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Verification of the results of environmental life cycle assessment of bulky waste management technologies using sensitivity analysis

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Life Cycle Assessment (LCA), sensitivity analysis, bulky waste, environmental impact, CML-IA, Impact 2002+, Greenhouse Gas Protocol, ReCiPe

Abstract
The calculation aimed to verify the life cycle assessment (LCA) results of the bulky waste management technology by using sensitivity analysis. Different sensitivity analyses for LCA were carried out to point out which of the tested methods gave the most reliable LCA results. The main factor that helped to find the best-fitted method was CO2 emissions. The LCA analyses were performed by IOŚ-PIB using SimaPro software based on the technology data obtained during the Urbanrec project. The sensitivity analysis was conducted twofold: the LCA analysis was carried out for different time horizons in the frame of the ReCiPe method egalitarian (E), individual (I), and hierarchic (H). In the second step, the LCA results for the ReCiPe method were compared with the LCA results for methods: CML-IA, Impact 2002+, and the Greenhouse Gas Protocol (GGP). The results of the LCA for all endpoints are sensitive to changes in the time horizon, which is reflected in the change in impact assessment methods used in calculations. The biggest differences are visible between the egalitarian and individual perspectives. In the second case of the sensitivity analysis, differences in results between the individual analytical methods used for LCAs can be observed. The obtained results show a high sensitivity of LCA results from the adopted time horizon, as well as moderate sensitivity of the carbon footprint depending on the method of analysis used.

1. INTRODUCTION

Environmental Life Cycle Assessment (LCA) is a technique designed to assess the environmental risks associated with the product system or activity either directly, by identifying and quantifying the energy and materials used and the waste introduced into the environment, or indirectly, by evaluating the environmental impact of such materials, energy, and waste [Fava 1991; Groen et al. 2014; Samson-Bręk et al. 2019]. The assessment relates to the whole lifespan of the product or activity, from the mining and mineral material processing, product manufacturing process, distribution, use, re-use, maintenance, and recycling up to the final disposal and transportation [Fava 1991; Samson-Bręk et al. 2019]. Different sources of uncertainty can affect the results of a LCA analysis. The main uncertainty defined in the literature is connected with the choice of method, initial assumptions like system boundaries, allocation rules or quality of the available input data (especially secondary data) [Cellura et al. 2011; Kowalski et al. 2007; Huijberts 1998] Therefore, a sensitivity analysis is recommended to verify the obtained LCA results and to determine their validity. According to the ISO 14044 standard, a sensitivity analysis is mandatory for calculations whose results are made public. Sensitivity analysis is understood as "a systematic procedure for estimating the effects of the choice of methods and data used on the results of a study" [Heijungs 2002]. The purpose of a sensitivity analysis is to assess the reliability of results and conclusions by determining how they are affected by uncertainty in data, choice of allocation method, calculation of category indicator values, etc." In LCA studies, sensitivity analysis is applied at all stages from the establishment of system boundaries, exclusion criteria and assumptions on input and output data, through the selection of impact categories, the classification, normalisation and characterisation process, to the weighting methods, allocation rules to the interpretation of results. For example, sensitivity analysis is performed on input and output data. For modelling the environmental impact of waste management systems, a few models have been developed such as IWM-2, EPIC/CSR, MSW-DST, ORWARE, WISARD, WRATE, LCA-IWM, and EASEWASTE [Grzesik et al. 2016]. Ten years ago, a sensitivity analysis for a LCA concerning technology's impact on the

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environment was performed with the use of the following methods: CML 2 baseline 2000, Eco-indicator 95, EDIP/UMIP 97, IPCC 2007, and Impact 2002+ [Cerulla et al. 2011; Koroneos et al. 2012]. Actually, there are a few new approaches to conducting the sensitivity analysis. One of them is One-at-a-time (OAT), in which a subset of the input parameters is changed at the same time to see how much influence it has on the result. Matrix perturbation (MP) is a method of sensitivity analysis in which the first-order partial derivatives are used as estimators of local sensitivity, which can be converted into relative multipliers [Heijungs 2002]. The method of elementary effects (MEE) is a screening method designed by Morris and adjusted by Campolongo [Campolongo et al. 2007]. To apply MEE, the ranges of the individual parameters are taken into account, where a range is defined as the upper and lower boundary of an input parameter. MEE can be seen as an extended OAT approach [Koning et al. 2010; Mutel et al. 2013; Saltelli et al. 2008]. Key issue analysis (KIA) was introduced in a LCA by Heijungs [Heijungs 2004] as a method for determining the contribution to variance using a first-order Taylor expansion. This method calculates the variance decomposition up to the first order as the covariance between input parameters. To apply this method only the variances of the individual parameters are used [Heijungs et al. 2004; Heijungs et al. 2005; Mutel et al. 2013]. Standardized regression coefficients (SRC) are obtained from the slope of the line from the least-square fitting, and they estimate the contribution to output variance for each input parameter. Sensitivity analyses that consistently analyse the sensitivity of each parameter in the model are usually performed with sampling-based approaches, such as the Monte Carlo simulation, with an added procedure for variance decomposition. The method by Sobol assigns a sensitivity measure to each input parameter by calculating how much of the output variance can be allocated to each input parameter [Wei et al. 2015; Sobol 2001]. The model can be decomposed into terms of increasing order called Sobol's main effects (SME), which are equal to the contribution of variance caused by each input parameter to the output variance. This method calculates the interaction effects and the total effect index. The Sobol's total effect index (STE) is the variance between the sum of the main and interaction effects of an input parameter [Saltelli et al. 2010]. Very often, a sensitivity analysis is performed by changing the value of some parameters, for example, the substitution ratio between secondary steel and primary steel [Biganzoli et al. 2018] or the lifetime of the product [Gradin et al. 2020].

The evaluation method in a LCA is chosen depending on what categories of environmental impact we want to evaluate. In this article, we will look at methods that return results in the form of CO_2 equivalent emissions. This factor was chosen because greenhouse gas (GHG) emissions are one of the core factors that have a negative impact on the environment. The European Commission in different legislation emphasizes the need to decarbonize the economy, which can be achieved, among other ways, through the use of low-emission technologies for the production of various products [Council of the European Commission 2023; European Commission 2020; European Commission 2022; European Commission 2023]. Taking into account the above-mentioned analyses conducted, the frame of this article aims to assess which of the tested methods gives the most reliable LCA results of CO_2 emissions in the whole life cycle. The conclusion of the conducted analysis is to indicate the most comprehensive method for assessing the impact of bulky waste management on the environment in terms of CO_2 emissions.

In the frame of this article, the sensitivity analyses were carried out based on the report data collected during the Urbanrec project. The full final report and project description can be found on the Cordis website [Urbanrec 2019]. During the project, innovative solutions have been developed to promote the reduction, recycling, and reuse of bulky waste. By recycling materials derived from bulky waste such as polyurethane or latex foams, different blends of plastics, textiles and wood, new products have been developed: adhesives, solvents, foams, fibre-reinforced composites, and wood-plastic composites.

2. METHODOLOGY

2.1. The functional unit

The functional unit was defined as 1 ton of mixed bulky waste collected and manufactured.

2.2. The system boundaries of the LCA

The system boundaries of LCA analysis are presented in Figure 1. The waste management system presented in Figure 1 is a proposition of managing part of the waste resulting from the Urbanrec project. The destination of collected bulky waste [Urbanrec 2019] is as follows:

- sorting centre 83,1%
- wood recycling 12,6%
- steel and iron recycling 3,2%
- landfilling 1,1%.

Different waste fractions from the sorting centre can be used in new technologies to produce new products such as boxes from wood plastic composites, chairs or boxes from fibre-reinforced composites, insulation panels, mattresses, and chemicals.

From the sorting centre, plastic (29%), wood (17,4%), textiles (7,7%), and foam (11%) can be used in new technologies [Urbanrec 2019].

All input data for calculations were actual data that came from technologies elaborated on during the Urbanrec project.

2.3. Methodology of sensitivity analysis

There are more than 20 well-known LCA software products in the international market. The first task faced

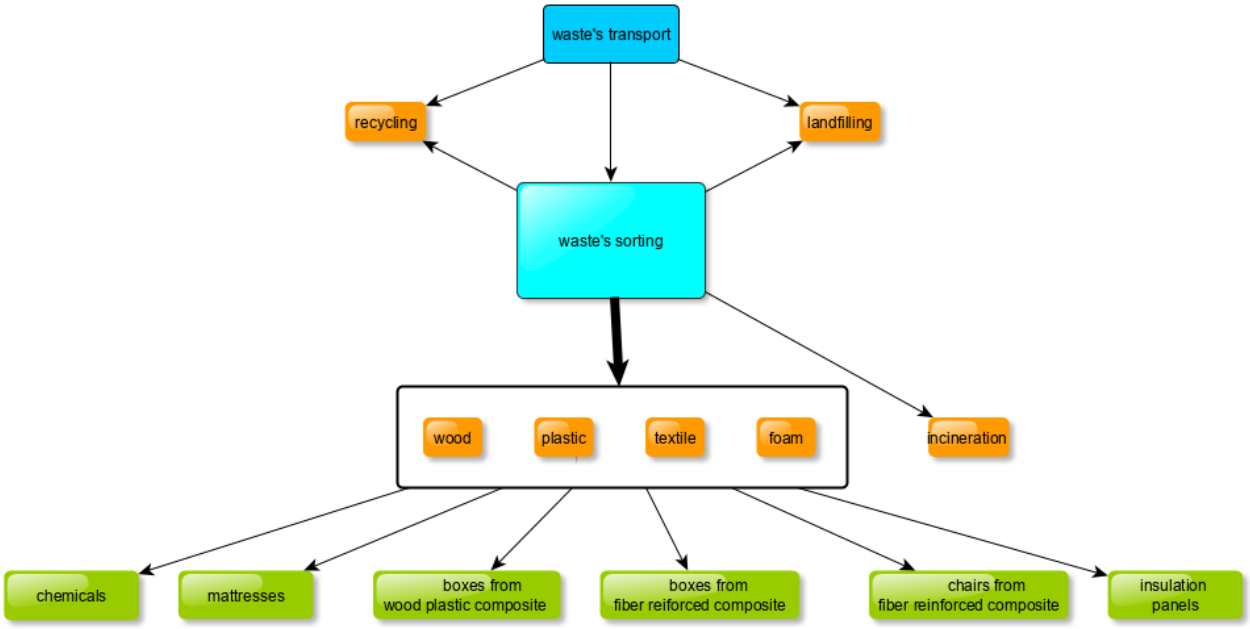


Figure 1. System's boundaries of bulky waste management system

by the potential user is to choose the proper tool for their particular problem. The choice has to be made based on a combination of the user's financial capabilities and functional requirements, on a case-by-case basis. One of the most market-popular software is SimaPro, and in the frame of this article, the LCA analyses were conducted using the latest available version of the SimaPro software—9.5.0.0.
The sensitivity analysis was conducted in two variants:
1. Comparison of different time horizons in the frame of the ReCiPe method.
2. Comparison of the environmental LCA results for the greenhouse effect category under three different methods: CML-IA, Impact 2002+, and the GGP.
The ReCiPe method is available in three variants: egalitarian (E), individual (I), and hierarchic (H). The egalitarian variant covers a very long-term horizon (even as long as 200 years), while the individual variant applies to a short one (of about 20 years). The hierarchic variant covers a balanced time horizon while taking into account the long- and short-term perspectives [Huijberts 1998].
CML-IA is a LCA methodology developed by the Center of Environmental Science (CML) of Leiden University in The Netherlands. This method is an update of the CML 2 baseline 2000 and corresponds to the files published by CML in August 2016 (version 4.7). The CML-IA (baseline) method elaborates on the problem-oriented midpoint approach and this approach is recommended for simplified studies. The CML Guide provides a list of impact assessment categories grouped into:

1. Obligatory impact categories (category indicators used in most LCAs).
2. Additional impact categories (operational indicators exist but are not often included in LCA studies).
3. Other impact categories (no operational indicators available, therefore impossible to include quantitatively in LCAs).

The main impact categories (midpoints) available in the CML-IA calculation method are described below:

- Depletion of abiotic resources (abiotic depletion—elements, ultimate reserves, abiotic depletion—fossil fuels). Abiotic depletion (elements, ultimate reserves) is related to the extraction of minerals due to inputs in the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals (kg antimony equivalents/kg extraction) based on concentration reserves and the rate of deaccumulation. Abiotic depletion of fossil fuels is related to the Lower Heating Value (LHV) expressed in MJ per kg of m3 fossil fuel. The reason for taking the LHV is that fossil fuels are considered to be fully substitutable.
- Global warming—the characterisation model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for the development of characterisation factors. Factors are expressed as Global Warming Potential for a time horizon of 100 years (GWP100), in kg carbon dioxide equivalent/kg emission [UNFCCC 2020].
- Ozone layer depletion—the characterisation model is developed by the World Meteorological Organisation (WMO) and defines the ozone depletion potential of different gases (kg CFC-11 equivalent/ kg emission) [WMO 2020].
- Human toxicity (HTP), Freshwater aquatic ecotoxicity (FAETP inf), Marine aquatic ecotoxicology (MAETP), and Terrestrial ecotoxicity (TETP). Characterisation factors,

expressed as Human Toxicity Potentials (HTP), are calculated with a USES-LCA, describing fate, exposure, and effects of toxic substances for an infinite time horizon. For each toxic substance, HTP's are expressed as 1,4-dichlorobenzene equivalents/ kg emission.
- Photochemical oxidation (high NOx)—the model is developed by Jenkin et al. [Derwent et al. 1996] and defines photochemical oxidation expressed in kg ethylene equivalents per kg emission.
- Acifidication potential expressed in kg SO_2 equivalents per kg of emissions. The model was developed by Huijbregts [Huijbregts et al. 2003].
- Eutrophication potential developed by Heijungs [Campolongo et al. 2007] and expressed in kg PO_4 equivalents per kg emission.

IMPACT 2002+ is a combination of four methods: IMPACT 2002, Eco-indicator 99, CML, and IPCC, but the most similarities can be observed compared to the Eco-indicator 99. Compared to Eco-indicator 99, the following changes were implemented:
- IMPACT 2002 factors replaced Eco-indicator's Human Health carcinogenic and non-carcinogenic factors and aquatic and terrestrial ecotoxicity factors.
- CML factors were used for aquatic acidification and aquatic eutrophication. The Aquatic eutrophication CF implemented in this method are those for a P-limited watershed.
- Climate change was redefined, separated from Human Health impacts, and added as a separate damage category. The characterisation factors of IPPC 2001 500a were used for this impact category.
- For fossil fuel depletion, the energy content was used instead of the surplus energy needed for extraction. In the resource depletion category, however, mineral extraction and fossil fuel depletion results were added together even though fossil energy content and surplus energy for minerals represent different concepts.
- The Eco-indicator 99 factors for respiratory effects, ionizing radiations, land use, and mineral extraction remained unchanged.

The respective midpoint units are the following:
- kg chloroethylene equivalents into the air (written "kg $C_2H_3Cl_{eq}$") for carcinogens and non-carcinogens;
- kg PM2.5 equivalents into the air (written "kg $PM2.5_{eq}$") for respiratory inorganics;
- Bq C-14 equivalents into the air (written "Bq $C\text{-}14_{eq}$") for ionizing radiation;
- kg CFC-11 equivalents into air (written "kg $CFC\text{-}11_{eq}$") for ozone layer depletion;
- kg ethylene equivalents into the air (written "kg C_2H_4 $_{eq}$") for respiratory organics;
- kg triethylene glycol equivalents into water (written "kg TEG water") for aquatic ecotoxicity;
- kg triethylene glycol equivalents into the soil (written "kg TEG soil") for terrestrial ecotoxicity;
- kg SO_2 equivalents into the air (written "kg $SO_{2\ eq}$") for terrestrial acid/nutri;
- m^2 organic arable land (written "m^2org.arable") for land occupation;
- kg SO_2 equivalents into the air (written "kg $SO_{2\ eq}$") for aquatic acidification;
- kg PO_4--- equivalents into a P-limited water (written "kg PO_4 P-lim") for aquatic eutrophication;
- kgCO_2 equivalents into the air (written "kg $CO_{2\ eq}$") for global warming,
- MJ primary non-renewable (written "MJ primary") for non-renewable energy; and
- MJ surplus (written "MJ surplus") for mineral extraction.

The respective damage units are DALY for human health, PDF*m^2*yr for ecosystem quality, kg_{eq} CO_2 into the air (written "kg $CO_{2\ eq}$") for climate change, and MJ primary non-renewable (written "MJ primary") for resources.
The last method used in LCA calculation is the GGP method. This method has been developed especially for the road testing process of the WRI/WBCSD, which aims to test the usability of the draft (GGP) carbon footprint standards (GHG 2020). The characterisation factors per substance are identical to the IPCC 2007 GWP (100a) method in SimaPro. The only difference is that carbon uptake and biogenic carbon emissions are included in this method and that a distinction is made between:
1. Fossil-based carbon (carbon originating from fossil fuels);
2. Biogenic carbon (carbon originating from biogenic sources such as plants and trees);
3. Carbon from land transformation (direct impacts); and
4. Carbon uptake (CO_2 that is stored in plants and trees as they grow).

3. RESULTS

3.1. Sensitivity analysis for different time horizons in the ReCiPe method

The analysis was performed based on actual input data obtained during the Urbanrec project. Analysis was performed for different time horizons for Endpoints in the ReCiPe 2016 global method. The sensitivity analysis was carried out concerning 3 endpoints: human health, ecosystems, and resources, as well as three time perspectives: egalitarian, hierarchic, and individual. From the results presented in Figures 2, 3, and 4, it can be seen that the results of the LCA for all endpoints are sensitive to changes in the time horizon, reflected in the change in impact assessment methods used in calculations. The biggest differences are visible between the egalitarian and individual perspectives.
The individualistic perspective is based on short-term interest, undisputed impact types, and technological optimism about human adaptation to climate change. The values for the individualist time horizon are the lowest among all the three analysed time horizons because the calculations take into account the shortest period of

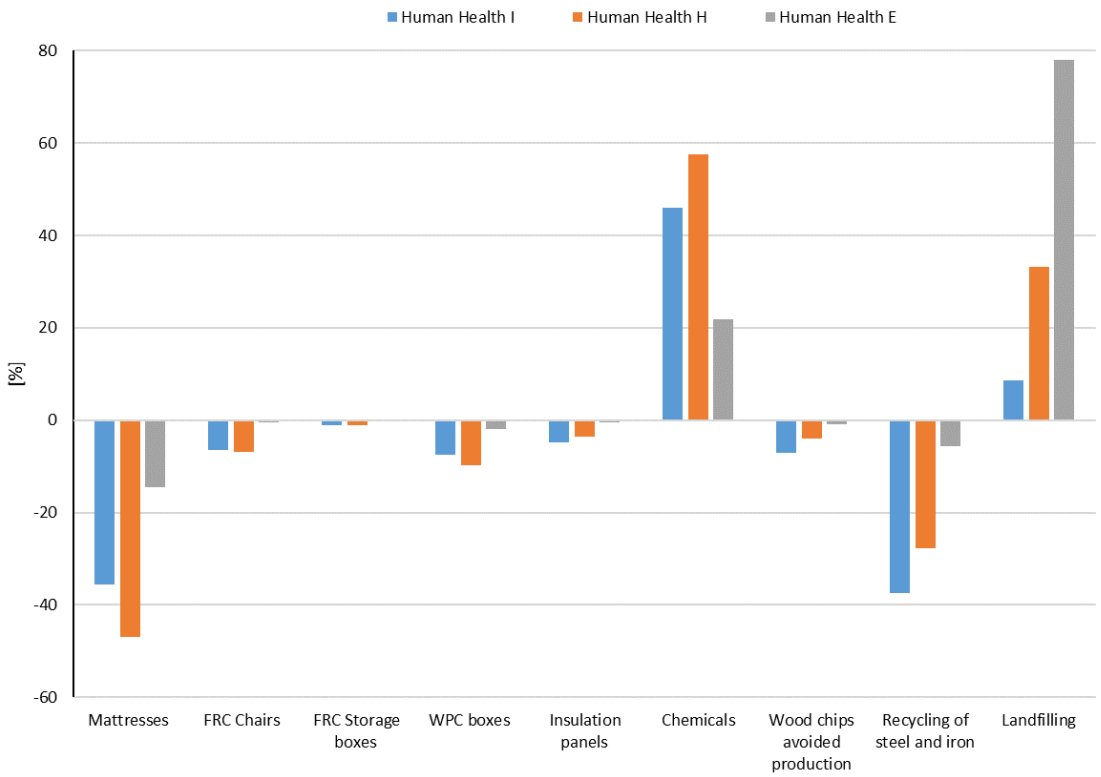


Figure 2. Sensitivity analysis for human health endpoint in three-time perspectives: ReCiPe endpoint (H), ReCiPe endpoints (I), and ReCiPe endpoint (E)

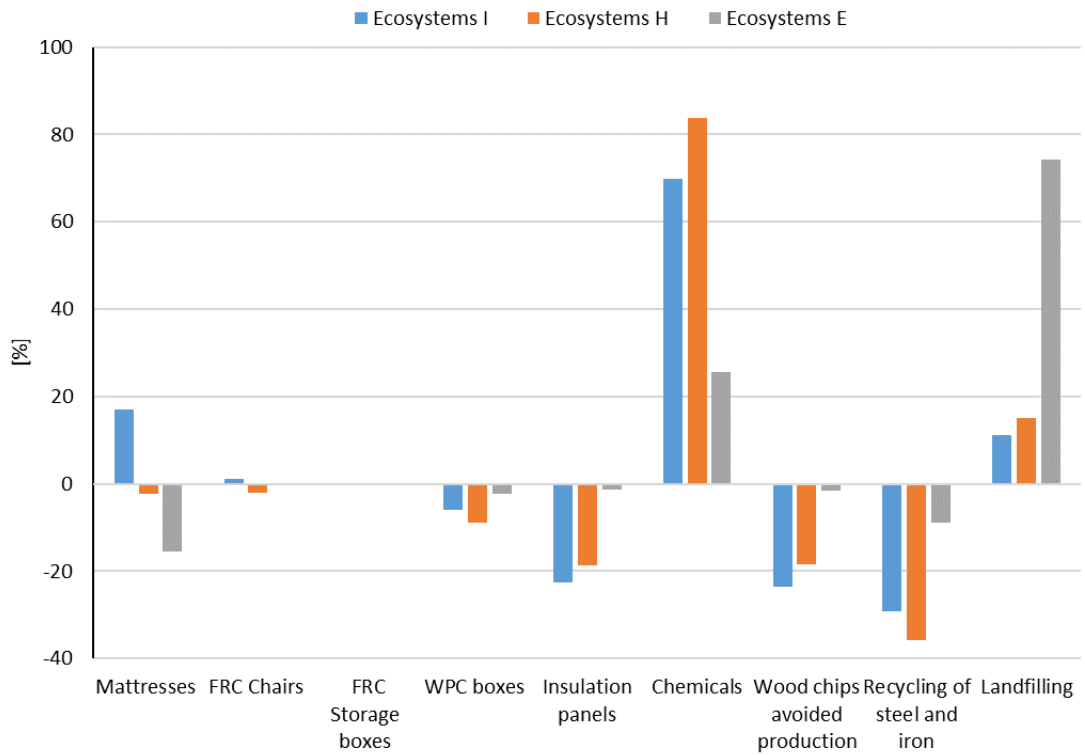


Figure 3. Sensitivity analysis for ecosystems endpoint in three-time perspective: ReCiPe endpoint (H), ReCiPe endpoints (I), and ReCiPe endpoint (E)

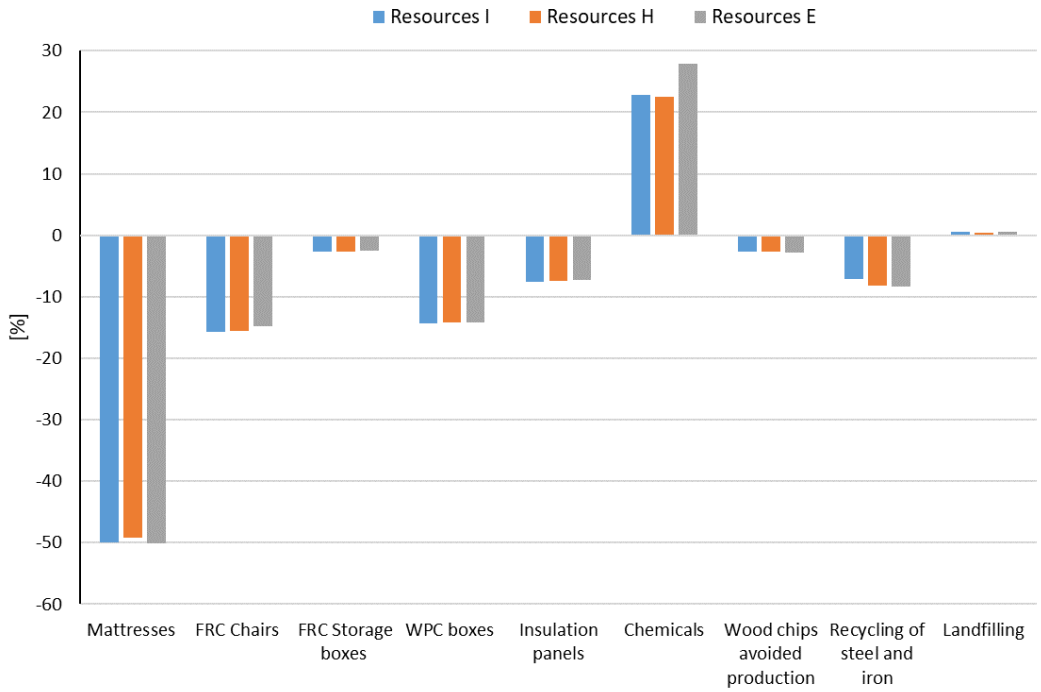


Figure 4. Sensitivity analysis for resources endpoint in three-time perspective: ReCiPe endpoint (H), ReCiPe endpoints (I), and ReCiPe endpoint (E)

exposure of the environment to the effects of harmful factors (Figures 2, 3, and 4). In the egalitarian time horizon, which is the most precautionary perspective, taking into account the longest time frame and all impact pathways for which data are available, the exposure of the environment to the negative impact of pollutants is the longest, with the highest accumulation of harmful substances in the environment. It is especially visible in the case of the environmental impact of the waste storage process in a landfill. The ReCiPe method for the hierarchic time perspective is based on scientific consensus concerning the time frame and plausibility of impact mechanisms, and therefore it is the most frequently used time variant of the ReCiPe method in LCA analysis [Dekker et al. 2020; Feng et al. 2023; Huijbregts et al. 2017].

3.2. Different methods of global warming calculation

In this article, as part of the sensitivity analysis, the impact of the new method of bulky waste management on GHG emissions expressed in a carbon dioxide equivalent was analysed. The analysis was conducted using the most frequently used LCA methods available in the SimaPro software like CML-IA, Impact 2002+, ReCiPe, and the GGP. The results of the analysis using three different methods are summarized in Table 1.

As shown in Table 1, all products obtained as a result of the recycling of bulky waste are characterised by a significant reduction in CO_2 emissions. An exception is the process of depositing waste in a landfill, which generates a significant burden on the environment. Particularly noteworthy are the significant differences in the obtained results between the CML-IA, Impact 2002+, and ReCiPe Midpoint Hierarchic methods and the GGP in the avoided production of wood chips category, as well as between the Impact 2002+ and ReCiPe Midpoint Hierarchic, GPP, and CML-IA methods for the landfilling category. Such a significant difference in the obtained carbon footprint estimates results primarily from different methods of allocating CO_2 emissions between individual impact categories. In the GGP method, carbon uptake and biogenic carbon emissions are included in this method and CO_2 emission is divided between fossil-based carbon, biogenic carbon, and carbon from land transformation as well as carbon uptake (CO_2 stored in plants and trees as they grow). In the Impact 2002+ method, the global warming carbon footprints are given for emissions into the air only. At the damage level, the impact of global warming is presented in a separate damage category that is expressed in kg $CO_{2\text{-eq}}$ into the air/kg, identical to the midpoint category. In ReCiPe, the global warming potential expresses the amount of additional radiative forcing integrated over time (20, 100 or 1,000 years) caused by the emission of 1kg of GHG relative to the additional radiative forcing integrated over that same time horizon caused by the release of 1 kg of CO_2. A similar approach can be seen in the Impact 2002+ method. In this method, the GHG emission is calculated from a 100-year perspective.

Table 1. Global warming impact category calculated with different LCA methods, (kg $CO_{2\,eq}$)

method calculation	heat production	mattresses production	frc chairs production	frc boxes production	wpc boxes production	insulation panels production	chemicals production	avoided production of wood chips	recycling of steel and iron	landfilling
CML-IA	-0.40	-218.29	-29.14	-4.98	-43.97	-21.90	297.19	-12.86	-148.37	81.87
Impact 2002+	-0.38	-187.87	-25.27	-4.33	-40.29	-17.71	282.71	-12.24	-145.43	16.60
Greenhouse Gas Protocol	-0.40	-229.53	-19.05	-3.33	-70.15	-28.80	348.76	-109.26	-150.87	100.09
ReCiPe Midpoint H	-0.40	-230.71	-31.55	-5.38	-45.97	-23.50	303.77	-13.15	-151.30	99.22

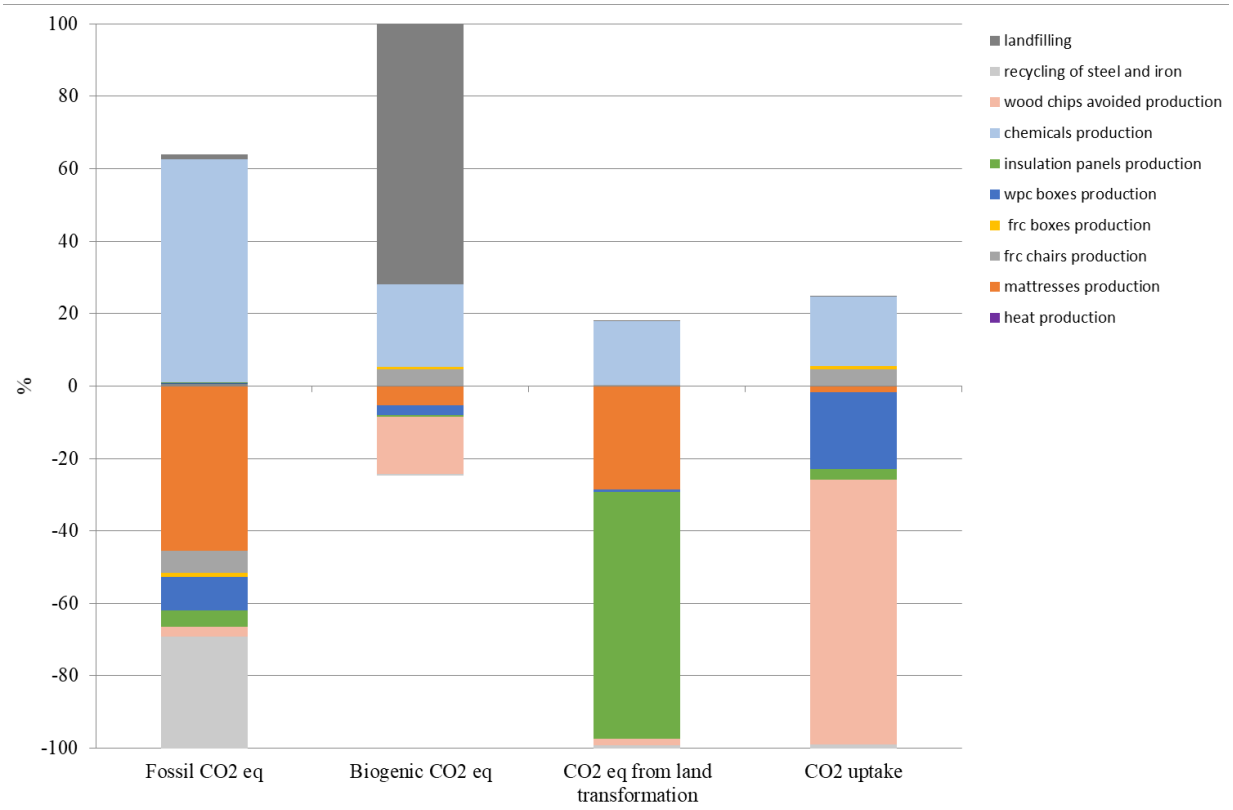


Figure 5. Carbon dioxide emission assessment using the GGP v.1.02 (single issue) method

Taking into account the method of dividing CO_2 emissions described above in the analysed methods of the environmental impact of bulky waste management processes, the most optimal method is GGP. This method takes into account carbon dioxide removal and biogenic carbon dioxide emissions and allows for the division of CO_2 emissions into emissions from fossil coal, biogenic carbon, and carbon resulting from land conversion (Figure 5). When analysing the results presented in Figure 5, it should be noted that the adverse impact on the environment is related to the production of chemicals from waste. This involves the need to use significant energy inputs in the production process and additionally use chemical substances of fossil origin necessary in the process. In the case of waste storage, special attention is paid to biogenic carbon emissions generated during the decomposition of the biodegradable fraction contained in large-sized waste (e.g. wood or natural fabrics).

4. CONCLUSIONS

The presented study is crucial for the decision-making process regarding waste management. The LCA methodology is important in optimising the different waste flow fractions optimisation using various treatment methods, to minimise the environmental impacts. However, the environmental impact is dependent on which calculation method will be chosen. Each method has its strengths and weaknesses. Methods should be chosen according to the user's needs and uncertainty properties. In the frame of this article, there were different methods of sensitivity analysis analysed like CML-IA, Impact 2002+, ReCiPe, and the GGP. In these calculations, the main factor taken into account was GHG emissions expressed as carbon dioxide emissions. The obtained results pointed-out that the best-fitted method for environmental bulky waste accessing is the GGP method. This is the most comprehensive method that takes into account carbon dioxide removal and biogenic carbon dioxide emissions, and allows for the division of CO_2 emissions into emissions from fossil coal, biogenic carbon, and carbon resulting from land conversion.

Moreover, the publication also analysed the impact on the results of the LCA analysis of the time horizon using the ReCiPe method. Based on the results obtained, it was concluded that the results depend on the selected time horizon. The most appropriate time horizon is the medium term.

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