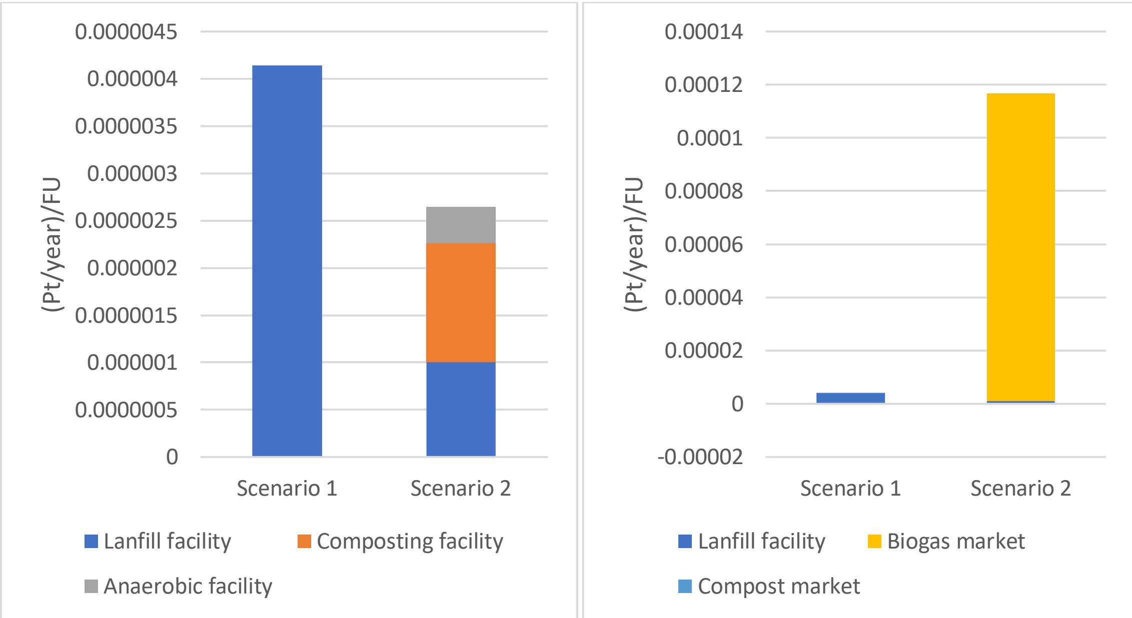
Figure 15. *(a) Treatment impacts for the treatment phase to fine particulate matter formation of scenarios 1 and 2 with a 1% cut. (b) Main contributors of the FORM treatment process to the same midpoint impact category with a 1% cut*

Moreover, global warming for human health, decreases its score in 14%, from 0,092 to 0,079 (Pt/year)/FU. This decrease comes from the FORM treatment which has a negative score in the midpoint impact category [26], as it can be seen in Figure 14.

The reduce in the impact of global warming is related to the lower impact in fossil fuel scarcity category. As fewer fossil fuels are used, less carbon dioxide to air is emitted 3,85 (kg/year)/FU compared to the 4,09 (kg/year)/FU of the first scenario. This emission is the main contributor this midpoint impact. This reduction comes from the treatment processes which in scenario 1 saved 0,145 (kg/year)/FU and when the biological treatment is added it saves 0,381 (kg/year)/FU of CO_2. In this reduction the contribution of the biogas production is of $-5,19 \cdot 10^{-4}$ (Pt/year)/FU, which suppose the 0,65% and the production of compost the 0,2% of the total waste management process for this impact category.

The land use midpoint impact category increase in $1 \cdot 10^{-4}$ (Pt/year)/FU which is because of the FORM treatment. Looking at Figure 16 it can be seen the contributions of the landfill treatments and the biological treatment to each scenario. In Figure 16a it can be seen that the reduction on the workload of the landfill has as decrease in his impact of $3,14 \cdot 10^{-6}$ (Pt/year)/FU. The fact that the biological treatment adds two extra facilities, anaerobic and composting facilities, only represents 1,6·10^{-6} (Pt/year)/FU, which is not enough for explaining the increase in the impact. Rather this increase comes from the market of biogas, Figure 16b.

Markets are an activity in SimaPro software which output is a consumption mix of all the process included the market activity. In the case of biogas this includes not only the energy but also the facility, the same occurs with the composting market activity. Figure 16b shows the significant difference between both markets, and as well the different in punctuation of the biogas market to the sanitary landfill facility, main contributor in scenario 1. Biogas markets shows a great impact in land use impact category [72] and thus the increase in this category is due to this activity.



(a) (b)

Figure 16. *(a) Main contributors to the land use impact category of lanfill and organic fraction treatment in scenario 1 and 2. (b) Main contributors to the land use impact category of lanfill and organic fraction treatment in scenario 1 and 2 including the biogas market and compost market*

Figure 17 shows the endpoint impact categories scores of the second scenario. All the scores are reduced compared to scenario 1. The score which reduction is the lowest the ecosystems one, where several midpoint impact categories have higher punctuation than in the first scenario. One of this is land use, which has been explained previously and the other are terrestrial acidification and terrestrial ecotoxicity.

Terrestrial acidification increase is due to the composting process [26] that has a punctuation of $1,95\cdot10^{-5}$ (Pt/year)/FU which compensates the reduction of the impact of the landfill process in $2,015\cdot10^{-6}$ and increase the final impact in $1,75\cdot10^{-5}$ (Pt/year)/FU.

Terrestrial ecotoxicity in due to the heat use in the industrial composting. This heat has a punctuation of $1,58\cdot10^{-6}$ (Pt/year)/FU which is compensate by the production of biogas and compost resulting the organic fraction treatment in an overall score of $1,06\cdot10^{-6}$. The reduction of the landfill impact is of $2,81\cdot10^{-7}$ (Pt/year)/FU but the impact of the FORM treatment results in a final increase of $7,79\cdot10^{-7}$ (Pt/year)/FU. However, the rest of the midpoint categories have reduced their impacts thanks to the composting and anaerobic digestion processes. The sum of all of this gives an overall reduction of 9,7% from $9,7\cdot10^{-3}$ to $8,8\cdot10^{-3}$ (Pt/year)/FU.

The resource category has also reduced its impact. This has been explained with the reduction of the midpoint impact category fossil fuel scarcity. In scenario 1 it had an impact of $2,2\cdot10^{-3}$ (Pt/year)/FU while in scenario 2 of $1,9\cdot10^{-3}$ (Pt/year)/FU.

About the human health impact category, the reduction from 0,33 to 0,29 (Pt/year)/FU has come from the reduction of three of the four main impact categories, global warming and human toxicity which have been explained before.

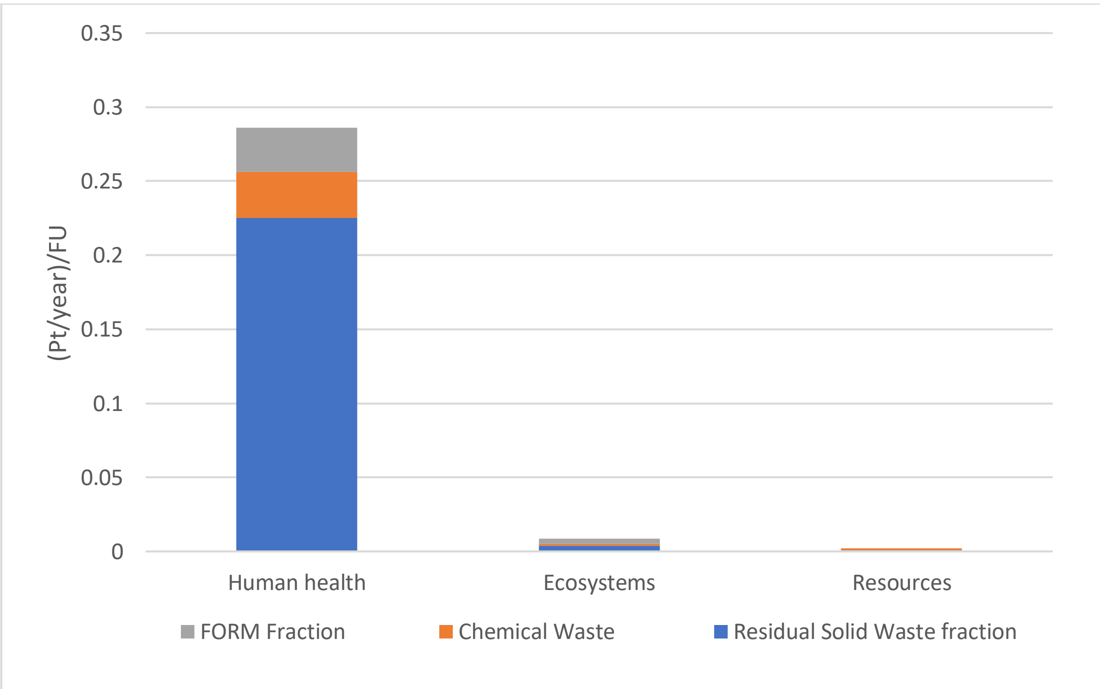


Figure 17. *Weighted impact contribution for endpoint categories of the three groups of waste in scenario 2.*

Figure 18 is shown for a better comparison of both scenarios. The overall score for scenario 1 is of 0,342 (Pt/year)/FU while for scenario 2 is of 0,297 (Pt/year)/FU. This reduction of 13,2% for the second scenario means that performing a selective separation of the FORM fraction results in a more environmentally friendly situation than the actual one.

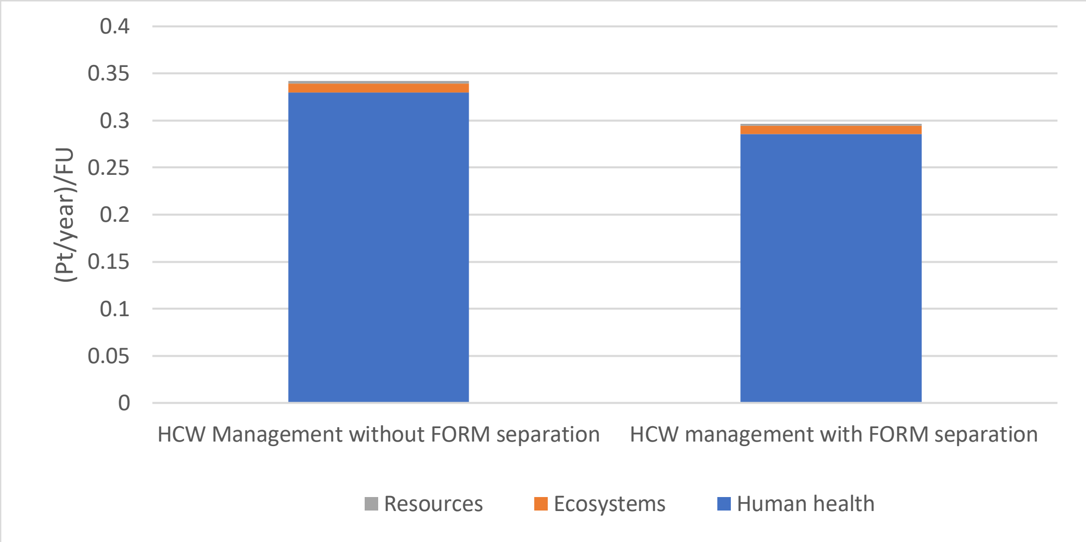


Figure 18. *Endpoint categories comparison for scenario 1 (left) and scenario 2 (right)*

7.2. UNCERTAINTY AND DATA QUALITY ANALYSIS

For the uncertainty determination a Monte Carlo analysis with 10.000 runs has been performed for both scenarios. The results showed that the lowest uncertainty is for mineral and fossil resource scarcity, global warming potential, ozone formation, acidification, land use, terrestrial ecotoxicity, and ionizing radiation with a coefficient of variation (CV) lower than 10%. Eutrophication and human non-carcinogenic toxicity have a higher CV, between 10% and 19%, while freshwater and marine ecotoxicity, and human carcinogenic toxicity have a CV value higher than 40%, Table 15.

Table 15. *Environmental impact for both scenario, standard deviation, and CV*

		Scenario 1			Scenario 2		
Midpoint category	**Unit**	**Average impact per FU**	**Standard deviation**	**CV (%)**	**Average impact per FU**	**Standard deviation**	**CV (%)**
Global warm., Hum. Health	DALY	$5{,}5 \cdot 10^{-6}$	$2{,}93 \cdot 10^{-7}$	5,33	$3{,}91 \cdot 10^{-13}$	$7{,}39 \cdot 10^{-15}$	1,89
Global warm, Terrestrial ecosy.	species·yr	$1{,}7 \cdot 10^{-8}$	$8{,}83 \cdot 10^{-10}$	5,33	$4{,}74 \cdot 10^{-6}$	$8{,}97 \cdot 10^{-8}$	1,89
Global warm, Freshwater ecosy.	species·yr	$4{,}5 \cdot 10^{-13}$	$2{,}41 \cdot 10^{-14}$	5,33	$1{,}43 \cdot 10^{-8}$	$2{,}71 \cdot 10^{-10}$	1,89

Table 15. *Environmental impact of scenario 1, standard deviation, and coefficient of variation (continuation)*

		Scenario 1			Scenario 2		
Midpoint category	**Unit**	**Average impact per FU**	**Standard deviation**	**CV (%)**	**Average impact per FU**	**Standard deviation**	**CV (%)**
Stratosp., ozone depl.	DALY	$3{,}2\cdot10^{-9}$	$3{,}34\cdot10^{-11}$	1,06	$2{,}71\cdot10\text{-}^{9}$	$7{,}23\cdot10^{-11}$	2,67
Ioniz., rad.,	DALY	$9{,}3\cdot10^{-10}$	$1{,}57\cdot10^{-11}$	1,70	$9{,}56\cdot10^{-10}$	$1{,}62\cdot10^{-11}$	1,69
Ozone form., Hum. Health	DALY	$1{,}2\cdot10^{-8}$	$6.68\cdot10^{-11}$	0,55	$1{,}18\cdot10^{-8}$	$6{,}78\cdot10^{-11}$	0,57
Fine parti., mat. Formation	DALY	$7{,}1\cdot10^{-6}$	$6.88\cdot10^{-8}$	0,97	$7{,}16\cdot10^{-6}$	$6{,}95\cdot10^{-8}$	0,97
Ozone form., Terrestrial ecosy.	species·yr	$1{,}8\cdot10^{-9}$	$9.58\cdot10^{-12}$	0,55	$1{,}72\cdot10^{-9}$	$9{,}74\cdot10^{-12}$	0,57
Terrestrial acid.	species·yr	$4{,}9\cdot10^{-9}$	$4.60\cdot10^{-11}$	0,93	$5{,}00\cdot10^{-9}$	$4{,}69\cdot10^{-11}$	0,94
Freswater eut.	species·yr	$6{,}1\cdot10^{-9}$	$1.15\cdot10^{-9}$	18,91	$4{,}72\cdot10^{-9}$	$2{,}79\cdot10^{-10}$	5,92
Marine eut.	species·yr	$4{,}5\cdot10^{-12}$	$5.94\cdot10^{-13}$	13,17	$3{,}35\cdot10^{-12}$	$1{,}45\cdot10^{-13}$	4,32
Terrestrial ecotoc.	species·yr	$3{,}0\cdot10^{-10}$	$3.07\cdot10^{-12}$	1,03	$3{,}00\cdot10^{-10}$	$3{,}04\cdot10^{-12}$	1,01
Freshwater ecotoc.	species·yr	$4{,}3\cdot10^{-10}$	$2.10\cdot10^{-10}$	48,43	$1{,}75\cdot10^{-10}$	$5{,}21\cdot10^{-11}$	29,79
Marine eco.	species·yr	$8{,}9\cdot10^{-11}$	$4.22\cdot10^{-11}$	47,60	$3{,}71\cdot10^{-11}$	$1{,}05\cdot10^{-11}$	28,32
Human carc. Toxicity	DALY	$3{,}4\cdot10^{-6}$	$3.44\cdot10^{-7}$	10,08	$3{,}33\cdot10^{-6}$	$1{,}67\cdot10^{-7}$	5,02
Human non-carc. Toxicity	DALY	$3{,}8\cdot10^{-6}$	$2.04\cdot10^{-6}$	54,45	$1{,}86\cdot10^{-6}$	$5{,}08\cdot10^{-7}$	27,36
Land use	species·yr	$5{,}3\cdot10^{-9}$	$7.18\cdot10^{-11}$	1,35	$5{,}71\cdot10^{-9}$	$7{,}38\cdot10^{-11}$	1,29
Mineral res. Scarcity	USD2013	$2{,}0\cdot10^{-3}$	$1.11\cdot10^{-4}$	5,56	$1{,}86\cdot10^{-3}$	$1{,}11\cdot10^{-4}$	5,94
Fossil res. Scarcity	USD2013	$3{,}1\cdot10^{-1}$	$5.99\cdot10^{-3}$	1,95	$2{,}61\cdot10^{-1}$	$5{,}88\cdot10^{-3}$	2,25

The high CV in human carcinogenic toxicity and freshwater and marine ecotoxicity suggest that the model needs more primary emissions data. This three midpoint impact categories are mainly affected by treatment processes, Figure 7, thus these results shows that more specific data of the emissions of the treatment plants should be obtained. The CV in scenario 2 is lower than for the first scenario, this could be, due to having an extra treatment process, there is more primary data, which reduces the uncertainty. In any case, in Figure C3 and C4 it can be seen that these values does not affect the final data, the endpoint categories have a CV lower than 10%.

Moreover, an uncertainty analysis in the comparison of both scenarios have been performed, Figure 19. The results of this analysis shows that in 100% of the simulations performed the second scenario presents a lower environmental impact that scenario 1. It can be seen that the error bar is the first scenario is always higher than for the scenario 2, thus performing a selective separation of the organic fraction and performing a specific treatment for it is an environmentally friendly option.

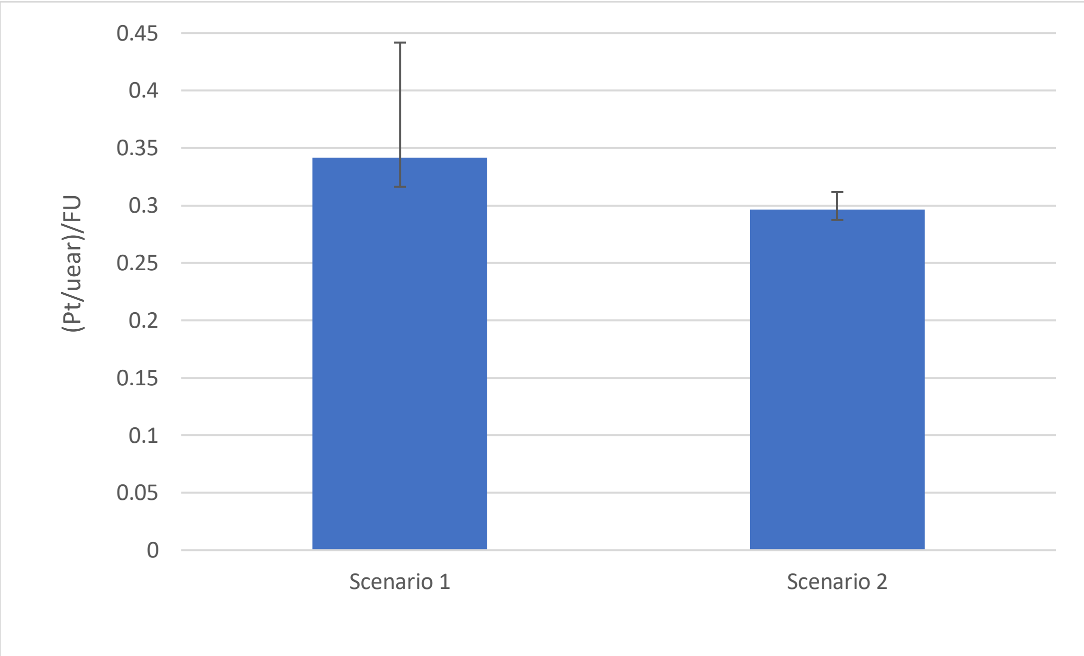


Figure 19. *Uncertainty analysis of the comparison between scenarios 1 and 2*

The results obtained from the environmental analysis are in accordance with the literature search performed in this work. First of all, the distribution of the waste generated by the hospital is in accordance with what has been found in literature where the majority of the waste generated corresponds to the general waste group although is slightly higher being the values found in literature around 50-60% and in this case is of 84%. As Granollers hospital is a medium hospital, it does not produce radioactive waste or a high quantity of chemical waste. Also, infectious waste, 8% is under the usual values, but the majority of the studies are conducted in big hospital so in them the infectious waste is higher as more medical operations are performed. Chemical waste is around the usual values, 8%. Also the composition of the general waste is similar to the one of the annual memory of waste in Spain [56] and other studies [73], [74], [75].

Moreover, the information of the quantities and composition of the healthcare composition has been obtained from official documents from Spain, and part of them (paper, metals, yard) from documents or studies conducted in Catalonia. Information that could not be found has been replaced by the ecoinvent data background which lasted version is from 2021 [36].

Electronic waste modelling has been done with data of a case study conducted in India, but as the total account of this waste is of 0,04% of the total waste it does not have an important effect in the final result. Treatment information also has been taken from official Spain or European documents of best available techniques. The composition of the waste that made up the organic fraction also has been done following European guidelines.

Finally, the results obtained are in accordance with other studies [26], [27] about the most affected midpoint categories as well as the benefits of performing a specific treatment for the organic fraction. It has to be considered that the scores obtained in this analysis are lower compared to other, as other ones consider higher waste quantities as the use other FU. Also, the tendencies follow other studies that by performing adequate selective separation methods the environmental footprint is reduce [24].

7.3. LIFE CYCLE COSTING ANALYSIS

Once the environmental footprint has been analysed a study of the cost of both scenarios was performed. The bar plot of Figure 20 shows the costs of the three stages of the waste management process in both scenarios.

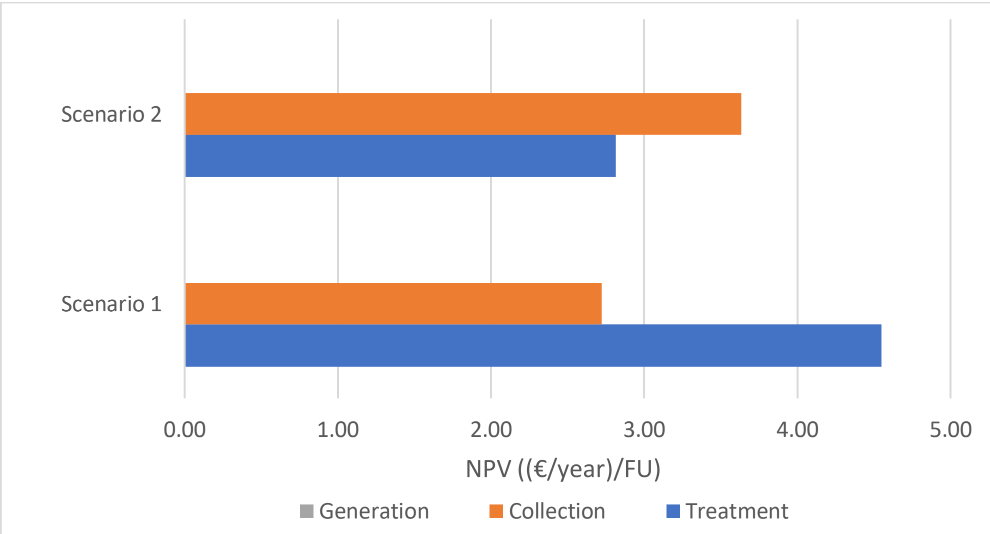


Figure 20. *LCC results of the generation, collection, and treatment stages for both scenarios*

Waste generation cost are 0 in both cases. This is because no information has been possible to find about this step, neither the hospital has provided any. In any case, the costs of waste generation would be constant, as the amount of waste generated does not change when going from scenario 1 to scenario 2.

Moreover, a clear difference between both scenarios can be seen in the collection costs. While in scenario 1 treatment costs accounts for the bulk of the expenditure, 63%. In scenario 2, is the collection costs that accounts for the bulk representing the 56% of the total cost. This difference comes from in the treatment cost from 4,55 (€/year)/FU to 2,82 (€/year)/FU because of the increase in the discount rate due to separating the organic fraction from the rest of the waste. The reduction in total costs comes from the less workload the landfill process has, from 1,16 (kg/year)/FU to 0,28 (kg/year)/FU. This can be seen more clearly in Figure 21 which shows the treatment cost for both scenarios. Landfill process has the highest treatment costs of the three treatments for general waste group, reducing the workload also reduces the overall price of the treatment.

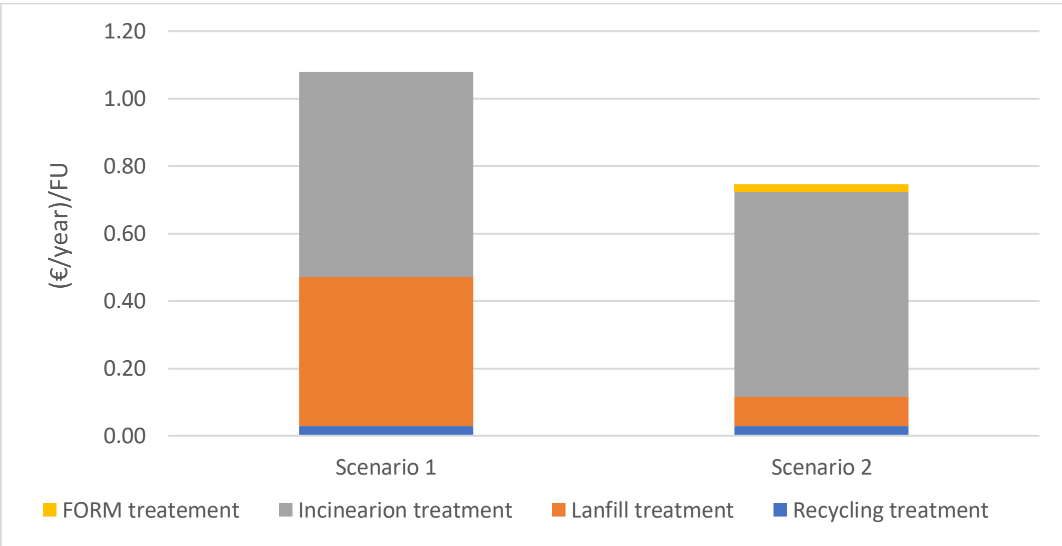


Figure 21. *LCC results in relation to the treatment processes for both scenarios*

For the incineration and recycling treatment their workload has not changed so their cost is maintained constant in both scenarios, 0,61 (€/year)/FU for the incineration treatment and 0,03 (€/year)/FU for the recycling process.

Although in scenario 2 an extra process is introduced, the organic fraction treatment is not an expensive process, as is not energy demanding. As it has been explained before, part of the biogas produced is use for generating electricity for self-consume, so the process is cheaper than incineration process that is very energy demand.

On the other hand, the NPV of the collection cost increases, from 2,72 (€/year)/FU to 3,63 (€/year)/FU. The increase is because the need of an extra employee to be able to manage the organic fraction selectively separated. In Figure 22 It can be seen the relation between different variables that affect the collection costs.

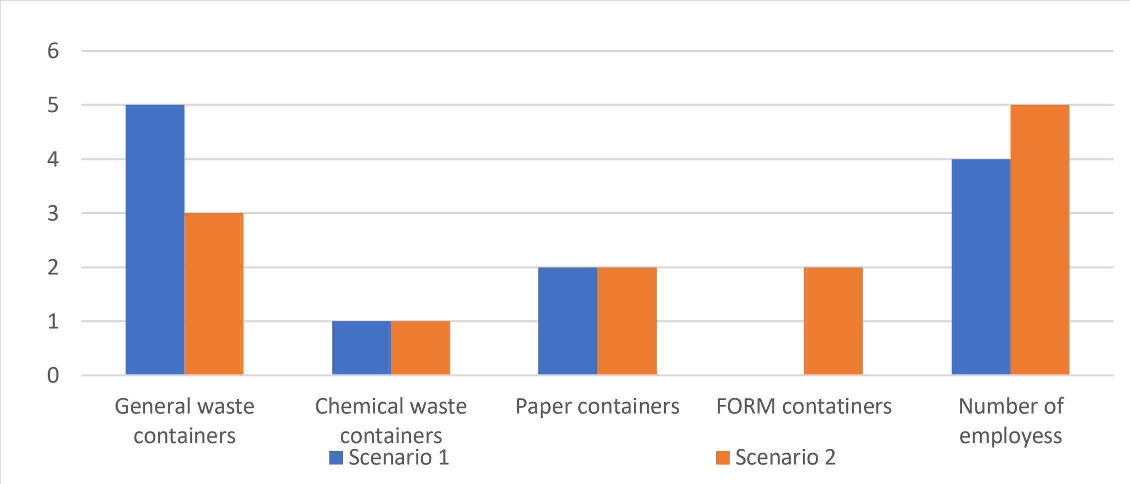


Figure 22. *Container and number of employees for scenario 1 and scenario 2*

In scenario 1 the number of containers for the general waste group is of 5, while in scenario 2 is of 3. These two containers are used for the organic fraction separated and as an extra activity is conducted in the hospital more workers will be needed, in this case 1 extra employee. The need of hiring one extra worker is the reason of the increasing price in the collection costs. Furthermore, containers that are no longer used to store waste from the general waste group and are used to store FORM waste also have a lower cost, due to the reductions granted by Barcelona City Council. So, this also contributes to reducing the cost of the treatment stage.

In Figure 23 shows a bar plot with the total costs, Equation 8, and environmental cost for both scenarios. As it has been showing the overall cost of scenario 2 is lower than the one of scenario 1 as it shown in Figure 22 where the total costs is reduced from 7,27 (€/year)/FU to 6,45 (€/year)/FU thanks to the selective separation of the organic fraction from the general waste group.

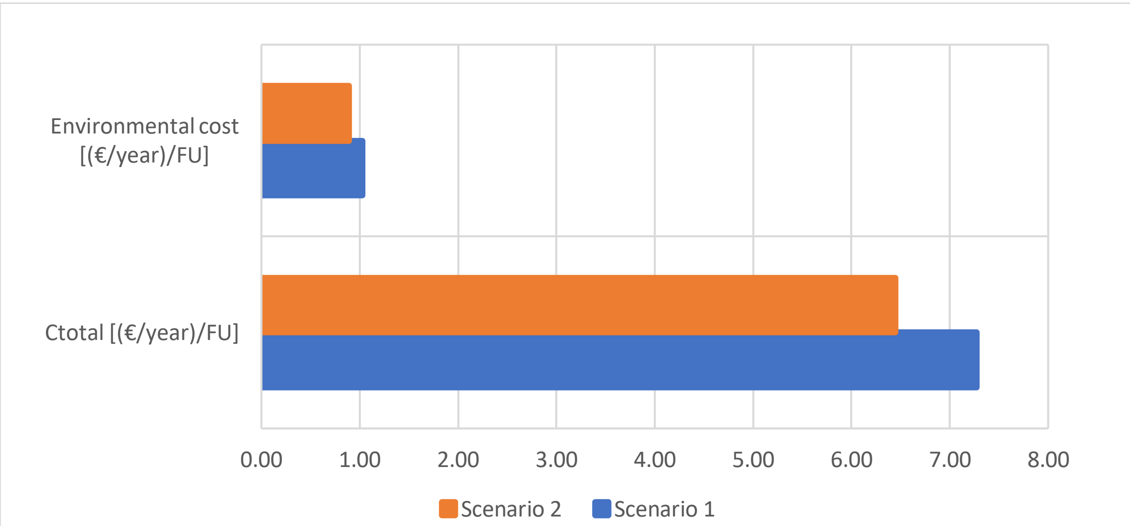


Figure 23. *Net and environmental cost for scenario 1 and scenario 2*

The environmental costs are also reduced thanks to the FORM treatment that reduces the total emissions of CO_2 from 5,22 (kg/year)/FU to 4,37 (kg/year)/FU and CH_4 emissions from 0,036 to 0,017 (kg/year)/FU. This effect is shown in the reduction of the cost from 1,02 to 0,89 (€/year)/FU. Moreover, this environmental cost could be considered as the cost of waste generation as this stage is one that contributes the most to the overall environmental impact.

7.4. OPTIMIZATION ANALYSIS

In the optimization analysis, as it has been explained previously, it has been studied the effect in the total cost of separating other fractions, glass, plastic, and debris. Another objective of this study was if still separating the organic fraction, if other fractions are also separated, is economically profitable. So, the starting point for this optimization analysis would be scenario 1, previously explained. Results are shown in the spider chart of Figure 24 in which also scenario 2 is included to be able to make a better comparison between the results obtained.

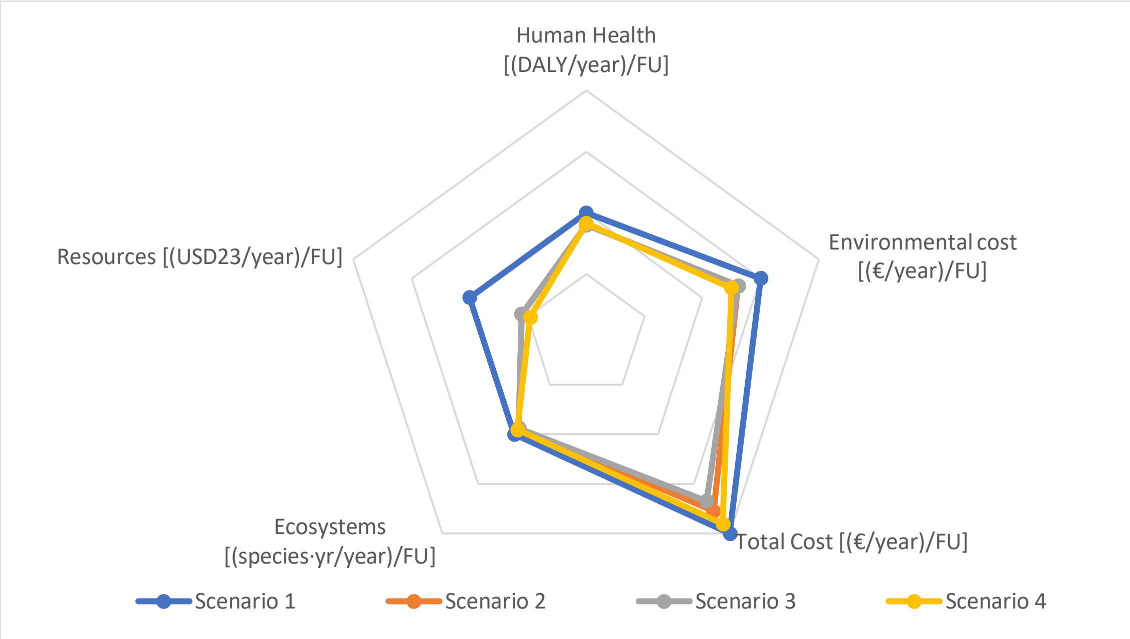


Figure 24. *Spider chart of the 4 scenarios analysed. Values go in ascending other from the centre to the edge*

As has been argue so far, scenario 2 compared to scenario 1 is economically and environmentally better. Scenario 3 evaluated if selective separation of plastic and glass was economically favourable. The results showed that performing a selective separation is more economic, but only selectively separating glass. The total cost is reduced from 7,27 (€/year)/FU of scenario 1 to 6,09 (€/year)/FU. Comparing it to scenario 2 the price is reduced in 0,83 (€/year)/FU. The main factors that affect this value are shown in Figure 25.

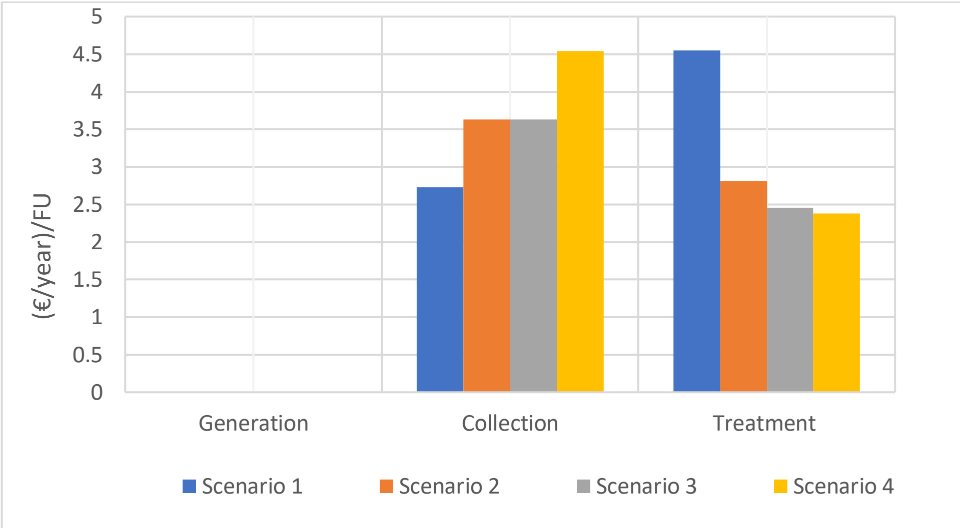


Figure 25. *Breakdown of the generation, treatment, and collection costs of the 4 scenarios analysed*

Figure 25 shows the breakdown of the three stages of the waste management process for the four scenarios analysed. Here it can be seen that the differences between scenario 2 and scenario 3 is the price in the treatment stage that is reduce from 2,46 to 2,38 (€/year)/FU. This result comes from adding the reducing factor of separating glass, 0,25%. Although the factor of separating plastic is higher 0,5%, the quantity of glass is higher than the one of plastic 0,32 and 0,27 (kg/year)/FU respectively, so if the plastic would be separated instead of the glass, an extra container for non-selective separation would be needed. Therefore, hiring an extra worker should be done, resulting in an increase in treatment and collection costs.

On the other hand, no transfer of mass has been performed from one treatment process to other so the environmental impacts and their monetary value that does not increase, neither decrease between scenario 2 and 3. Transportation does not contribute significantly to the environmental impact so although one more trip has to be done in scenario 3, this does not affect the overall environmental impact, neither the environmental cost.

Scenario 4 of Figure 24 resembles the one where also the construction and demolition waste is separated. Part of the debris is suitable for going into recycling process such as asphalt or ceramics, etc, as has been mentioned earlier. Looking at table 12, out of the total construction and demolition waste, following the information found in literature [43], [44], 80% of it can be recycle.

From the information shown in Figure 24 it can be seen that the overall net cost of scenario 4 is lower than scenario 1 but higher than scenario 2 and 3, being of 6,92 (€/year)/FU. Figure 25 shows that this difference in price comes from the collection stage. Due to selective separating the debris from the rest of the waste, an extra container has to be added. Also, not only debris, but plastic is selectively separated in this scenario so one more selective separation has to be carried out, compared to scenario 3. More staff must be hire in order to perform this extra activity which leads to increase the collection stage cost up to 4,54 (€/year)/FU. A more visual representation of how many containers are needed for each waste fraction and the number of employees for each scenario in shown in Figure 26.

Looking at Figure 26, in scenario 4 the plastic is separated and the glass not, in contrast to scenario 3. This happens because in scenario 3 as mentioned separating glass would mean more collection and treatment costs. In scenario 4 the debris is separated, reducing the quantity of the general waste fraction, so although glass is in higher quantity than plastic it does not suppose an extra container, neither more staff, as it would happen in the third scenario. Furthermore, the separation of plastic is promoted by a higher reduction factor than the one of the glass residues.

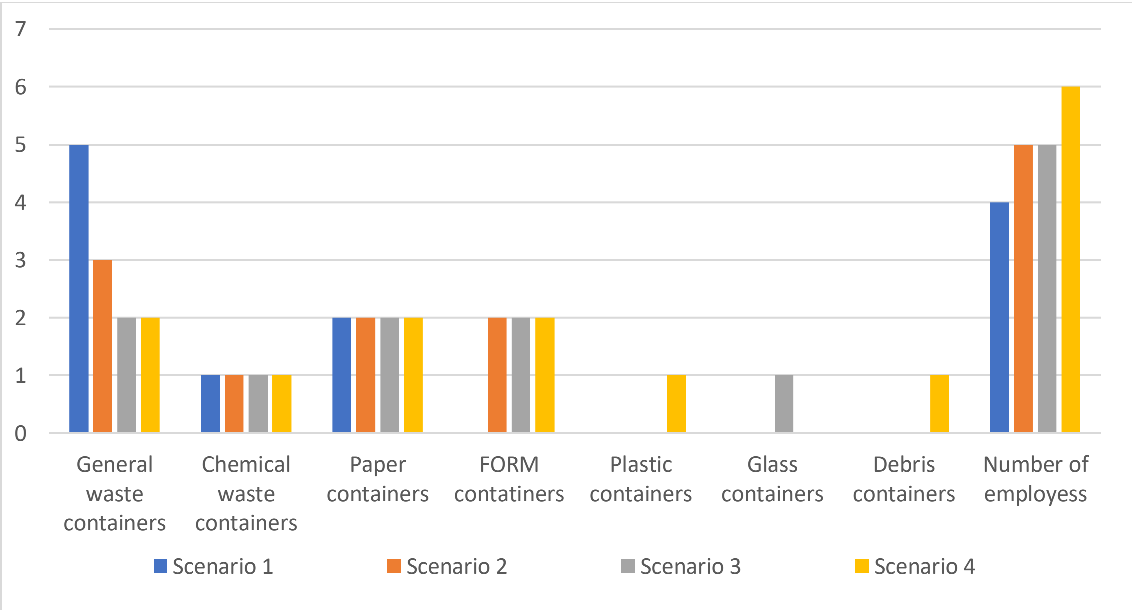


Figure 26. *Container and number of employees for 4 scenarios analysed*

On the other hand, although in scenario 4 one more worker is needed than for scenario 1, the total cost in lower for the fourth scenario. This happens because treatment costs are lower than for scenario 1, Figure 25, and thus compensate the increase in the collection cost. This decrease in the treatment cost comes from the reduction of due to the selective separation of the plastic, and due to the reduction in the cost of treatment processes.

In the other scenarios all the construction waste goes to landfill, but in this last scenario most of goes to recycling process and a small part to FORM treatment reducing the landfill workload to 0,04 (kg/year)/FU. Both, FORM, and recycling process are cheaper than landfill so the increase in workload for these two treatments does not compensate the price of landfill and thus the treatment cost is lower, 0,67 (€/year)/FU, for scenario 4 reducing the overall net cost.

Environmental costs has also been reduced from 0,89 to 0,85 (€/year)/FU. This is due to recycling process and FORM treatment being two treatments that have low emissions of methane, carbon dioxide, and dinitrogen monoxide compared to landfilling. Increasing the workload of these two processes has resulted in lower emissions of these three pollutants.

However, the environmental impact has increased. The three endpoint categories have increased its values compared to scenarios 2 and 3, but still is more environmentally friendly than scenario 1.

As it was explained before, recycling process has a significant impact in human carcinogenic toxicity midpoint impact category due to emissions of chromium (IV) so increasing its workload may have increase the emissions of this substances that is the major contributor to this impact. Also, FORM treatment has a positive score in fine particle matter formation, although it reduces the impact in human non-carcinogenic category, but the sum of the increase in these two midpoint categories compensate are enough to result in an increase in human health category its value from $5{,}27\cdot10^{-5}$ (DALY/year)/FU to $5{,}35\cdot10^{-5}$ (DALY/year)/FU.

Ecosystem endpoint category has increase from $4{,}56\cdot10^{-7}$ to $4{,}65\cdot10^{-7}$ [(species·yr)/year]/FU. This increase may be due to the impact of both treatments in the midpoint impact categories related to this endpoint one. For example, recycling process increase the impact in freshwater eutrophication due to the emissions of phosphate, while FORM treatment has a negative impact for the environment in terrestrial acidification midpoint category because of emissions of nitrogen and sulphur oxides.

On the other hand, the resource scarcity endpoint category reduce its impact. This reduction comes from the save in conventional fossil fuels due to the FORM treatment as has been explained before.

The use of conventional fuels increase because of recycling treatment, the energy used is from the electrical grid, but also reduces the impact in mineral resource scarcity. The reduce in this midpoint impact category comes from saving the extraction of more minerals due to these ones being reuse. This compensates the increase of use of fossil fuels and therefore the final impact of the endpoint category is reduced from 0,225 to 0,195 (USD23/year)/FU.

8. CONCLUSIONS

In the present work an LCA and LCC has been performed in order to evaluate the actual situation of the waste management process of Granollers hospital and present several alternative scenarios. The LCA study has been conduct with a hierarchist perspective, using as functional unit the quantity of waste generated by one inhabitant inside the area of influence of the hospital, which would be relate to the waste produced by 0,001 occupied beds. The study included three stages, waste generation, collection, and treatment, and it showed that the main midpoint impact categories affected were global warming potential, fine particulate matter formation and human toxicity. Also, the uncertainty analysis conducted to validate the model shows that 16 out of the 19 midpoint categories has a low uncertainty, while for freshwater and marine ecotoxicity, and human non-carcinogenic impact categories more primary data should be obtained.

Result showed that performing a selective separation of the organic fraction and delivering it to an appropriate treatment reduce the environmental impact by 0,045 (Pt/year)/FU or 45,17 Pt/year per bed occupied. This separation also has economic benefits by reducing the waste management cost in 0,82 (€/year)/FU or 820 € per occupied bed, thanks to the reducing factors offered by the local community.

Furthermore, the two other scenarios analysed with the objective of reducing the total costs of the waste process resulted that separating selectively glass, FORM and paper reduces the cost. Scenario 3, in which an extra fraction is separated has the lowest net cost, 6.090 € per bed occupied, with the same environmental impact as scenario two. In Scenario 4, in which the plastic and debris is not separated is more expensive that scenario 3, 6.920 € per bed occupied, and its environmental impact is higher than in the second scenario due to increase workload in recycling treatment, which has some important environmental impacts such as the emission of chromium (VI). So, for an improvement of the hospital waste management, scenario 3 should be chosen as is the one that is cheaper than the actual one and has the lowest environmental impact.

Finally, this work has shown how performing an LCA and LCC studies can help organisations optimise their processes to be more environmentally friendly and economic. Additionally, currently most of the studies of waste management process focus on the infectious waste of the hospital, but this work has demonstrated that the general waste that can be treated as MSW is the major contributor to the environmental impact and thus more studies focus on this fraction should be performed.

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ANNEX A

A1. SCENARIO 1 ENVIRONMENTAL ANALYSIS

Table A1. *Midpoint category results of the environmental analysis results of each waste fraction (includes waste generation, collection, and treatment for each fraction)*

Midpoint impact category	Unit	Total	General waste	Chemical waste
Global warm., Hum. health	Pt	$9{,}17\cdot10^{-2}$	$7{,}63\cdot10^{-2}$	$1{,}54\cdot10^{-2}$
Global warm, Terrestrial ecosy.	Pt	$4{,}48\cdot10^{-3}$	$3{,}73\cdot10^{-3}$	$7{,}54\cdot10^{-4}$
Global warm, Freshwater ecosy.	Pt	$1{,}23\cdot10^{-7}$	$1{,}02\cdot10^{-7}$	$2{,}06\cdot10^{-8}$
Stratosp., ozone depl.	Pt	$5{,}28\cdot10^{-5}$	$5{,}08\cdot10^{-5}$	$2{,}00\cdot10^{-6}$
Ioniz., rad.,	Pt	$1{,}55\cdot10^{-5}$	$1{,}55\cdot10^{-5}$	$-1{,}84\cdot10^{-8}$
Ozone form., Hum. Health	Pt	$2{,}02\cdot10^{-4}$	$1{,}83\cdot10^{-4}$	$1{,}85\cdot10^{-5}$
Fine parti., mat. Formation	Pt	$1{,}18\cdot10^{-1}$	$1{,}09\cdot10^{-1}$	$9{,}32\cdot10^{-3}$
Ozone form., Tererrestrial ec.	Pt	$4{,}75\cdot10^{-4}$	$4{,}30\cdot10^{-4}$	$4{,}51\cdot10^{-5}$
Terrestrial acid.	Pt	$1{,}34\cdot10^{-3}$	$1{,}23\cdot10^{-3}$	$1{,}03\cdot10^{-4}$
Freswater eut.	Pt	$1{,}64\cdot10^{-3}$	$1{,}56\cdot10^{-3}$	$7{,}61\cdot10^{-5}$
Marine eut.	Pt	$1{,}22\cdot10^{-6}$	$1{,}21\cdot10^{-6}$	$7{,}62\cdot10^{-9}$
Terrestrial ecotoc.	Pt	$8{,}03\cdot10^{-5}$	$7{,}42\cdot10^{-5}$	$6{,}11\cdot10^{-6}$
Freshwater ecotoc.	Pt	$1{,}16\cdot10^{-4}$	$1{,}13\cdot10^{-4}$	$3{,}09\cdot10^{-6}$
Marine eco.	Pt	$2{,}38\cdot10^{-5}$	$2{,}32\cdot10^{-5}$	$6{,}51\cdot10^{-7}$
Human carc. Toxicity	Pt	$5{,}70\cdot10^{-2}$	$5{,}30\cdot10^{-2}$	$3{,}97\cdot10^{-3}$
Human non-carc. Toxicity	Pt	$6{,}20\cdot10^{-2}$	$6{,}01\cdot10^{-2}$	$1{,}95\cdot10^{-3}$
Land use	Pt	$1{,}43\cdot10^{-3}$	$1{,}39\cdot10^{-3}$	$4{,}23\cdot10^{-5}$
Mineral res. Scarcity	Pt	$1{,}42\cdot10^{-5}$	$7{,}08\cdot10^{-7}$	$1{,}35\cdot10^{-5}$
Fossil res. Scarcity	Pt	$2{,}19\cdot10^{-3}$	$1{,}23\cdot10^{-3}$	$9{,}60\cdot10^{-4}$

Table A2. *Midpoint category results of the environmental analysis results of each waste collection process stage*

Midpoint impact category	Unit	Total	Generation	Collection	Treatment
Global warm., Hum. health	Pt	$9{,}17\cdot10^{-2}$	$7{,}17\cdot10^{-2}$	0	$2{,}00\cdot10^{-2}$
Global warm, Terrestrial ecosy.	Pt	$4{,}48\cdot10^{-3}$	$3{,}51\cdot10^{-3}$	0	$9{,}77\cdot10^{-4}$
Global warm, Freshwater ecosy.	Pt	$1{,}23\cdot10^{-7}$	$9{,}58\cdot10^{-8}$	0	$2{,}67\cdot10^{-8}$
Stratosp., ozone depl.	Pt	$5{,}28\cdot10^{-5}$	$5{,}14\cdot10^{-5}$	0	$1{,}42\cdot10^{-6}$
Ioniz., rad.,	Pt	$1{,}55\cdot10^{-5}$	$1{,}51\cdot10^{-5}$	0	$4{,}24\cdot10^{-7}$
Ozone form., Hum. Health	Pt	$2{,}02\cdot10^{-4}$	$2{,}06\cdot10^{-4}$	0	$-4{,}47\cdot10^{-6}$
Fine parti., mat. Formation	Pt	$1{,}18\cdot10^{-1}$	$1{,}11\cdot10^{-1}$	0	$7{,}16\cdot10^{-3}$
Ozone form., Tererrestrial ec.	Pt	$4{,}75\cdot10^{-4}$	$4{,}91\cdot10^{-4}$	0	$-1{,}53\cdot10^{-5}$
Terrestrial acid.	Pt	$1{,}34\cdot10^{-3}$	$1{,}14\cdot10^{-3}$	0	$1{,}98\cdot10^{-4}$
Freswater eut.	Pt	$1{,}64\cdot10^{-3}$	$1{,}01\cdot10^{-3}$	0	$6{,}28\cdot10^{-4}$

Table A2. *Midpoint category results of the environmental analysis results of each waste collection process stage (continuation)*

Midpoint impact category	Unit	Total	Generation	Collection	Treatment
Marine eut.	Pt	$1{,}22\cdot10^{-6}$	$5{,}44\cdot10^{-7}$	0	$6{,}75\cdot10^{-7}$
Terrestrial ecotoc.	Pt	$8{,}03\cdot10^{-5}$	$9{,}00\cdot10^{-5}$	0	$-9{,}73\cdot10^{-6}$
Freshwater ecotoc.	Pt	$1{,}16\cdot10^{-4}$	$3{,}47\cdot10^{-5}$	0	$8{,}16\cdot10^{-5}$
Marine eco.	Pt	$2{,}38\cdot10^{-5}$	$7{,}34\cdot10^{-6}$	0	$1{,}65\cdot10^{-5}$
Human carc. Toxicity	Pt	$5{,}70\cdot10^{-2}$	$1{,}11\cdot10^{-2}$	0	$4{,}59\cdot10^{-2}$
Human non-carc. Toxicity	Pt	$6{,}20\cdot10^{-2}$	$1{,}87\cdot10^{-2}$	0	$4{,}33\cdot10^{-2}$
Land use	Pt	$1{,}43\cdot10^{-3}$	$5{,}79\cdot10^{-3}$	0	$-4{,}36\cdot10^{-3}$
Mineral res. Scarcity	Pt	$1{,}42\cdot10^{-5}$	$5{,}00\cdot10^{-5}$	0	$-3{,}58\cdot10^{-5}$
Fossil res. Scarcity	Pt	$2{,}19\cdot10^{-3}$	$3{,}86\cdot10^{-3}$	0	$-1{,}67\cdot10^{-3}$

Table A3. *Midpoint category results of the environmental analysis results of each treatment process*

Midpoint impact category	Unit	Total	Recycling	Incineration	Landfill
Global warm., Hum. health	Pt	$9{,}17\cdot10^{-2}$	$-2{,}51\cdot10^{-4}$	$7{,}81\cdot10^{-3}$	$1{,}24\cdot10^{-2}$
Global warm, Terrestrial ecosy.	Pt	$4{,}48\cdot10^{-3}$	$-1{,}26\cdot10^{-5}$	$3{,}82\cdot10^{-4}$	$6{,}07\cdot10^{-4}$
Global warm, Freshwater ecosy.	Pt	$1{,}23\cdot10^{-7}$	$-3{,}33\cdot10^{-10}$	$1{,}04\cdot10^{-8}$	$1{,}66\cdot10^{-8}$
Stratosp., ozone depl.	Pt	$5{,}28\cdot10^{-5}$	$6{,}35\cdot10^{-8}$	$9{,}01\cdot10^{-7}$	$4{,}54\cdot10^{-7}$
Ioniz., rad.,	Pt	$1{,}55\cdot10^{-5}$	$1{,}44\cdot10^{-6}$	$-1{,}03\cdot10^{-6}$	$1{,}22\cdot10^{-8}$
Ozone form., Hum. Health	Pt	$2{,}02\cdot10^{-4}$	$-9{,}70\cdot10^{-6}$	$4{,}73\cdot10^{-6}$	$4{,}62\cdot10^{-7}$
Fine parti., mat. Formation	Pt	$1{,}18\cdot10^{-1}$	$2{,}31\cdot10^{-3}$	$4{,}65\cdot10^{-3}$	$1{,}94\cdot10^{-4}$
Ozone form., Tererrestrial ec.	Pt	$4{,}75\cdot10^{-4}$	$-2{,}75\cdot10^{-5}$	$1{,}10\cdot10^{-5}$	$1{,}08\cdot10^{-6}$
Terrestrial acid.	Pt	$1{,}34\cdot10^{-3}$	$1{,}56\cdot10^{-4}$	$3{,}90\cdot10^{-5}$	$2{,}66\cdot10^{-6}$
Freswater eut.	Pt	$1{,}64\cdot10^{-3}$	$1{,}45\cdot10^{-4}$	$5{,}94\cdot10^{-5}$	$4{,}23\cdot10^{-4}$
Marine eut.	Pt	$1{,}22\cdot10^{-6}$	$2{,}63\cdot10^{-7}$	$4{,}36\cdot10^{-9}$	$4{,}07\cdot10^{-7}$
Terrestrial ecotoc.	Pt	$8{,}03\cdot10^{-5}$	$-1{,}22\cdot10^{-5}$	$2{,}13\cdot10^{-6}$	$3{,}71\cdot10^{-7}$
Freshwater ecotoc.	Pt	$1{,}16\cdot10^{-4}$	$-7{,}28\cdot10^{-6}$	$1{,}64\cdot10^{-6}$	$8{,}73\cdot10^{-5}$
Marine eco.	Pt	$2{,}38\cdot10^{-5}$	$-1{,}27\cdot10^{-6}$	$3{,}53\cdot10^{-7}$	$1{,}74\cdot10^{-5}$
Human carc. Toxicity	Pt	$5{,}70\cdot10^{-2}$	$4{,}15\cdot10^{-2}$	$3{,}49\cdot10^{-3}$	$9{,}09\cdot10^{-4}$
Human non-carc. Toxicity	Pt	$6{,}20\cdot10^{-2}$	$4{,}03\cdot10^{-3}$	$1{,}23\cdot10^{-3}$	$3{,}80\cdot10^{-2}$
Land use	Pt	$1{,}43\cdot10^{-3}$	$-4{,}40\cdot10^{-3}$	$4{,}17\cdot10^{-5}$	$6{,}17\cdot10^{-6}$
Mineral res. Scarcity	Pt	$1{,}42\cdot10^{-5}$	$-3{,}62\cdot10^{-5}$	$3{,}39\cdot10^{-7}$	$4{,}28\cdot10^{-8}$
Fossil res. Scarcity	Pt	$2{,}19\cdot10^{-3}$	$-1{,}75\cdot10^{-3}$	$7{,}58\cdot10^{-5}$	$2{,}00\cdot10^{-6}$

Table A4. *Endpoint category results of the environmental analysis results of each waste fraction (includes waste generation, collection, and treatment for each fraction)*

	Unidad	Total	General waste	Chemical waste
Total	Pt	0,342	0,309	0,033
Human health	Pt	0,330	0,299	0,031
Ecosystems	Pt	0,010	0,009	0,001
Resources	Pt	0,002	0,001	0,001

A2. SCENARIO 2 ENVIRONMENTAL ANALYSIS

Table A5. *Midpoint category results of the environmental analysis results of each waste fraction (includes waste generation, collection, and treatment for each fraction)*

Midpoint impact category	Unit	Total	Residual waste	Chemical waste	FORM fraction
Global warm., Hum. health	Pt	$7,91·10^{-2}$	$5,40·10^{-2}$	$1,54·10^{-2}$	$9,63·10^{-3}$
Global warm, Terrestrial ecosy.	Pt	$3,87·10^{-3}$	$2,64·10^{-3}$	$7,54·10^{-4}$	$4,71·10^{-4}$
Global warm, Freshwater ecosy.	Pt	$1,06·10^{-7}$	$7,22·10^{-8}$	$2,06·10^{-8}$	$1,29·10^{-8}$
Stratosp., ozone depl.	Pt	$4,52·10^{-5}$	$2,02·10^{-5}$	$2,00·10^{-6}$	$2,30·10^{-5}$
Ioniz., rad.,	Pt	$1,59·10^{-5}$	$1,33·10^{-5}$	$-1,84·10^{-8}$	$2,62·10^{-6}$
Ozone form., Hum. Health	Pt	$1,97·10^{-4}$	$1,19·10^{-4}$	$1,85·10^{-5}$	$6,04·10^{-5}$
Fine parti., mat. Formation	Pt	$1,19·10^{-1}$	$8,80·10^{-2}$	$9,32·10^{-3}$	$2,21·10^{-2}$
Ozone form., Tererrestrial ec.	Pt	$4,65·10^{-4}$	$2,78·10^{-4}$	$4,51·10^{-5}$	$1,41·10^{-4}$
Terrestrial acid.	Pt	$1,35·10^{-3}$	$8,42·10^{-4}$	$1,03·10^{-4}$	$4,08·10^{-4}$
Freswater eut.	Pt	$1,28·10^{-3}$	$7,44·10^{-4}$	$7,61·10^{-5}$	$4,56·10^{-4}$
Marine eut.	Pt	$9,06·10^{-7}$	$4,33·10^{-7}$	$7,62·10^{-9}$	$4,65·10^{-7}$
Terrestrial ecotoc.	Pt	$8,11·10^{-5}$	$6,64·10^{-5}$	$6,11·10^{-6}$	$8,60·10^{-6}$
Freshwater ecotoc.	Pt	$4,74·10^{-5}$	$4,24·10^{-5}$	$3,09·10^{-6}$	$1,96·10^{-6}$
Marine eco.	Pt	$1,01·10^{-5}$	$8,87·10^{-6}$	$6,51·10^{-7}$	$5,38·10^{-7}$
Human carc. Toxicity	Pt	$5,56·10^{-2}$	$5,35·10^{-2}$	$3,97·10^{-3}$	$-1,85·10^{-3}$
Human non-carc. Toxicity	Pt	$3,11·10^{-2}$	$2,98·10^{-2}$	$1,95·10^{-3}$	$-6,43·10^{-4}$
Land use	Pt	$1,54·10^{-3}$	$-7,31·10^{-4}$	$4,23·10^{-5}$	$2,23·10^{-3}$
Mineral res. Scarcity	Pt	$1,33·10^{-5}$	$-4,26·10^{-6}$	$1,35·10^{-5}$	$4,03·10^{-6}$
Fossil res. Scarcity	Pt	$1,86·10^{-3}$	$9,52·10^{-4}$	$9,60·10^{-4}$	$-4,77·10^{-5}$

Table A6. *Midpoint category results of the environmental analysis results of each waste collection process stage*

Midpoint impact category	Unit	Total	Generation	Collection	Treatment
Global warm., Hum. health	Pt	$7,91·10^{-2}$	$2,31·10^{-1}$	0	$7,36·10^{-3}$
Global warm, Terrestrial ecosy.	Pt	$3,87·10^{-3}$	$7,17·10^{-2}$	0	$3,60·10^{-4}$
Global warm, Freshwater ecosy.	Pt	$1,06·10^{-7}$	$3,51·10^{-3}$	0	$9,83·10^{-9}$
Stratosp., ozone depl.	Pt	$4,52·10^{-5}$	$9,58·10^{-8}$	0	$-6,17·10^{-6}$
Ioniz., rad.,	Pt	$1,59·10^{-5}$	$5,14·10^{-5}$	0	$8,90·10^{-7}$
Ozone form., Hum. Health	Pt	$1,97·10^{-4}$	$1,51·10^{-5}$	0	$-8,96·10^{-6}$
Fine parti., mat. Formation	Pt	$1,19·10^{-1}$	$2,06·10^{-4}$	0	$8,24·10^{-3}$
Ozone form., Tererrestrial ec.	Pt	$4,65·10^{-4}$	$1,11·10^{-1}$	0	$-2,59·10^{-5}$
Terrestrial acid.	Pt	$1,35·10^{-3}$	$4,91·10^{-4}$	0	$2,15·10^{-4}$
Freswater eut.	Pt	$1,28·10^{-3}$	$1,14·10^{-3}$	0	$2,63·10^{-4}$
Marine eut.	Pt	$9,06·10^{-7}$	$1,01·10^{-3}$	0	$3,62·10^{-7}$
Terrestrial ecotoc.	Pt	$8,11·10^{-5}$	$5,44·10^{-7}$	0	$-8,95·10^{-6}$
Freshwater ecotoc.	Pt	$4,74·10^{-5}$	$9,00·10^{-5}$	0	$1,28·10^{-5}$
Marine eco.	Pt	$1,01·10^{-5}$	$3,47·10^{-5}$	0	$2,71·10^{-6}$
Human carc. Toxicity	Pt	$5,56·10^{-2}$	$7,34·10^{-6}$	0	$4,45·10^{-2}$
Human non-carc. Toxicity	Pt	$3,11·10^{-2}$	$1,11·10^{-2}$	0	$1,23·10^{-2}$
Land use	Pt	$1,54·10^{-3}$	$1,87·10^{-2}$	0	$-4,25·10^{-3}$
Mineral res. Scarcity	Pt	$1,33·10^{-5}$	$5,79·10^{-3}$	0	$-3,67·10^{-5}$
Fossil res. Scarcity	Pt	$1,86·10^{-3}$	$5,00·10^{-5}$	0	$-2,00·10^{-3}$

Table A7. *Midpoint category results of the environmental analysis results of each treatment process*

Midpoint impact category	Unit	Total	Recycling	Incineration	Landfill	FORM treatment
Global warm., Hum. health	Pt	$7,91·10^{-2}$	$-2,51·10^{-4}$	$7,81·10^{-3}$	$4,02·10^{-9}$	$-4,30·10^{-9}$
Global warm, Terrestrial ecosy.	Pt	$3,87·10^{-3}$	$-1,26·10^{-5}$	$3,82·10^{-4}$	$1,10·10^{-7}$	$-7,25·10^{-6}$
Global warm, Freshwater ecosy.	Pt	$1,06·10^{-7}$	$-3,33·10^{-10}$	$1,04·10^{-8}$	$2,96·10^{-9}$	$4,75·10^{-7}$
Stratosp., ozone depl.	Pt	$4,52·10^{-5}$	$6,35·10^{-8}$	$9,01·10^{-7}$	$1,12·10^{-7}$	$-4,15·10^{-6}$
Ioniz., rad.,	Pt	$1,59·10^{-5}$	$1,44·10^{-6}$	$-1,03·10^{-6}$	$4,71·10^{-5}$	$1,22·10^{-3}$
Ozone form., Hum. Health	Pt	$1,97·10^{-4}$	$-9,70·10^{-6}$	$4,73·10^{-6}$	$2,62·10^{-7}$	$-9,76·10^{-6}$
Fine parti., mat. Formation	Pt	$1,19·10^{-1}$	$2,31·10^{-3}$	$4,65·10^{-3}$	$6,45·10^{-7}$	$1,95·10^{-5}$
Ozone form., Tererrestrial ec.	Pt	$4,65·10^{-4}$	$-2,75·10^{-5}$	$1,10·10^{-5}$	$1,03·10^{-4}$	$-4,43·10^{-5}$
Terrestrial acid.	Pt	$1,35·10^{-3}$	$1,56·10^{-4}$	$3,90·10^{-5}$	$9,87·10^{-8}$	$-4,56·10^{-9}$

Table A7. *Midpoint category results of the environmental analysis results of each treatment process (continuation)*

Midpoint impact category	Unit	Total	Recycling	Incineration	Landfill	FORM treatment
Freswater eut.	Pt	$1{,}28 \cdot 10^{-3}$	$1{,}45 \cdot 10^{-4}$	$5{,}94 \cdot 10^{-5}$	$9{,}00 \cdot 10^{-8}$	$1{,}06 \cdot 10^{-6}$
Marine eut.	Pt	$9{,}06 \cdot 10^{-7}$	$2{,}63 \cdot 10^{-7}$	$4{,}36 \cdot 10^{-9}$	$2{,}12 \cdot 10^{-5}$	$-2{,}75 \cdot 10-^{6}$
Terrestrial ecotoc.	Pt	$8{,}11 \cdot 10^{-5}$	$-1{,}22 \cdot 10^{-5}$	$2{,}13 \cdot 10^{-6}$	$4{,}22 \cdot 10^{-6}$	$-5{,}91 \cdot 10^{-7}$
Freshwater ecotoc.	Pt	$4{,}74 \cdot 10^{-5}$	$-7{,}28 \cdot 10^{-6}$	$1{,}64 \cdot 10^{-6}$	$2{,}21 \cdot 10^{-4}$	$-6{,}79 \cdot 10^{-4}$
Marine eco.	Pt	$1{,}01 \cdot 10^{-5}$	$-1{,}27 \cdot 10^{-6}$	$3{,}53 \cdot 10^{-7}$	$9{,}23 \cdot 10^{-3}$	$-2{,}14 \cdot 10^{-3}$
Human carc. Toxicity	Pt	$5{,}56 \cdot 10^{-2}$	$4{,}15 \cdot 10^{-2}$	$3{,}49 \cdot 10^{-3}$	$1{,}50 \cdot 10^{-6}$	$1{,}14 \cdot 10^{-4}$
Human non-carc. Toxicity	Pt	$3{,}11 \cdot 10^{-2}$	$4{,}03 \cdot 10^{-3}$	$1{,}23 \cdot 10^{-3}$	$1{,}04 \cdot 10^{-8}$	$-9{,}03 \cdot 10^{-7}$
Land use	Pt	$1{,}54 \cdot 10^{-3}$	$-4{,}40 \cdot 10^{-3}$	$4{,}17 \cdot 10^{-5}$	$4{,}85 \cdot 10^{-7}$	$-3{,}25 \cdot 10^{-4}$
Mineral res. Scarcity	Pt	$1{,}33 \cdot 10^{-5}$	$-3{,}62 \cdot 10^{-5}$	$3{,}39 \cdot 10^{-7}$	$4{,}02 \cdot 10^{-7}$	$-1{,}54 \cdot 10^{-5}$
Fossil res. Scarcity	Pt	$1{,}86 \cdot 10^{-3}$	$-1{,}75 \cdot 10^{-3}$	$7{,}58 \cdot 10^{-5}$	$3{,}50 \cdot 10^{-8}$	$2{,}54 \cdot 10^{-7}$

Table A8. *Endpoint category results of the environmental analysis results of each waste fraction (includes waste generation, collection, and treatment for each fraction)*

	Unidad	Total	Residual waste	Chemical waste	FORM fraction
Total	Pt	0,297	0,230	0,033	0,033
Human health	Pt	0,286	0,225	0,031	0,030
Ecosystems	Pt	0,009	0,004	0,001	0,004
Resources	Pt	0,002	0,001	0,001	$-4{,}36 \cdot 10^{-5}$

ANNEX B

B1. LIFE CYCLE COSTING ANALYSIS

Table B1. *Treatment processes cost for scenario 1*

	Hazardous incineration	Landfill	Recycling	Biological treatment
Waste group	Chemical waste	General waste	General waste	FORM fraction
Quantity [(kg/year)/FU]	0,24	1,02	1,70	0
Cost (€/t)	350,00	60		
Cost (€/kg)	0,35	0,06		
Cost [(€/year)/FU]	0,0839	0,06	0,0039	0
Power (kWh/t)	-	-	30,00	46
Power (kWh/kg)	-	-	0,03	0,046
Power (kWh/FU)	-	-	0,08	0,08
Cost (€/kWh)	-	-	0,051	0

Table B2. *Containers cost for scenario 1*

	General waste	Chemical waste	Paper fraction
Volume [(L/year)/FU]	4,29	0,24	1,75
Volume (L/year)	1.715.136,33	95.885,92	698.559,78
Volume (L/day)	4.699	262,70	1.913,86
Container size (L)	1000	360	1000
Number of containers	5	1	2
Price (€/year)	44.055,50	3.168,20	318,50

Table B3. *Treatment processes cost for scenario 2*

	Hazardous incineration	Landfill	Recycling	Biological treatment
Waste group	Chemical waste	General waste	General waste	FORM fraction
Quantity [(kg/year)/FU]	0,24	0,20	1,70	0,81
Cost (€/t)	350,00	60		
Cost (€/kg)	0,35	0,06		
Cost [(€/year)/FU]	0,0839	0,01	0,0039	0,00285
Power (kWh/t)	-	-	30,00	46
Power (kWh/kg)	-	-	0,03	0,046
Power (kWh/FU)	-	-	0,08	0,08
Cost (€/kWh)	-	-	0,051	0,037

Table B4. *Containers cost for scenario 2*

	General waste	Chemical waste	Paper fraction	FORM fraction
Volume [(L/year)/FU]	2,48	0,24	1,75	1,81
Volume (L/year)	991.090,54	95.885,92	698.559,78	724.045,79
Volume (L/day)	2.715,32	262,70	1.913,86	1.983,69
Container size (L)	1000	360	1000	1000
Number of containers	3	1	2	2
Price (€/year)	26.433.30	3.168,20	318,50	318,50

Table B5. *Working taxes* [76]*

Worker's contribution	Contingency	4,70%	666,07
	Training	0,10%	14,17
	Unemployment	1,55%	219,66
	IRPF	2,00%	283,43
Social security	Common contingencies	23,60%	3,344,52
	Professional contingencies	1,50%	212,58
	Training	0,60%	85,03

*Calculation performed multiplying the percentages to the gross salary of Table B6

Table B6. *Collection costs*

Gross salary (€/year)	Worker's contribution taxes (€/year)	**Social security taxes (€/year)**	Final cost passed on to the company (€/year)	Final cost passed on to the company [(€/year)/FU]
14.171,71	1.183,34	3.642,13	16.630,50	0,042

Table B7. *LCC results*

	Net cost ((€/year)/FU)	Environmental Cost [(€/year)/FU]
Scenario 1	7,27	1,02
Scenario 2	6,45	0,89

B2. MATHEMATICAL OPTIMIZATION

Table B8. *Treatment processes cost for scenario 3*

	Hazardous incineration	Landfill	Recycling	Biological treatment
Waste group	Chemical waste	General waste	General waste	FORM fraction
Quantity [(kg/year)/FU]	0,24	0,20	1,70	0,81
Cost (€/t)	350,00	60		
Cost (€/kg)	0,35	0,06		
Cost [(€/year)/FU]	0,0839	0,01	0,0039	0,00285
Power (kWh/t)	-	-	30,00	46
Power (kWh/kg)	-	-	0,03	0,046
Power (kWh/FU)	-	-	0,08	0,08
Cost (€/kWh)	-	-	0,051	0,037

Table B9. *Containers cost for scenario 3*

	General waste	Chemical waste	Paper fraction	FORM fraction	Glass fraction
Volume [(L/year)/FU]	1,77	0,24	1,75	1,81	0,70
Volume (L/year)	709.113,41	95.885,92	698.559,78	724.045,79	281.977,13
Volume (L/day)	1.942,78	262,70	1.913,86	1.983,69	772,54
Container size (L)	1000	360	1000	1000	800
Number of containers	2	1	2	2	1
Price (€/year)	17.622,2	3.168,20	318,50	318,50	318,5

Table B10. *Treatment processes cost for scenario 4*

	Hazardous incineration	Landfill	Recycling	Biological treatment
Waste group	Chemical waste	General waste	General waste	FORM fraction
Quantity [(kg/year)/FU]	0,24	0,04	1,82	0,815
Cost (€/t)	350,00	60		
Cost (€/kg)	0,35	0,06		
Cost [(€/year)/FU]	0,0839	$2{,}55 \cdot 10^{-3}$	0,0042	0,00285
Power (kWh/t)	-	-	30,00	46
Power (kWh/kg)	-	-	0,03	0,046
Power (kWh/FU)	-	-	0,08	0,08
Cost (€/kWh)	-	-	0,051	0,037

Table B9. *Containers cost for scenario 3*

	General waste	Chemical waste	Paper fraction	FORM fraction	Plastic fraction	Debris fraction
Volume [(L/year)/FU]	1,53	0,24	1,75	1,81	0,60	0,26
Volume (L/year)	611.231,33	95.885,92	698.559,78	724.045,79	239.853,84	104.472,98
Volume (L/day)	1.674,61	262,70	1.913,86	1.983,69	657,13	286,23
Container size (L)	1000	360	1000	1000	660	360
Number of containers	2	1	2	2	1	1
Price (€/year)	17.622,2	3.168,20	318,50	318,50	137,54	3.168,20

Table B10. *Optimization results*

	Net Cost ((€/year)/FU)	Environmental cost [(€/year)/FU]	Human Health [(DALY/year)/FU]	Ecosystems [(species·yr/year)/FU]	Resources [(USD23/year)/FU]
Scenario 1	7,27	1,02	$5{,}85 \cdot 10^{-5}$	$4{,}86 \cdot 10^{-7}$	0,41
Scenario 2	6,45	0,89	$5{,}27 \cdot 10^{-5}$	$4{,}56 \cdot 10^{-7}$	0,23
Scenario 3	6,09	0,89	$5{,}27 \cdot 10^{-5}$	$4{,}56 \cdot 10^{-7}$	0,23
Scenario 4	6,92	0,85	$5{,}35 \cdot 10^{-5}$	$4{,}65 \cdot 10^{-7}$	0,19

ANNEX C

C.1. UNCERTAINTY ANALYSIS

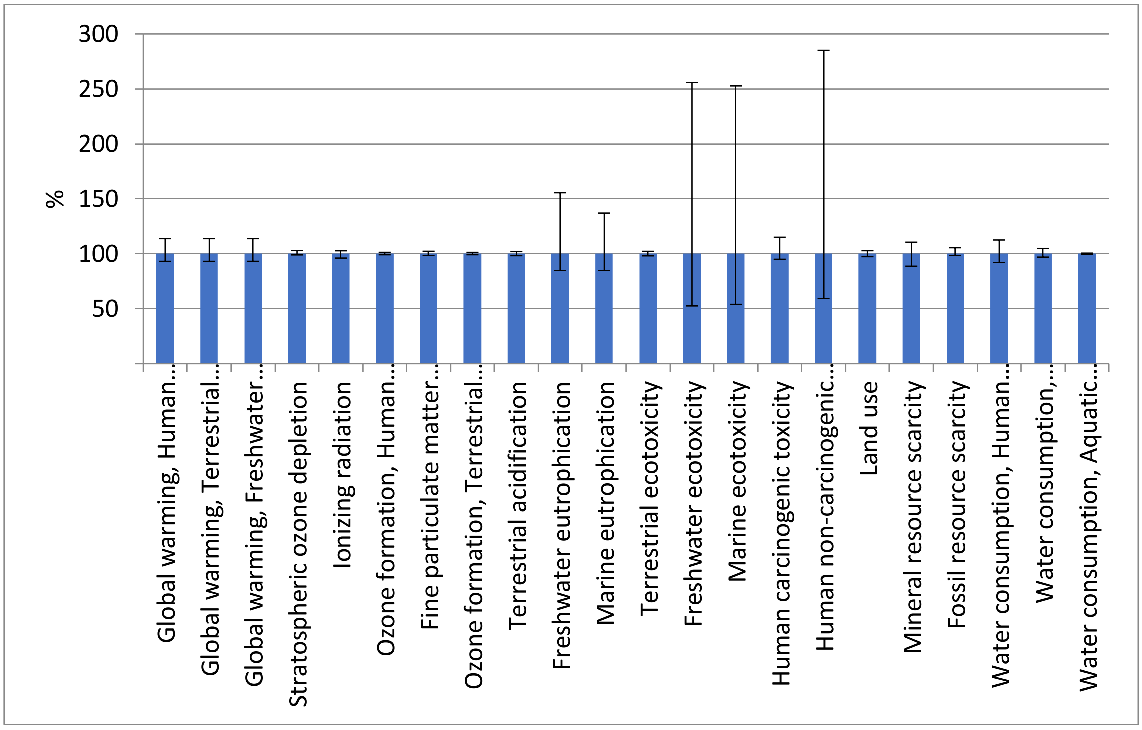

Figure C1. *Midpoint impact categories uncertainty analysis for scenario 1*

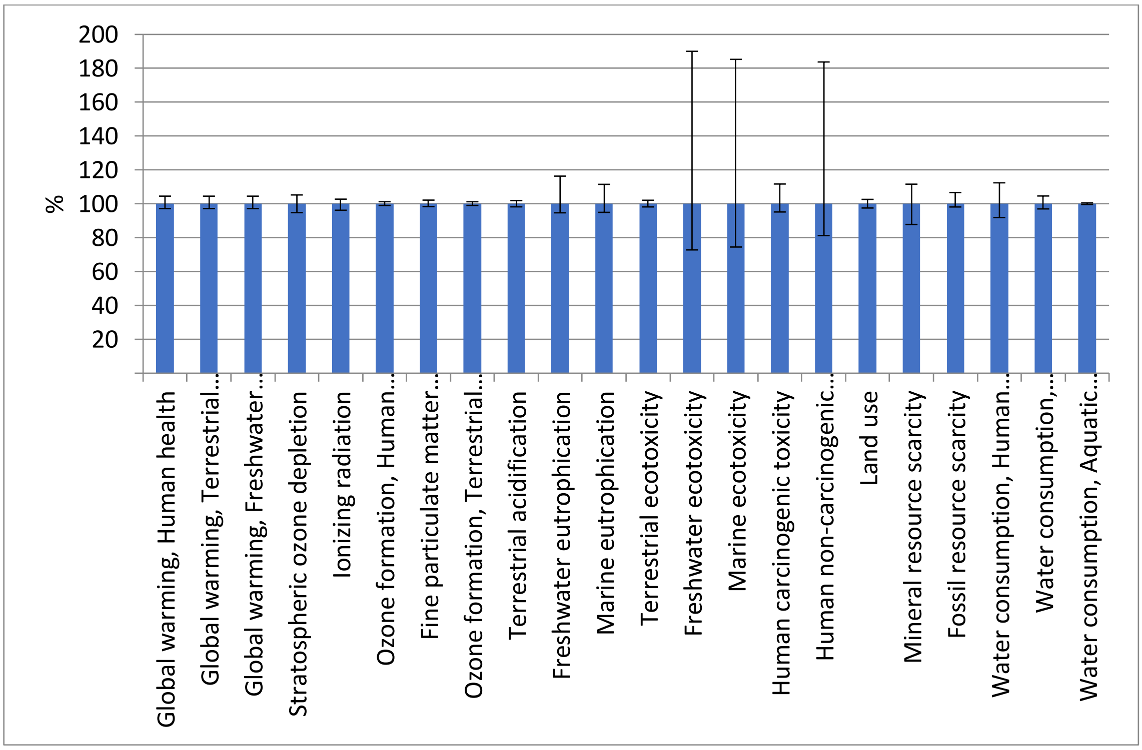

Figure C2. *Midpoint impact categories uncertainty analysis for scenario 2*

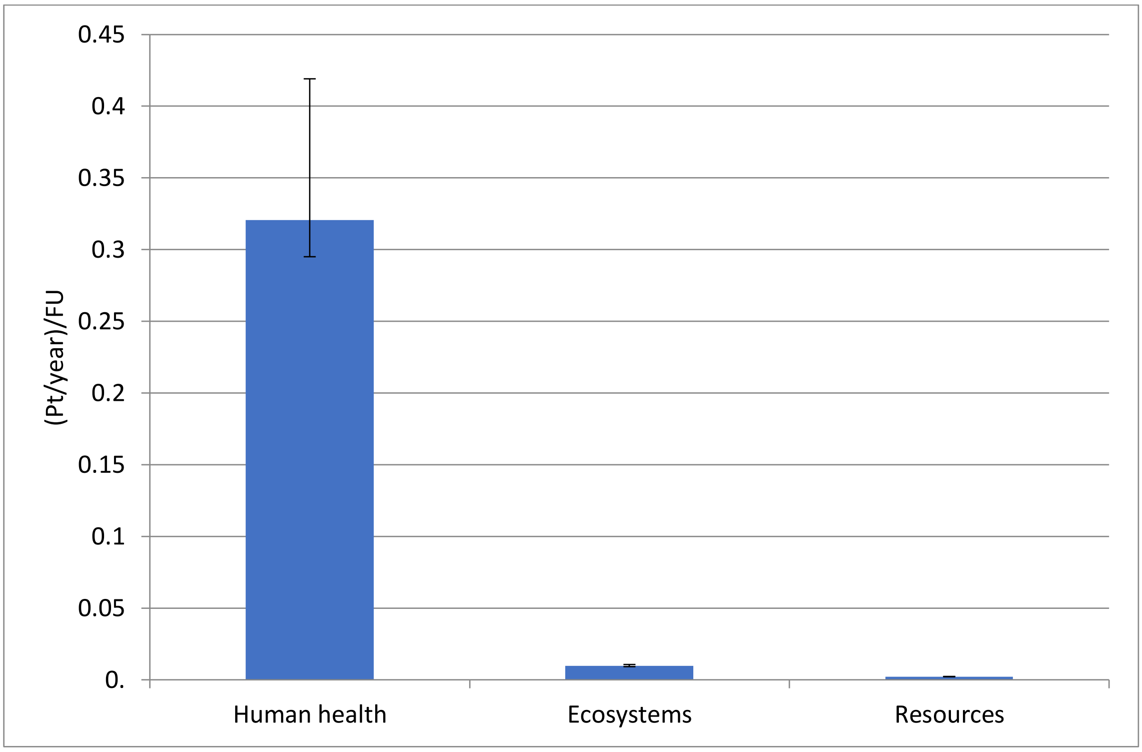

Figure C3. *Endpoint impact categories uncertainty analysis for scenario 1*

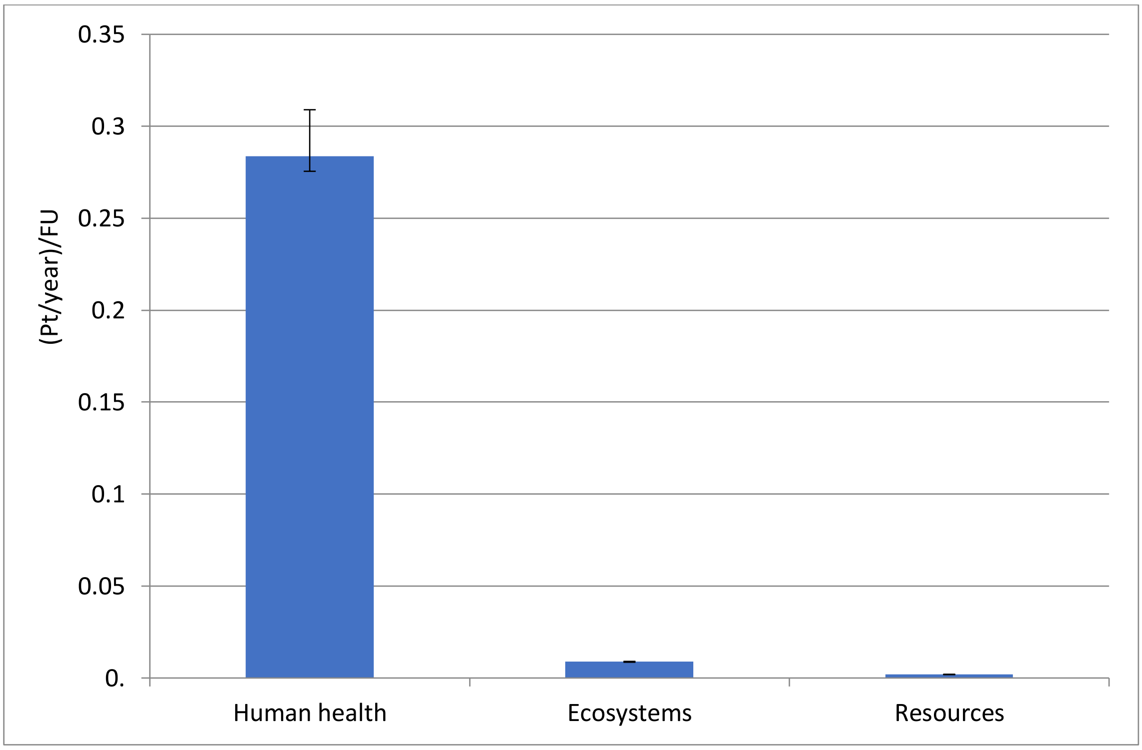

Figure C4. *Endpoint impact categories uncertainty analysis for scenario 2*