The contribution of the maintenance phase for the environmental life-cycle impacts of a residential building

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ABSTRACT: In Portugal, there is a large and excessive housing supply. Therefore a responsible and adequate attitude towards its management is strongly required. A tailored preservation of the housing infrastructure, embracing both environmental and financial aspects, will facilitate monitoring its expected degradation, minimizing running-costs, extending lifetime and fulfilling occupants' satisfaction. This study will be focused on assessing the contribution of the maintenance phase for the whole environmental life-cycle impacts of a single family dwelling in Portugal. The aim of the study is to assess the environmental impacts related to the maintenance scenarios of a conventional residential building in order to identify materials and building technologies that contribute most to those impacts. This research will disclose the relevance of the maintenance phase on the total life-cycle impacts of a conventional residential building and will provide a basis for supporting decision-making during the selection of optimized materials, construction products and technologies.

1 INTRODUCTION

The construction in general and the building sector in particular, play an important role on environmental degradation. Thus, it is necessary to promote the sustainability of construction. The buildings during their life cycle, which develops from the construction phase until the phase of demolition, passing through the phases of operation, maintenance and rehabilitation, leading to numerous environmental impacts is important to know in order to boost the development of new solutions and their implementation during the project. It is thus important to perform an analysis of the various phases of the life cycle of buildings, in order to assess the environmental impacts associated with each of these and know what the environmental impacts categories most affected.

In residential buildings, most of the environmental impacts are associated with the operation phase and to the energy consumption for heating, cooling, electrical appliances, production of hot water and lighting (Ortiz et al, 2009). The type and quantity of materials used in a building are factors that most influence the embodied environmental impacts and energy. Additionally it influences the amount of waste produced in the construction, maintenance and end-of-life phases. In Portugal, it is estimated that in a conventional building (with a lifetime of 50 years), the embodied energy in building materials is around 3750 kWh/m2, corresponding to about 10-15% of the total energy consumed during the operation phase (Mateus et al, 2007).

In Portugal, the existing information in the field of environmental impacts associated with construction, more specifically in the building sector is still scarce. Thus, it is intended that this study contributes to reducing the environmental impacts of the life-cycle of a building.

The main objective of this study is to determine which materials and building technologies that contribute most to the overall environmental impacts. For this purpose the life-cycle of a conventional residential building will be analyses. The case study is a detached single family house, since this is the most common type of house in Portugal.

2 DESCRIPTION OF BUILDING

The building under study is a traditional detached single family house with two floors (ground floor and first floor) a total net area of approximately 268 m2 and typology T4 (four bedrooms). The house is located in the municipality of Esposende, district of Braga. On the ground-floor this building has a garage, laundry, kitchen, living room, hall and toilet room. On the first floor it has two bedrooms, one with a private toilet, one office and one toilet. Figure 1 presents the ground and first floors of the building under study.

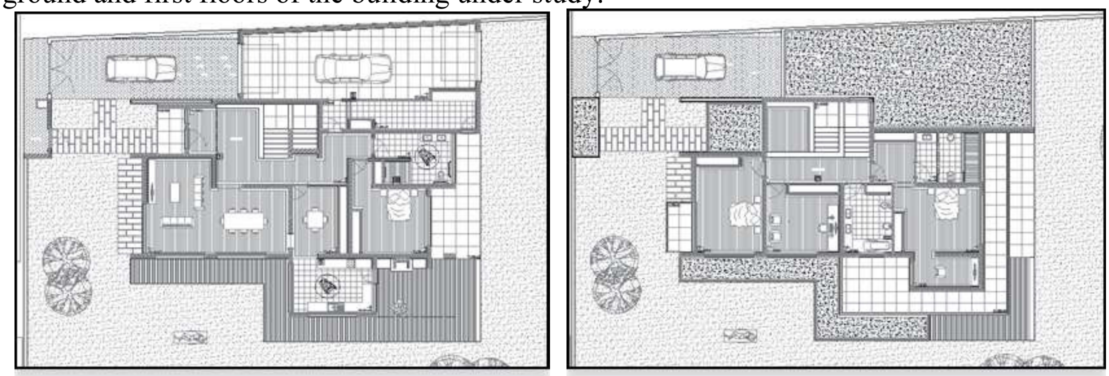

Figure 1. Plant of the ground and first floor.

This building uses a conventional building system, consisting in lightweight slabs and reinforced concrete pillars and beams. Walls are cast in hollow brickwork. The external walls have a double hollow brick section with a 10 cm thick air gap partially filled with insulation - extruded polystyrene (XPS). On the outside, most of the area is finished with a painted conventional mortar, being the remaining area finished with hardwood (less conventional in Portugal). Figures 2 and 3 show the elevations of the building and the used finishing materials.

Indoor walls are single hollow brick walls finished in both sides with painted plaster. Wet areas (toilets, kitchen and laundry) are covered with ceramic tiles.

The coating of the floors of sanitary facilities, kitchen, laundry room, garage and balconies are in ceramic tiles, while in other areas are finishes in varnished wood. All ceilings, with the exception of the exterior, toilets and garage are finished with plasterboard, with rock wool in the air gap. Window's glazing is in double glass and aluminum frames with thermal break. The exterior doors have two faces in wood, with the air space completely filled with extruded polystyrene. The interior doors are in fiberwood.

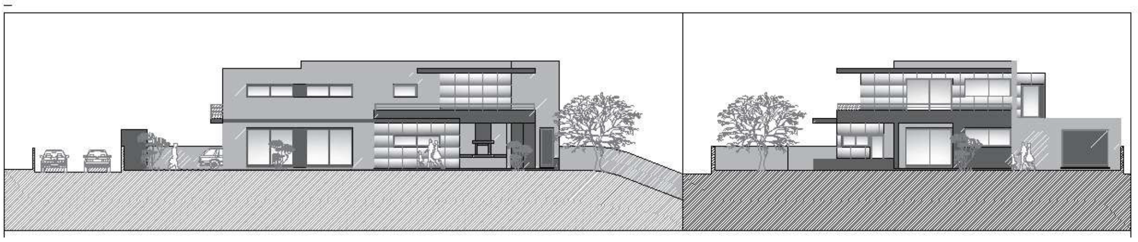

Figure 2. South and East Elevation.

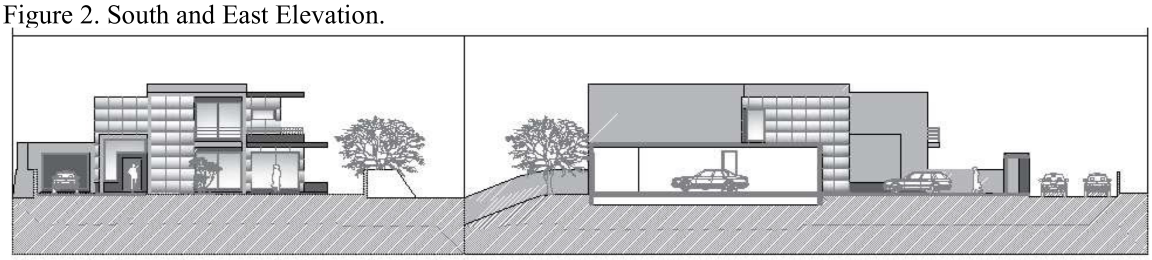

Figure 3. West and North elevations.

3 METHODOLOGY

This study follows the general methodology for life-cycle assessment (LCA). This methodology allows assessing potential environmental impacts of a product or system during all life-cycle phases.

3.1 *Purpose and scope*

The purpose of this study, as stated above, consists in identifying the materials and building solutions which most contribute to the overall impacts of a conventional building. This step involves defining the context in which the study will be undertaken and identifying the boundaries of the study.

3.2 *Inventory analysis*

For the environmental impacts assessment it was necessary to collect information concerning the various phases of the building's life-cycle.

For the construction phase it was necessary to quantify the materials used in building elements and to identify the location of companies that manufacture the materials. The quantification of the materials was based on the documents published by the National Laboratory of Civil Engineering, LNEC (Manso et al, 2007). In relation to the transportation of materials, this process is an important input in the LCA analysis, since it is related with considerable environmental impacts. This input is most related to the fossil fuels consumed during transportation of materials.

As already mentioned, the case study is located in Esposende. Therefore, for considering the transport distances, the study assumes that the building materials and products are coming from the nearest companies.

For the maintenance phase was necessary to conduct a study on possible scenarios of maintenance, with their frequencies, applied to the building under study. The maintenance scenarios were defined based on two studies, one national and other international (Cóias, 2009 &Perret, 1995). Maintenance operations were divided into three basic categories: minor repairs, major repairs, and total replacement. Small repair operations corresponds to those applied in a area corresponding to 5% of the total area of the building element, the major repair operations corresponds to an area corresponding to 10% of the element, and the total replacement of materials involves the replacement of all materials used in the building element.

The quantification of materials used for maintenance operations is based on the estimated number of applications for a period of 50 years. Table 1 presents the quantities of materials used during the phases of construction and maintenance for that lifetime period.

Figure 4 shows the frequency of maintenance operations during the building's lifetime period. Figure 5 shows the accumulated frequency of maintenance operations.

Regarding the operation phase, study considers the energy consumption for acclimatization (heating and cooling) and for the preparation of hot water. Additionally the study considers the operational water consumption. The energy consumption during the operation phase is obtained using the Portuguese Thermal Building Code (RCCTE, 2006). The amount of water consumed in the operation of the building was estimated using the calculation method presented in the parameter P14 of the building sustainability assessment tool SBToolPT (SBTool, 2010).

The end-of-life scenario considers that metal and glass products are partial recycled (80% for the reinforcing steel, 95% for the other types of steel and 95% for glass materials) and that remaining materials are landfilled.

3.3 *Assessment of impacts*

The environmental impacts assessment was performed using the software tool SimaPro. This tool has embedded LCI inventories which minimizes the time and difficulty of LCI data processing and analysis.

In this study the "endpoint" LCA method Eco-indicator 99 was used, considering an Egalitarian perspective. This is the approach that better meets the aims of the study, since this it is bases in a long term perspective that consider all potential effects. Additionally this is the approach normally used in similar studies In the Eco-indicator 99 LCA method the environmental performance is express in a single score – points (Pt). As lower is the score, better is the product under analysis.

Table 1. Quantities of materials used during the phases of construction and maintenance

Material	Amounts used during Construction Phase (kg)	Amounts used during Maintenance Phase (kg)
Bricks	120000	-
Reinforcing steel	9040	-
Concrete normal	712000	-
Ceramic tiles	5600	-
Bitumen sealing	2710	783
Cement mortar	177000	70200
Glass fibre	1810	6050
Steel, converter, unalloyed	2430	2080
Alkyd paint	1430	5420
Polystyrene foam slab	1300	1310
Lime mortar	9600	1470
Aluminium	271	541
Flat glass, uncoated	1700	-
Rock wool	820	-
Gypsum plaster board	4450	5340
Acrylic varnish	147	595
Wood massive	5570	1340
Gravel round at mine	58700	187000
Cement	1130	1220
Quicklime milled	271	293
Sand	35,5	-

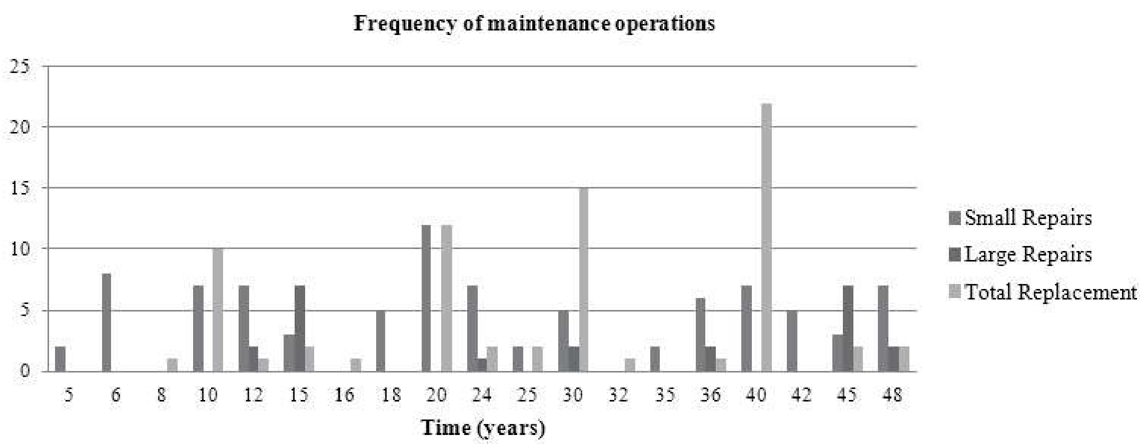

Figure 4. Frequency of the maintenance operations during the building lifetime.

4 PRESENTATION OF RESULTS

The results of this research work are presented in the following sections.

4.1 *Contribution of each material to the embodied impacts*

The first result obtained in this study shows the contribution of each material in the total embodied impacts of the building (Table 2). This result, in addition to the impacts associated with the production of materials, their transportation to the construction site and related construction processes' impacts, includes the end-of-life impacts, according to the abovementioned scenarios. Regarding the contribution of each material, results show that the use of wood positively influences the overall impacts of the building. This is impacts related with the CO2 fixation during tree growth.

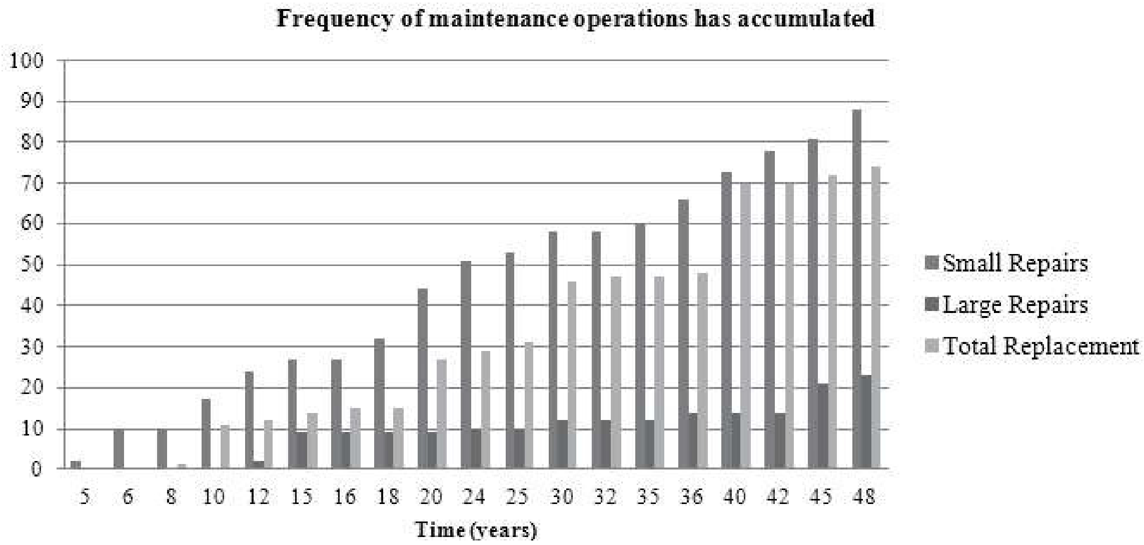

Figure 5. Accumulated frequency of maintenance operations.

Table 2. Contribution of each material to the total impacts of the construction phase.

Material	Total Impacts (Pt)	Contribution (%)
Steel, converter, unalloyed	3,85E+02	3,95
Gypsum plaster board	1,20E+02	1,23
Rock wool	1,16E+02	1,19
Bitumen sealing	4,60E+03	4,72
Glass fibre	3,91E+02	4,01
Flat glass, uncoated	1,27E+02	1,30
Aluminium	2,10E+01	1,65
Cement mortar	9,74E+02	10,00
Ceramic tiles	1,24E+03	12,72
Alkyd paint	3,78E+02	3,88
Lime mortar	1,43E+02	1,47
Bricks	1,34E+03	13,75
Polystyrene foam slab	4,49E+02	4,61
Reinforcing steel	1,39E+03	14,26
Concrete normal	2,02E+03	20,75
Acrylic varnish	2,18E+01	0,22
Gravel round at mine	1,17E+01	0,12
Quicklime milled	6,31E+00	0,06
Cement	2,84E+01	0,29
Wood massive	-1,57E+01	-0,16

Figure 6 shows the contribution of each used material, as a percentage of impacts the overall building impacts. Analysing this figure it is possible to verify that the materials that contribute most to environmental impacts are concrete, brick, and ceramic tiles.

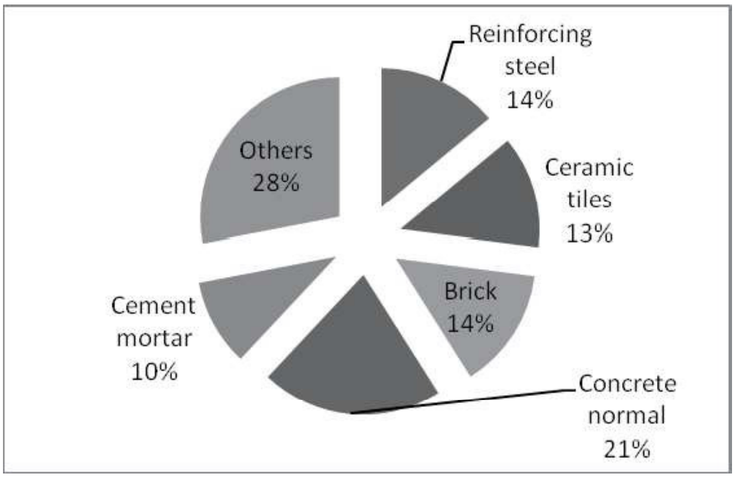

Figure 6. Contribution of the building materials to the environmental impacts of the construction and end-of-life phases.

4.2 *Contribution of each material for the total maintenance phase´s impacts*

This section analyzes the contribution of each material used during the maintenance phase to the total impacts of this phase. This analysis aims at verifying if the materials used in the maintenance phase have a similar contribution to the previous analysis.

Table 3 shows the materials that cause greater impacts during the maintenance phase. Analysing Table 3, it is possible to conclude that the materials that contribute most to the total impacts are not the same of the previous analysis. The reason lies in the fact that maintenance operations are mainly focused in the coatings of building solutions, while the construction phase related impacts are influenced most by those materials that are present in greater quantity:, concrete and brick.

Figure 7 presents, in percentage, the contribution of each maintenance material that most contributes for the environmental impacts of the maintenance phase. Results show that the materials that most contribute the environmental impacts of this phase are: paint impacts (24%), ceramic coatings (22%) and geotextile - glass fiber (22%).

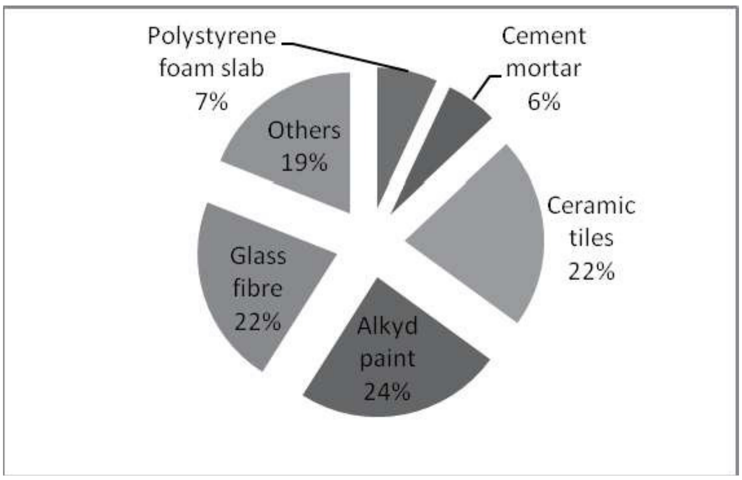

Figure 7. Contribution of maintenance materials to the environmental impacts of the maintenance and end-of-life phases.

Table 3. Contribution of each material to the environmental impacts of the maintenance and end-of-life phases.

Material	Contribution to the total impacts (Pt)	Contribution to the total impacts (%)
Steel, converter, unalloyed	3,57E+02	5,89
Bitumen sealing	1,33E+02	2,19
Ceramic tiles	1,35E+03	22,26
Alkyd paint	1,43E+03	23,57
Glass fibre	1,31E+03	21,60
Polystyrene foam slab	4,53E+02	7,47
Concrete normal	3,85E+02	6,35
Gypsum plaster board	1,44E+02	2,37
Acrylic varnish	8,83E+01	1,46
Aluminium	3,23E+02	5,32
Gravel round at mine	3,71 E+01	0,61
Cement	3,05E+01	0,50
Lime mortar	2,19E+01	0,36
Quicklime milled	6,83E+00	0,11
Wood massive	-3,79E+00	-0,06

4.3 *Contribution of each material to the whole impacts life-cycle impacts of the building*

This section examines the contribution of each material to the whole life-cycle impacts of the building. Table 4 shows for each material the total quantity used in construction and maintenance phase. This table also includes the respective impacts and the total contribution of each material to the whole building's life-cycle impacts.

Table 4 shows that the use of wood positively influences the overall impacts of the building. It is also possible to verify that although mortar and brick are the main materials in the composition of the building, their contribution to the overall impacts is not equally proportionate. This analysis includes the end-of-life scenarios and related transport.

Table 4. Materials used during the lifetime of the building and its contribution to the total life-cycle impacts.

Materials	Quantities (kg)	Material contribution to the life-cycle impacts (Pt)	Material contribution to the life-cycle impacts (%)
Aluminium	812	4,84E+02	3,06
Steel, converter, unalloyed	4430	7,43E+02	4,70
Bitumen sealing	3490	5,92E+00	3,79
Ceramic tiles	11700	2,60E+03	16,40
Alkyd paint	6860	1,81E+03	11,40
Concrete normal	712000	2,02E+03	12,80
Glass fibre	7860	1,70E+03	10,70
Reinforcing steel	9040	1,39E+03	8,78
Cement mortar	248000	1,36E+03	8,59
Brick	130000	1,34E+03	8,47
Polystyrene foam slab	2610	9,02E+02	5,70
Gypsum plaster board	9790	2,65E+02	1,67
Lime mortar	11100	1,65E+02	1,04
Flat glass, uncoated	1700	1,27E+02	0,80
Rock wool	820	1,16E+02	0,73
Acrylic varnish	743	1,10E+02	0,70
Cement	2350	5,89E+01	0,37
Gravel round at mine	24500	4,88E+01	0,31
Quicklime milled	564	1,31E+01	0,08
Wood massive	6920	-1,95E+01	-0,12

In Figure 8 it is visible the contribution of each used material to the whole building life-cycle impacts. The most significant contributions are related to ceramic tiles, concrete, alkyd paint and glass fibre. The ceramic tiles have a lifetime of 40 years and therefore, according to the time boundary of this study they are replaced one time. This situation justifies the greatest contribution of the ceramic tiles on the total impacts.

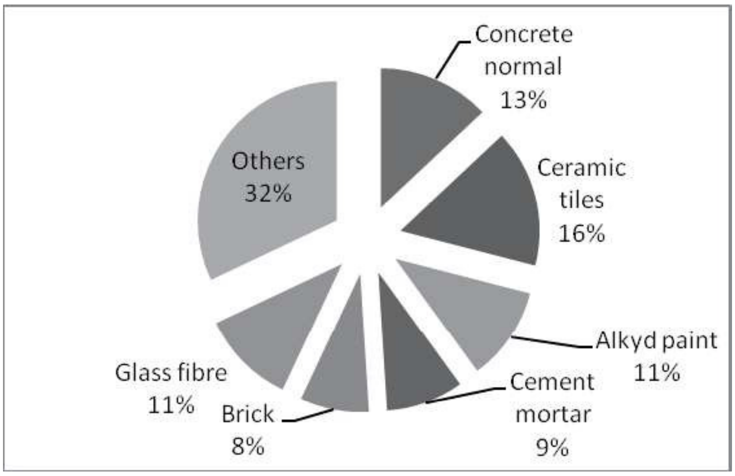

Figure 8. Graphical representation of the contribution of each material impacts to the overall life cycle of the building.

4.4 *Contribution of each life-cycle phase to the whole building environmental impacts*

The following analysis examines the contribution of each life-cycle phase to the total environmental impacts of the building. Table 5 shows the environmental impacts corresponding to each phase and the related percentage.

Table 5. Contribution of each phase to the building's life-cycle impacts.

	Construction Phase	Operation Phase	Maintenance Phase	End of life Phase	Total Impacts o f the building
Environmental impacts	1,13E+04	3,49E+04	2,42E+03	6,22E+03	5,90 E+04
Contribution of the phases	19,1%	59,2%	11,4%	10,3%	100%

Analyzing Table 5, it is noteworthy that the use phase is the one that causes major environmental impacts. With regard to construction, this contributes to more impacts than the maintenance phase.

The use phase is the largest contributor to total impacts of the building as it is occurring at this stage the highest consumption of energy, with the associated environmental impacts. Regarding the end-of-life, this has the smallest contribution to the overall impacts life cycle. This result was mainly due to the positive impacts of the scenarios derived from end-of-life question, in which it admits a high percentage of recycling of metal and glass materials used during construction and maintenance.

5 PROPOSALS OF IMPROVEMENT

This section gives suggestions for improvements, in order to diminish the whole life-cycle impacts of the building. This section presents three improvement proposals: two related with the used building technologies and one related with the operation energy consumption.

In the first proposal (Proposal 1) the building technologies used on the interior and exterior walls are changed. The reason for this change is based on the fact that the brick (ceramic) is a material that has a great contribution to the embodied impacts. In this scenario, interior walls were considered to be in plasterboard and the external wall in a single pane of hollow brick with an external thermal insulation composite system (ETICS), maintaining the same thermal characteristics of the base solution.

The second proposal (Proposal 2) is related with the substitution of all of all aluminium elements (window frames and suspended ceiling structure) used in building (with an average recycled content) by 100% recycled aluminium elements. This proposal aims at evaluating the influence of the recycling content of material that could have a 100% recycling content in the whole building life-cycle impacts.

The third and final proposal (Proposal 3) aims to determine how the reduction of the operational energy consumption contributes for the reduction of the environmental impacts. This proposal is based on the fact that operation phase is the one that contributes most the overall life-cycle impacts. This proposal assumes a 25% reduction in energy consumption for cooling, heating and hot water production. This reduction requires the improvement of the insulation thickness and the installation of renewable energy, for example, solar collectors. Nevertheless the additional construction impacts related to these improvements were not considered in this study.

Figure 9 presents graphically the contribution, individual and cumulative, of the three proposals. Analysing Figure 9 it is possible to notice that Proposal 3 is one that results in a greater reduction of the environmental life-cycle impacts. The main reason for this is that non-renewable energy consumption of provides an important contribution for the total life-cycle impacts.

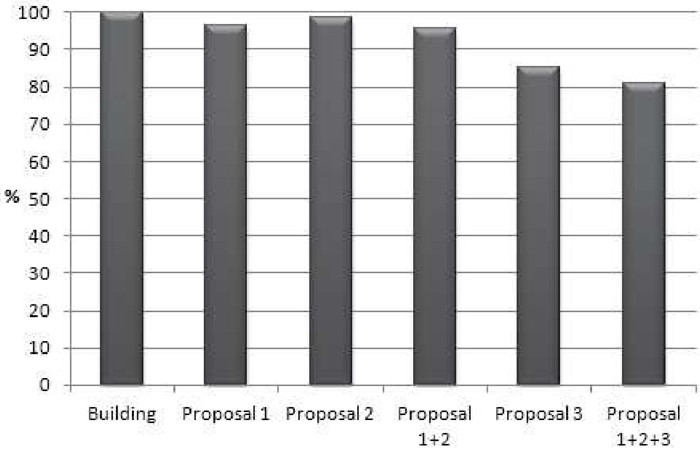

Figure 9. Reduction of environmental impacts resulting from the alternative design proposals.

Analysing the results it is possible to conclude that improving only three aspects in building design it is possible to decrease the overall life-cycle impacts in about 19%. Additionally, results show that although it is possible to reduce the environmental impacts of the building through the selection of building technologies with lower embodied environmental impacts (Proposals 1 and 2), designers should focus their attention on the design principles and solutions that lead to higher energy efficiency. Any additional investment in this area will have much more clear results.

6 CONCLUSIONS

The materialization of Sustainable Development concept in the building sector is only possible if some design principles are adopted since the preliminary design stages. This study was aimed to contribute to the current state-of-art in the sustainability of residential buildings in Portugal, identifying the construction materials and life-cycle phases that most contribute to the potential environmental impacts of a conventional residential building.

From this study it is possible to conclude that most of the impacts are related with the operation phase that accounts for about 59% of the whole building life-cycle impacts. The construction phase contributes in about 19%, following the maintenance phase with about 11%.

Regarding the contribution of each material to the overall impacts, it was found that the ceramic tiles, the concrete and alkyd paint are the larger contributors to the impacts.

This study also presents three improvement proposals that were aimed at mitigating the life-cycle impacts. Understanding the materials that cause major impacts, decisions can be made at the design stage in order to mitigate the embodied environmental impacts.

This work also shows that, although it is possible to reduce the environmental impacts of the building through the judicious choice of materials and building solutions, the most significant results are achieved when the operational non-renewable energy consumption is reduced. Therefore, designers must focus their attention on solutions and design principles that lead to the reduction of energy consumption for heating, cooling and hot water production.

At this stage, this work was focused on the environmental dimension of sustainable development and will move towards the assessment of the social and economy impacts of the proposed design improvements.

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