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Classification, characterisation, standardisation and weighting in life cycle analysis (LCA): a case study of teaching innovation for higher education

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Abstract

Training deficiencies in sustainability analysis can pose a barrier to advancing towards sustainable development. Life cycle assessment (LCA) is a basic tool in the analysis of the environmental performance of products. This paper describes exercise for teaching innovation for higher education in this field focused on the practical application of the impact assessment stage that involves transforming inventory data into impact values through classification, characterization, normalization and weighting. This exercise describes a parallel analysis of two heating systems, one based on natural gas and the other on biomass fuel for which inventory data and a simplified impact assessment method are available. This case study will allow students to become familiar with the conceptual and practical basis of the life cycle approach and the procedures described in ISO 14040.

Keywords: Teaching innovation, training, normalization, weighting, characterization, case study

1. Introduction

Multilateral organisations such as the United Nations and the European Commission have reported that deficiencies in the training of professionals in sustainability analysis may pose a barrier to progress towards sustainable development (UNEP and SETAC, 2011). A key area in environmental protection is that associated with the Integrated Product Policy (IPP) and eco-design, where Life Cycle Assessment (LCA) is a fundamental tool (Hauschild et al., 2018).

Universities and higher education institutions play a vital role in this transition. While they have responded to these demands by establishing sustainability programs or incorporating sustainability aspects into their existing curricula, there is still a lack of knowledge among students regarding the practical application of this life cycle approach in the consideration of products and services (Viere et al., 2021).

Basic knowledge of this subject begins with an understanding of the four iterative stages of LCA described in the standardized protocols of ISO 14040 and ISO 14044 (ISO, 2006a, 2006b) (see **Figure 1**):

- Definition of objective and scope: to establish the aim of the analysis along with a description of the system under investigation and decisions regarding system boundaries, functional unit, impact categories, impact assessment, limitations, etc.
- Inventory analysis: involving the gathering of data describing material and energy inputs and outputs associated with each stage of the product's life cycle.
- Life cycle assessment: involving the transformation of inventory data into impact values on each of the environmental categories selected.
- Interpretation: identification of key findings, drawing of conclusions and recommendations, assessing uncertainties and limitations, communicating results and decision making.

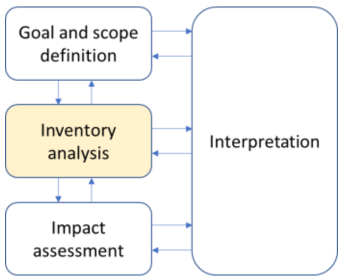

Figure 1 *Four stages in a life cycle assessment according to ISO 14040* (ISO, 2006a)

One of the most technical aspect in this LCA methodology relates to the application of the life cycle assessment stage, where elementary input and output flows of resources and emissions are transformed into impact values. ISO 14044 proposes carrying out this stage in four steps: classification of inventory flows, characterization, normalization and weighting. The former two steps are mandatory while the latter two are optional.

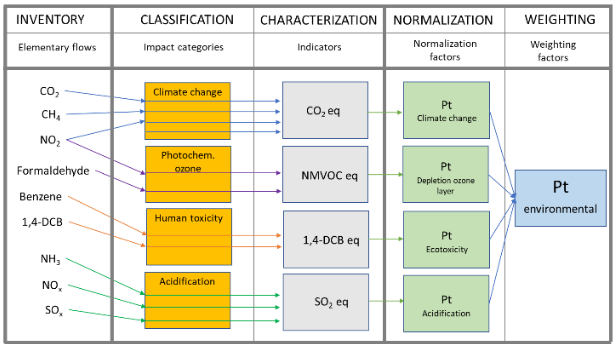

Figure 2 *Four steps in the inventory analysis stage of an LCA, according to ISO 14040*

The aim of this project is to produce an exercise that could be used for teaching LCA and could contribute the facilitating the training of professionals in this field. Two secondary goals were also identified: firstly, to give students an understanding of the practical implementation of the four stages involved in LCA. Secondly, to facilitate their understanding of the four stages in the impact assessment stage: classification, characterization, standardization and weighting.

2. Methodology

This exercise has been elaborated as a case study which describes the analysis of two heating systems, one based on natural gas and the other on biomass. This would be integrated into a broader training programme that would include theoretical training on the life cycle approach to product sustainability analysis, the ISO 14040 standard structure and environmental impact assessment methods. Various adaptations of this exercise have been applied in undergraduate and postgraduate engineering courses at the Polytechnic University of Madrid with very positive feedback from the students.

The implementation of this life cycle analysis methodology is carried out in 8 steps, as follows:

- STEP 1: LCA diagram of the heating system
- STEP 2: Analysis of emissions produced in the combustion stage and transform to FU
- STEP 3 Analysis of impact categories and life cycle assessment methodology
- STEP 4 Application of classification step
- STEP 5 Application of characterisation step
- STEP 6 Application of normalisation step
- STEP 7 Application of weighting step
- STEP 8 Interpretation of results

The exercise is carried out in two phases: in the first one, the lecturer will explain how these steps are implemented on the heating system based on natural gas. Following this and supported by the data provided, the student should replicate this procedure on the heating system based on biomass fuel.

The development of this task requires access to spreadsheet and would be facilitated by a template containing the inventory data and simplified impact assessment method. The information initially available to the student in this spreadsheet will be as follows:

- elementary flows to the atmosphere produced by the combustion of a physical unit of natural gas and biomass (see Table 1). The data for this exercise has been extracted from Ecoinvent (Wernet et al., 2016)
- lower heating value (LHV) of the natural gas (35.2 MJ/Nm^3) and biomass (18.8 MJ/kg) and the efficiency of the natural gas (95%) and the biomass (90%) boilers.
- impact assessment method applicable to this case study, including characterisation factors (for the impact categories climate change, photochemical ozone formation, human toxicity and acidification), normalisation factors and weighting factors (see Table 2). This data has been extracted from ReCiPe 2016 Midpoint (H) v 1.06 (Huijbregts et al., 2017).

3. Implementing the case study

STEP 1: The instructor will start by developing a life cycle diagram for the natural gas heating system, the result of which is depicted in Figure 2. This diagram describes the different processes structured according to the typical life cycle stages of raw material extraction, manufacturing, transport, use and maintenance and end of life. In this step, emphasis should be placed on the life

Table 1 *Elementary emissions to the atmosphere associated with the combustion of one fisical unit of natural gas (1 Nm3) and biomass (1 kg)*

	NATURAL GAS Emissions/fuel unit Fuel unit= 1 Nm3 NG		ELEMENTARY FLOWS Emissions/UF UF = 1 GJ thermal		BIOMASS Emissions/fuel unit Fuel unit= 1 kg biomass		ELEMENTARY FLOWS Emissions/UF UF = 1 GJ thermal	
Air emissions								
Butadiene	7.03E-09	kg	2.10E-07	kg		kg		kg
Acetaldehyde	6.54E-07	kg	1.95E-05	kg	1.47E-06	kg		kg
Acrolein	1.05E-07	kg	3.13E-06	kg				
Ammonia					4.18E-05	kg		kg
Benzene	1.96E-07	kg	5.86E-06	kg	2.20E-05	kg		kg
Carbon dioxide, fossil	1.96E+00	kg	5.87E+01	kg				
Carbon dioxide, biogenic					2.59E+00	kg		kg
Acetic acid	2.46E-06	kg	7.34E-05	kg	4.80E-05	kg		kg
Dinitrogen monoxide	1.79E-04	kg	5.35E-03	kg	7.25E-05	kg		kg
Benzene, ethyl	5.23E-07	kg	1.56E-05	kg	7.25E-07	kg		kg
Formaldehyde	1.16E-05	kg	3.47E-04	kg	3.14E-06	kg		kg
Fossil methane	1.39E-04	kg	4.17E-03	kg				
Biogenic methane					2.18E-04	kg		kg
Methanol					5.80E-04	kg		kg
Naphthalene	2.12E-08	kg	6.35E-07	kg				
Nitrogen oxides	1.67E-03	kg	4.98E-02	kg	3.14E-03	kg		kg
PAHs, polycyclic aromatic hy	3.59E-08	kg	1.07E-06	kg	2.68E-07	kg		kg
Particulate matter, < 2,5 um	1.08E-04	kg	3.22E-03	kg	2.18E-03	kg		kg
Propylene oxide	4.74E-07	kg	1.42E-05	kg				
Toluene	2.12E-06	kg	6.35E-05	kg	7.25E-06	kg		kg
Sulphur oxides	1.01E-05	kg	3.03E-04	kg	6.04E-05	kg		kg
NMVOCs, non-methane vola	3.44E-05	kg	1.03E-03	kg	5.08E-04	kg		kg
Xylene	1.05E-06	kg	3.13E-05	kg	2.90E-06	kg		kg

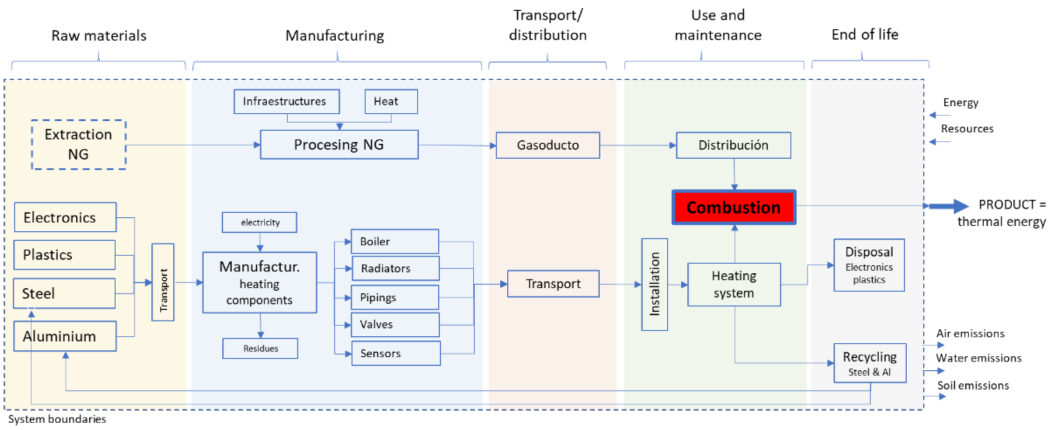

Figure 2 *LCA diagram of a heating system based on natural gas*

Table 3. *Classification and characterization steps in the impact assessment of the emissions generated by the combustion of NG (template for biomass combustion)*

Classified elementary flows

Climate change	NATURAL GAS kg emitted/GJ	BIOMASS kg emitted/GJ	Characterisation factors	
Fossil carbon dioxide	5.87E+01		1	kg CO2 eq/kg
Biogenic carbon dioxide			0	kg CO2 eq/kg
Dinitrogen monoxide	5.35E-03		298	kg CO2 eq/kg
Fossil methane	4.17E-03		36	kg CO2 eq/kg
Biogenic methane			34	kg CO2 eq/kg
Human toxicity - non-cancer				
Acetaldehyde	1.95E-05		4.89	kg 1,4-DB eq/kg
Acrolein	3.13E-06		6150	kg 1,4-DB eq/kg
Benzene	5.86E-06		1.35	kg 1,4-DB eq/kg
Formaldehyde	3.47E-04		114	kg 1,4-DB eq/kg
Methanol			0.156	kg 1,4-DB eq/kg
Naphthalene	6.35E-07		8.16	kg 1,4-DB eq/kg
PAH, polycyclic aromatic hydrocarbons	1.07E-06		19.3	kg 1,4-DB eq/kg
Propylene oxide	1.42E-05		42.4	kg 1,4-DB eq/kg
Toluene	6.35E-05		0.82	kg 1,4-DB eq/kg
Xylene	3.13E-05		1.03	kg 1,4-DB eq/kg
Photochemical oxidant formation				
Acetic acid	7.34E-05		0.0326	kg NMVOC/kg
Formaldehyde	3.47E-04		0.877	kg NMVOC/kg
Methanol			0.0471	kg NMVOC/kg
Nitrogen oxides	4.98E-02		1	kg NMVOC/kg
Toluene	6.35E-05		1.08	kg NMVOC/kg
Terrestrial acidification				
Sulphur oxides	3.03E-04		1	kg SO2 eq/kg
Nitrogen oxides	4.98E-02		0.56	kg SO2 eq/kg
Ammonia			1.96	kg SO2 eq/kg

Characterised values

Climate change	60.42	0.00	kg CO2 eq
Human toxicity	0.06	0.00	kg 1,4-DB eq
Formation of photochemical oxidants	0.0502	0.00	kg NMVOC
Terrestrial acidification	0.0282	0.00	kg SO2 eq

cycle approach of the study, on the different processes that make up each stage and on the fact that this case study requires the analysis of two value chains: the heating equipment and the fuel (natural gas).

It should also be stressed that this simplified case study considers only a single process within the life cycle of the heating system (natural gas combustion). The student should understand that a full LCA of this system should include a broader range of processes and should be made acquaintance with the concept of system boundaries.

STEP 2: the student should understand the inventory flows associated with each process in the LCA diagram and the emission values described in the inventory data for the combustion of natural gas (in terms of kg of emission per physical unit of fuel combusted). This will be transformed into kg of emission per functional unit, which in this case is the production of 1 GJ of thermal energy. This will be calculated considering the lower heating values of each fuel and the efficiency of each boiler. The importance of the functional unit in LCA will be emphasized at this point.

STEP 3: the impact assessment method should be evaluated in this step, including the selection of impact categories, the characterization factors, the units of measurement and the different impact potentials for each elementary flow. The origin of the normalization factors and their relationship with global emissions in each impact category should also be discussed (in this case from ReCiPe2016) and other sources of information should also be identified (e.g., EF3.1, CML-IA, Impact World+).

Table 2 *Impact assessment method with characterization factors (for the categories of climate change, human toxicity, photochemical ozone formation and acidification) and normalization factors*

CHARACTERIZATION FACTORS

Climate change	Characterisation factors	
Fossil carbon dioxide	1	kg CO2 eq/kg
Biogenic carbon dioxide	0	kg CO2 eq/kg
Dinitrogen monoxide	298	kg CO2 eq/kg
Fossil methane	36	kg CO2 eq/kg
Biogenic methane	34	kg CO2 eq/kg

Human toxicity	Characterisation factors	
Acetaldehyde	4.89	kg 1,4-DB eq/kg
Acrolein	6150	kg 1,4-DB eq/kg
Benzene	1.35	kg 1,4-DB eq/kg
Formaldehyde	114	kg 1,4-DB eq/kg
Methanol	0.156	kg 1,4-DB eq/kg
Naphthalene	8.16	kg 1,4-DB eq/kg
PAH, polycyclic aromatic hyc	19.3	kg 1,4-DB eq/kg
Propylene oxide	42.4	kg 1,4-DB eq/kg
Toluene	0.82	kg 1,4-DB eq/kg
Xylene	1.03	kg 1,4-DB eq/kg

Photochemical oxidants	Characterisation factors	
Ácido acético	0.0326	kg NMVOC/kg
Formaldehído	0.877	kg NMVOC/kg
Metanol	0.0471	kg NMVOC/kg
Óxidos de nitrógeno	1	kg NMVOC/kg
Tolueno	1.08	kg NMVOC/kg

Acidification	Characterisation factors	
Óxidos de azufre	1	kg SO2 eq/kg
Óxidos de nitrógeno	0.56	kg SO2 eq/kg
Amoniaco	1.96	kg SO2 eq/kg

NORMALISATION FACTORS

	World Recipe H
Climate change	0.000145
Human toxicity	0.00307
Photochemical oxidants	0.0176
Terrestrial acidification	0.0262

STEP 4: Table 3 describes the application of the classification stage where individual elementary flows from the original inventory are placed in the spreadsheet within the environmental category that they affect.

STEP 5: The characterization step is carried out multiplying each of the elementary flows by its characterization factor and summing these results to yield the total impact produced in each of the impact categories considered. At this point, it should be important to discuss differences in the impact potentials of the various compounds emitted into the atmosphere and the use of a common unit of measurement for each impact category (see Table 3).

STEP 6: The normalization step is performed by dividing the previously calculated characterized impact values by the normalization factors (see Table 4). At this stage, the level of uncertainty introduced into the analysis should be discussed.

Table 4 Normalization and weighting steps in the impact assessment of the emissions generated by the combustion of NG (and template for combustion of biomass)

Normalized values

Values E6	NATURAL GAS	BIOMASS	Normalization factors INVERSE (1/NF) World Recipe H
Climate change	8761	249	6897
Human toxicity	183	91	326
Formation of photochemical oxidants	884	3310	57
Terrestrial acidification	739	2945	38
	10566	6594	

Normalizados en base 100		
Climate change	82.91%	3.77%
Human toxicity	1.73%	1.38%
Formation of photochemical oxidants	8.36%	50.19%
Terrestrial acidification	7.00%	44.67%
	100.00%	100.00%

Weighted values

	NATURAL GAS	BIOMASS	Weighting factors 20 Pt distributed among 4 categ
Climate change	70084	1989	8
Human toxicity	732	363	4
Formation of photochemical oxidants	5303	19858	6
Terrestrial acidification	1478	5891	2
	77,597	28,100	AGGREGATED indi

STEP 7: The weighting step in this exercise is applied by distributing points (20) among the impact categories according to the subjective importance assigned to each of them. In this step, a participatory exercise should be carried out to define these weighting factors among the four impact categories considered. This should open a discussion about the subjectivity of this step and the different perceptions that may stem from different cultural, geographical, political and economic backgrounds. The normalized values will be multiplied by these weighting factors produced by the students before adding them up to determine an aggregated impact indicator that describes the environmental performance of the natural gas heating system.

STEP 8: This interpretation step should be used to critically evaluate the results and identify the different impact categories contributing to the environmental performance of the heating system.

Based on the knowledge acquired in this first guided exercise, students will be given time to apply this procedure again (from Step 1 to Step 8) on the biomass heating system. This exercise will lead to the calculation of new set of characterized, normalized and final aggregated indicator.

The aim of this second exercise, carried out independently by the students, is to consolidate the knowledge acquired in the first exercise led by the teacher and to acquire initiative in the application of the LCA methodology. In this second analysis, Step 8 is of the utmost importance and should include: comparative analysis of inventory flows, characterized results, normalized values and aggregated indicator from the two heating systems; uncertainty and limitations of the exercise and the methodology; application of results for decision making.

4. Conclusions

This article describes a teaching innovation exercise focused on the development of knowledge and competences in the area of environmental sustainability analysis and specifically on the life cycle analysis tool. This work is presented in response to growing demand of students and professionals in this field. The exercise described in this article has proven to be effective for the training of undergraduate and postgraduate students unacquainted with such quantitative methodologies for sustainability measurement and the life cycle approach.

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