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Environmental Life-Cycle Impacts of a Single-family House in Portugal: Assessing Alternative Exterior Walls with two Methods

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ABSTRACT

The main goal of this paper is to assess alternative exterior walls options to support decision at project level of new buildings in Portugal towards reduced life cycle energy and environmental impacts. A life-cycle model for buildings has been developed focusing on alternative external wall systems (single, double) and contemporary materials. A comprehensive life cycle impact assessment (LCIA) is presented, including results for two well-known LCIA methods: *CML2001* and *Eco-indicator'99,* which are compared on their performance through application to the same life cycle inventory for a single-family house in Portugal.

Key Words: *Building envelope; environmental impacts; life cycle assessment; single-family house.*

1. INTRODUCTION

Building sector accounts for 40% of total energy consumption in European Union (EU) and is responsible for significant environmental impacts. To apply the European Energy Performance Building Directive 2002/91/EC in the Portuguese context, a new regulation with two codes have been implemented in 2006. The code of buildings thermal behavior characteristics, known as RCCTE [1], applied to residential buildings, aims to achieve indoor comfort with lower energy consumption levels; however it disregards the embodied energy and the life cycle environmental impacts of building materials which, according to a life cycle thinking perspective, should be accounted for.

The first life cycle (LC) studies for buildings [2, 3] were published about 10 years ago. For example, Keoleian [2, 3] evaluated life cycle energy, greenhouse gas (GHG) emissions, and costs of a single family house in Michigan to find opportunities for conserving energy throughout pre-use (materials production and construction), use (operational use and maintenance) and demolition phases. Since then, several LC studies have been published for buildings; however, most of them focused only on energy requirements and greenhouse gas emissions [4, 5, 6, 7, 8, 9]. Many of those studies [5, 6, 8, 9] showed that heating had a preponderant weight in life cycle energy requirements and GHG emissions for buildings located in temperate and cold climates. Concerning LC studies published for Portugal, Monteiro and Freire [10] developed a life cycle model for a typical single family house in Portugal and compared various exterior wall solutions in terms of primary energy and GHG emissions. Results showed that heating was the dominant process (representing 68% of LC energy requirements) followed by building materials (18%). Exterior walls were by far the most significant construction component with 35% of embodied energy and 43% of CO_2 emissions associated with the construction phase. The results also showed that the houses with wood in their compositions allowed a

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significant reduction in building GHG emissions and had lower non-renewable energy requirements.

Increasing efforts to reduce operational energy consumption in buildings may result in more (embodied) energy incorporated in construction and building materials. Consequently, the relative importance of material selection tends to rise and become more expressive, especially when considering low energy houses. For example in a environmental Life Cycle Assessment (LCA) study for a university building [11], in which a full set of environmental impact categories were considered, it was identified that improvements related to the building envelope at design stage could significantly reduce cumulative burdens even at the expense of greater material production burdens. Life cycle modeling enables these tradeoffs to be quantified [11].

In this research, a literature review has been performed to identify and characterize full environmental LCA studies performed to single family houses. We have found five studies that compare alternative building scenarios, using the CML LCIA method [12, 13, 14, 15, 16]. Briefly, Peuportier et al. [12] performed an environmental LC assessment of 3 houses in France, a standard, a solar house and a well insulated wood house. The conclusions pointed out that the wood high-insulated house had almost half of the impacts of a standard house. Two studies [15, 16] compared a standard house with a low energy alternative, one in Switzerland [15] and the other in Italy [16]. Other work assessed design improvements in a Spanish house [13] concluding that LC management played a signifcant role in supporting decision making; a comparison of the different LC phases of buildings (a Spanish vs. a Colombian house) evaluating different energy supplies for use phase showed that the origin of the energy source used in each Country played an important role to minimize environmental impacts of use phase [17].

More recently, a comprehensive European study [14, 18] assessed the improvement potential to reduce environmental impacts in EU buildings. Various types of buildings were assessed and different improvement options were tested as a higher insulation in walls and roofs. Results showed that new buildings are by far much better than existing ones. The study showed that the building envelope represents a significant part of the environmental impacts of new buildings, and that exterior walls are a significant component.

For Portugal only a few studies have applied the full LCA methodology to the entire LC of buildings. Armando Pinto [19] applied LCA to two residential buildings case studies and concluded that the construction and demolition phase are responsible for nearly 30% of the environmental impact of buildings. The impact categories used were the primary energy consumption, global warming, acidification, ozone layer depletion, water consumption and waste production, which were taken from different LCIA methods. Gervásio [20] performed a LC energy study of a Portuguese steel framing house and assessed the influence of thermal insulation thickness in LC energy requirements. Two systems for the sustainability assessment of buildings and building processes have been developed for Portugal, namely *Lider A* [21, 22] and the MARS-ER (Methodology for Relative Sustainability Assessment of Residential Buildings) [23, 24]. Martins [25] have used LCA to assess different building structures and Soares [26] to compare construction materials in Portugal.

For building LCA practitioners it is not obvious which method to choose and neither if the interpretation of results from different LCIA methods leads to coincident or contradictory conclusions [27]. Impact categories, characterization indicators and factors vary between LCIA methods. As different methods model different aspects, a meaningful comparison between them is difficult to perform [28]. We have not found in the literature review performed, any published study for buildings comparing LCIA methods with the purpose of determining the extent to which the results of a LCA are influenced by the LCIA method applied.

The present paper builds on a previous published study [10]. The main goal of this study is to perform a comprehensive environmental Life Cycle Assessment (LCA) of alternative exterior walls for a Portuguese single-family house aiming at identifying optimal environmental solutions. Results with two Life Cycle Impact Assessment (LCIA) methods (CML 2001 and Eco-indicator'99) have been calculated. This paper has 4 sections, including this introduction. The next section presents the method and the LC model developed. The third section presents the LCIA results obtained with two methods. The final section draws the conclusions together.

2. METHODS: LCA WITH TWO ALTERNATIVE LCIA APPROACHES

The life cycle assessment (LCA) is a methodology that evaluates the potential environmental impacts of products and services. LCA has four interrelated phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results [29, 30].

In the goal and scope definition phase, the study aims are defined and the system boundary is set in order to identify the processes included. The life cycle inventory involves data collection and calculation procedures to quantify relevant inputs (resources, materials and energy) and outputs (emissions and waste) associated with the functional unit. In LCIA the inventory data are aggregated into specific environmental impact categories. Various LCIA methods have been developed to convert the inventory data (inputs and outputs) into potential environmental impacts. According to ISO 14044 [30], a LCIA method is composed of two mandatory elements, classification that attributes environmental burdens to impact categories and characterization, which converts inventory results into category indicators through characterization factors. Each LCIA method has a specific set of impact categories and different LCIA methods will lead to distinct type of results (impact categories, units).

In this research, the variability between LCIA results has been assessed by applying two well-known LCIA methods: CML 2001 and Eco-indicator 99, to the same life cycle inventory model and scenarios. A fundamental difference between the two methods is that the CML 2001 has a problem-oriented approach with midpoint impact categories, while the Eco-indicator'99 has a damage oriented approach, resulting in end-point impact categories. [28, 31].

The CML 2001 method, developed under the lead of the Center of Environmental Science (Leiden University), has ten impact categories in the baseline version that is presented in Table 1. The most widely used categories are abiotic depletion (AD), global warming potential (GWP), acidification (Acid), eutrophication (Eut), ozone layer depletion (OLD) and photochemical oxidation (PO). Due to missing scientific robustness of the underlying methods, environmental impact categories related to human toxicity and ecotoxicity usually are not addressed [18, 32].

The Eco-indicator'99 (EI'99) method models the cause-effect chain up to the endpoints, resulting in damage impact categories, with considerably higher uncertainty than the mid-point approach. The characterization is firstly made for eleven impact categories, shown in Table 1, which according to their impact indicator can be grouped in three damage categories: human health, ecosystem quality and resources. The damage to human health is expressed in disability adjusted life years (DALY), which is an index used by the World Bank that represents the sum of years of life lost by premature mortality and the lost of years of productive life due to incapacity. The ecosystem quality damages are expressed in potentially disappeared fraction of species in a certain area over a period of time ($PDFm^2.y$) due to the environmental load (acidification, eutrophication, land use and ecotoxicity). The damage to resources is expressed by the indicator surplus energy (to extract minerals or fossil fuels) because it is assumed that mankind will extract the best resources first leaving the lower quality resources for future extraction [31].

The magnitude of the LCIA results can be further calculated relatively to some reference information. This is called Normalization and the aim is to better understand the relative magnitude for each indicator result. It may be also helpful in, for example, checking for inconsistencies and providing information on the relative significance of the indicator results.

The CML method has different sets of normalization: world (1990), Western Europe (1995) and the Netherlands (1997). In the present research, the Western Europe context was adopted. The normalization calculation consists of dividing the LCIA results of each impact category per the reference value (the total impact from emissions, extractions, radiation and land use, per impact category for Western Europe over a year) [31]. For the Eco-indicator'99, normalization is performed on damage category level for Europe (damage caused by one European per year), mostly based on 1993 as base year, with some updates. The normalization set is also dependent on the perspective chosen. There are three perspectives within the Eco-indicator'99 method: Hierarchist, Individualist and Egalitarian. The standard perspective, Hierarchist (H) was assumed in this study. The reference value used to calculate Eco-indicator'99 normalized results is taken for European context (environmental impact per year and per capita, considering a population of 386 million for Europe) [31].

3. LIFE CYCLE MODEL AND SCENARIO ANALYSIS

A model representing the two most significant building LC phases (construction and use phase) has been developed. An attributional LCA was implemented to the processes shown in Figure **1**. The aim of this model is to support decision at project level evaluating the LC environmental performance of a Portuguese single-family house with seven alternative exterior wall solutions. The model has been implemented in the Simapro 7 software (www.pre.nl).

Table 1. CML2001 and Eco-Indicador'99 impact categories

CML 2001 Category	**Unit**	**Eco-indicator99 Category**	**Unit**
Abiotic depletion	kg Sb eq	Fossil fuels Minerals	MJ surplus MJ surplus
Acidification Eutrophication	kg SO_2 eq kg PO_4 eq	Acidific./eutrophi.	$PDF*m^2.y$
Global warming	kg CO_2 eq	Climate change	DALY
Ozone layer depletion	kg CFC-11 eq	Ozone layer	DALY
Photochemical oxidation	kg C_2H_4	Resp. organics	DALY
Freshwater ecotoxicity Marine ecotoxicity Terrestrial ecotoxicity	kg 1,4-DB eq	Ecotoxicity	$PDF*m^2.y$
Human toxicity	kg 1,4-DB eq	Carcinogens Resp.inorganics	DALY DALY
		Radiation Land use	DALY $PDF*m^2.y$

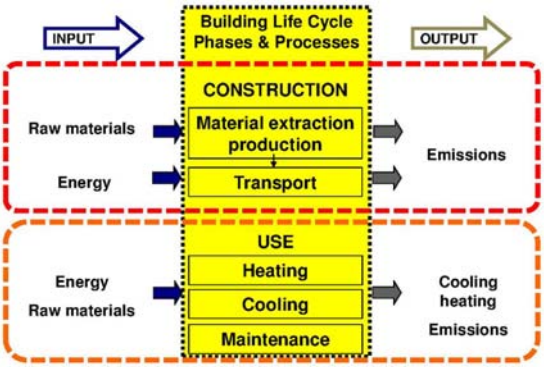

Figure 1. Building LC Phases and processes

Table 2. Single-family house scenarios

Scenario	Exterior wall Characteristics	insulation (cm)
H0.	Double hollow brick masonry	XPS 4
H1.	Double facing and hollow brick masonry	XPS 4
H2.	Lightweight concrete blocks masonry	EPS 5
H3.	Thermal concrete blocks masonry	EPS 4
H4.	Autoclaved aerated concrete block masonry	EPS 3
H5.	Hollow brick masonry & ext. wood cladding	XPS 4
H6.	Wood frame and cladding	XPS 5

The case study implemented is based on a typical single-family house located in Coimbra, Portugal, with an expected life span of 50 years and 132 m^2 of living area. The functional unit selected is the building living area over the building life span (132 m^2 x 50 years). The results report to it in order to analyze the whole building performance for the various exterior wall solutions. The house was assumed to be occupied by a 4-people family. Following the RCCTE [1], heating/cooling set-points of 20ºC/25ºC, respectively, were considered as well as 4 W/m^2 of internal heat gains (from lights, electrical appliances and occupants). In order to focus on the living area and building exterior walls, no basement, garage and loft were included in the analysis. Construction materials and techniques used in Portugal were assumed, and all the envelope elements were defined in order to fulfill the current thermal regulation requirements [1].

Table 2 lists the seven alternative scenarios considered. The double hollow brick wall was assumed to be the base case scenario because it represents a common construction practice in Portugal. The other exterior walls studied have different materials in their composition (facing brick, concrete blocks and wood), but were defined to have similar thermal coefficients (U-values between 0.47 and 0.51 $W/m^2.ºC$) and thus generate similar heating and cooling requirements. More details about the external wall scenarios are provided in Monteiro and Freire [10]. The house technical drawings are shown in Figure 2.

Construction phase is defined by material production and transport processes. An additional 5% of materials (by mass) were accounted to consider losses on site due to cutting and fitting processes. Eight different building components were considered: exterior and interior walls, roof, first floor, ground floor, structure, windows and doors. The main building construction data were obtained from the *ecoinvent* database [33], which presents average European data for the production of construction and building materials. Transportation of the construction materials to building site was included assuming lorry transportation, with European fleet average characteristics. For scenario analysis it was assumed that exterior wall materials travelled 65 km.

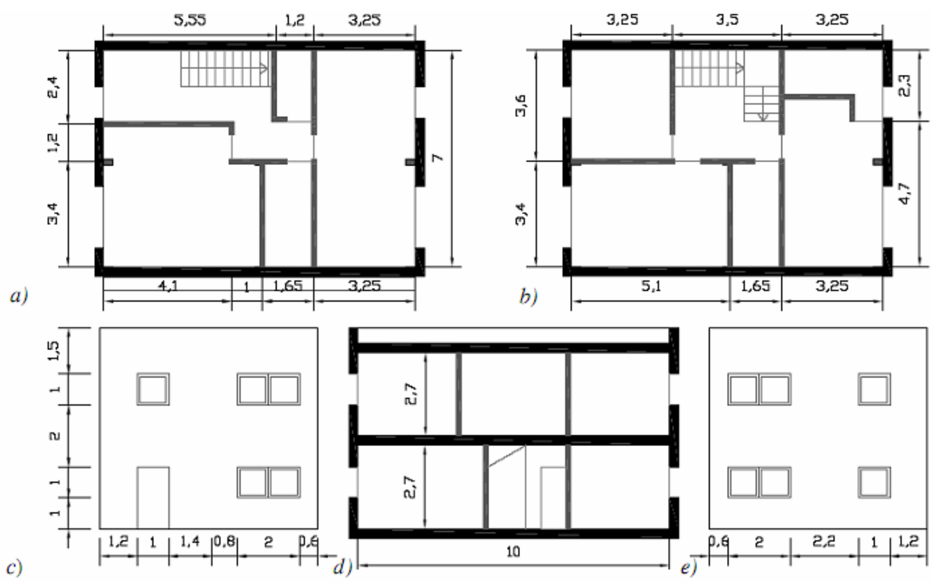

Figure 2. Building technical drawings

The use phase included the heating and cooling operational requirements and building maintenance. The heating and cooling system of the house is a 10 kW heat pump with a coefficient of performance (COP) of 2.8 for heating and 2.0 for cooling. The annual operational energy (heating and cooling) was calculated based on the RCCTE (2006) simplified method [1]. Similar heating and cooling requirements were obtained for all the exterior wall scenarios: on average 71.8 kWh/m^2.year for heating and 3.8 kWh/m^2.year for cooling (a maximum variation of 3% among the scenarios). A maintenance activity schedule for each building component was established based on material producers' information and on [2, 34].

Some simplifications were employed in the LC analysis developed. In the construction phase, the equipments used and the transportation of laborers to work site were not included because the relevance of these processes is minor in residential buildings. Some equipment and processes of the use phase were also excluded from the system boundary: interior furniture, electrical appliances, HVAC equipment and sanitary ceramics, energy used for lighting, cooking, heating water and water consumption. The end of life phase (dismantlement and demolition) was not included because it is considered to be of minor importance for South European single family houses. According to a recent European study, it accounts for less than 3.2% of the overall environmental impacts [18], and it is a difficult phase to foresee, particularly because buildings are long lasting [12].

4. RESULTS AND DISCUSSION

4.1 CML2001 LCIA Results

Life cycle impact assessment results of CML 2001 have been calculated for seven exterior wall house scenarios. The results show that the scenario with the lowest environmental impacts, in nine out ten categories, is the wood wall house (H6). Two scenarios have high environmental impacts: H1 (facing brick wall house) and H3 (thermal concrete block house). H1 has highest impacts for abiotic depletion, global warming (GWP) and eutrophication; H3 for acidification, human toxicity, photochemical oxidation and ecotoxicity.

Comparing the house scenarios with highest and lowest LC impacts for each category, we observed that H6 has less 15% of GWP impacts and 6% of abiotic depletion and of eutrophication impacts than H1. The wood wall house has also less 8% of photochemical oxidation and 5% of acidification than H3. Concerning ozone layer depletion, H6 has the highest impacts mostly due to the type and thickness of the Insulation (XPS). The scenarios with lower impacts are those with EPS insulation applied with ETICS – H2, H3 and H4; these scenarios have less 24% of the H6 impacts.

CML 2001 LCIA normalized results are presented in Figure 3. It can be seen that heating is the most important LC process for eight categories. Observing the scenario with higher impacts for each category, heating represents between 63% of emissions (eutrophication) to 86% (terrestrial ecotoxicity). The second most important process is materials production, which holds 21% of emissions (GWP) to 7% of emissions (terrestrial ecotoxicity).

CML LCIA normalized results show that marine ecotoxicity is the most significant impact category; however, ecotoxicity categories have high uncertainty and still miss scientific robustness [14, 32]. Thus, not much attention was given in our research to the four toxicity categories. Abiotic depletion is the second most significant impact category, being followed by terrestrial toxicity, acidification and global warming. Ozone layer depletion (OLD) is the category with the lowest normalized impacts.

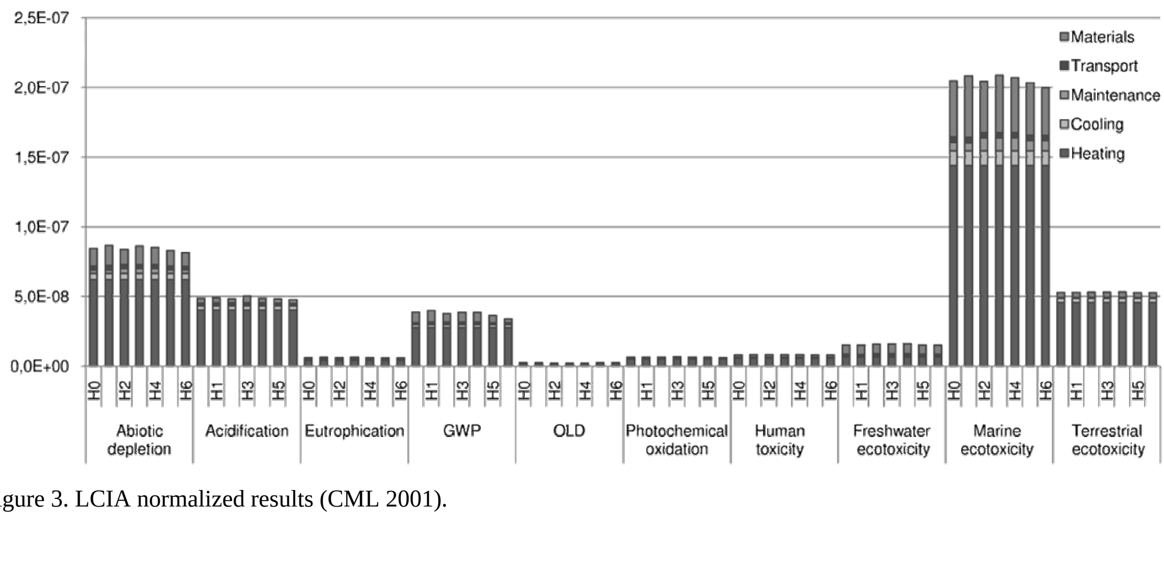

Figure 3. LCIA normalized results (CML 2001).

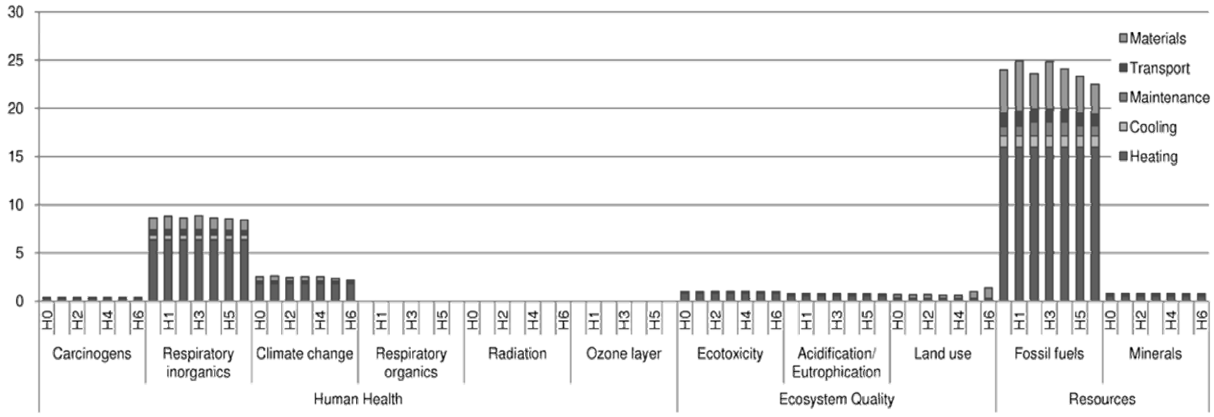

Figure 4. LCIA normalized results (Eco-indicator'99)

4.2 Eco-indicator'99 LCIA Results

Eco-indicator'99 (EI'99) results for the seven building scenarios were calculated. The normalized results are shown in Figure 4. Regarding the scenario with the lowest environmental impacts, similar results to the CML approach can be observed. The wood wall scenario (H6) performs better in nine out of eleven categories. Moreover, heating is also the most significant LC process for seven Eco-indicator categories. Evaluating the scenario with the highest impacts for each category, heating represents between 56% (ozone layer) to 78% (ecotoxicity). Material production is the most significant process for 3 impact categories, accounting from 57% (respiratory organics) to 80% (land use); for the remaining categories it is the second most expressive LC process.

Looking at the scenarios with highest and lowest LC results for each category, we observed that H6, when compared to H1, has less 10% at fossil fuels, 15% at climate change, 6% at acidification/eutrophication and respiratory organics. Comparing H6 to H3 results, H6 has less 4% at minerals category, 5% at respiratory inorganics, and 2% at ecotoxicity. In terms of radiation category, H6 has less 16% of the H4 impacts, whereas in land use category H4 presents less 56% of the H6 impacts, In OLD category, the variation of EI'99 results is similar to CML results.

It can be observed in Figure 4 that the fossil fuels category is the most significant one for all scenarios. The total fossil fuel building requirements represent an annual European consumption equivalent to 22.5 persons (189 GJ surplus) for wood house (H6) and 24.8 persons (210 GJ surplus) for double brick house (H1).

Eco-indicator'99 normalized results have been further grouped in three damage categories: resources, ecosystem quality and human health, which are presented in Figure 5. Scenario H6 has the lowest impacts for the resources and human health categories, which are the most significant (mostly due to fossil fuels, respiratory inorganics and climate change impact categories). Comparing the house scenarios with highest and lowest impacts, H6 presents less 10% than H1 impacts at resources category, and less 7% than H1 at human health.

However, in terms of ecosystem quality category, H4 shows the lowest environmental impacts (24% less than H6). This is due to the land use impact category, in which the wood wall house scenario (H6) has the highest impacts because of land use change.

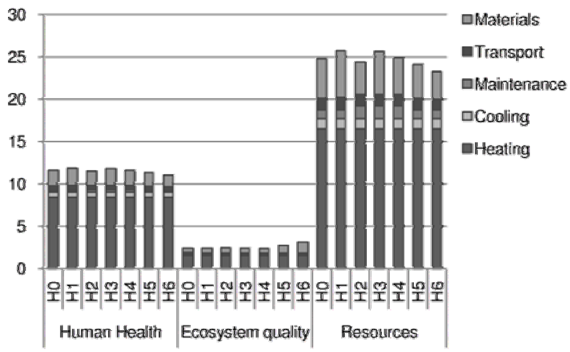

Figure 5. LCIA damage normalized results (EI'99)

5. CONCLUSIONS

A comprehensive environmental Life Cycle Assessment (LCA) of seven alternative exterior walls for a Portuguese single-family house has been performed with the goal of identifying optimal environmental solutions. The house was assumed to be occupied by a 4-people family and the operational energy for heating and cooling was estimated according to current Portuguese thermal building regulations. Two life cycle impact assessment (LCIA) methods have been applied: CML 2001 (problem oriented) and Eco-indicator 99 (damage oriented). The LCIA results obtained with both methods show concordance towards the following conclusions: i) heating is the most important life-cycle process, followed by material production; ii) the wood wall house is the preferable exterior wall scenario in terms of environmental impacts; iii) the facing brick wall house and the thermal concrete block house in general have the highest environmental impacts. A total reduction of 15% of GWP (CML2001) or climate change (EI'99) can be achieved for a house with wood walls instead of facing brick walls.

A detailed comparative analysis of the environmental impact calculated for the two LCIA methods show that five CML categories (global warming, ozone layer depletion, acidification, eutrophication and abiotic depletion) have similar results to their counterpart Eco-indicator categories. However, the remaining categories do not show similar results, namely CML 2001 and EI'99 point out different scenarios with the highest impacts for each category. Concerning normalized LCIA results, the two methods lead to different conclusions. EI'99 normalized results show fossil fuels, respiratory organics and climate change as the most significant categories. CML 2001 indicates that marine ecotoxicity categories followed by abiotic depletion, terrestrial toxicity, acidification and global warming are the most significant impacts.

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