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ABSTRACT

The purpose of this study is to perform a Life-Cycle Energy and Greenhouse Gas Assessment (GHG) of a prefabricated modular house named "Moby". It aims at identifying opportunities to improve its environmental performance, without altering its production concept, i.e., to be a modular and pre-fabricated building. This is based in a dual concept of a prefab industrialized core (referred as "Moby's Core") and an onsite personalized assemblage and finishing (referred as "Moby's Shell").

A life-cycle model and inventory assessment was implemented to assess the energy and GHG incorporated in the materials used in its construction, during workers, modules and materials transportation and in use phase. Energy consumption for modules and workers transportation at different locations was accounted for, which permitted to verify the influence of the final location on the overall house impacts. The use phase energy consumption was assessed using thermal dynamic simulation for an expected life time of 50 years.

The following alternatives to the base prototype were studied: (i) commercial options proposed by the production company, which included four different typologies / layouts (from a one-bedroom to a four bedrooms models) and three different finishing lines and materials ("basic", "standard" and "delux); (ii) alternatives proposed in the scope of this research to analyse the environmental performance of the prototype, explicitly, different structures (concrete, wood and LSF) and different insulation materials (XPS, rockwool and cork). These variations were analysed and the results were compared.

The most important results were identified at the materials level, being the impacts of Core (79% of Embodied Energy and Greenhouse Gas Emissions) nearly four times the impacts of the Shell (21% of Embodied Energy and Greenhouse Gas emissions), emphasizing the need for structural redefinition of the prefabrication process and, the small impact of finishing materials in the whole.

Regarding transportation, it was verified that it has a great influence during the construction and assemblage phases, varying from 8% of Embodied Energy (EE) and 13 % of Greenhouse Gas emissions (GHG) (Aveiro scenario) to 44% of EE and 52% of GHG (Rio de Janeiro scenario). However impacts do not always increase

proportionally to the distance, as the mean of transportation strongly influences the results. When including use phase transportation only represents 2% of global EE and GHG being just 1% of GHG in the worst case scenario of GHG emission associated with energy consumption during the use phase (with an emission factor for electricity of 609 gCO_2/kWh)

The results comparing the different typologies showed that increasing the number of rooms of the modular house led to a reduction in impacts by functional unit: Embodied Energy (EE) and Embodied GHG (GHG) i) per area (EE/m^2 and GHG/m^2), ii) per estimated number of inhabitants (EE/hab and GHG/hab) and iii) per number of rooms (EE/nr bedrooms and GHG/nr bedrooms). Moreover, increasing the cost of modular houses (improving the range of finishing lines) led to higher embodied impacts (due to the extra layers added to the envelope).

Insulation materials included on the external walls did not significantly influence the results, as the total impacts of alternative insulation materials only varied in one or two percentage point. Structural materials influenced the environmental profile of the case study because the primary structure, the exterior wall, floor and roof in which structure is included, stand for 56% of the total EE. In this sense, Light Steel Framing (LSF) has proved to be the preferable material.

Moby prototype was found to have an embodied GHG range of 20,5 -24,4 tCO_2, and required 390-424 GJ energy. This equates to 367-436 $kgCO_2$ m^2 and 7,0 -7,6 GJ per m^2 primary energy per floor area. This variation is due to analysed alternative structural materials. These values fit into values range of other studies results in literature to similar construction methods.

Keywords

Prefabricated building

Life-cycle assessment

Building energy efficiency

Embodied energy and GHG assessment

RESUMO

O objetivo deste estudo é realizar uma Avaliação de Ciclo de Vida de uma casa pré-fabricada modular denominada por Moby, focando o consumo de energia e a emissão de gases de efeito de estufa (GEE). Tem como objetivo identificar oportunidades de melhoria do seu desempenho ambiental, sem alterar o seu conceito de produção, ou seja, ser um edifício modular e pré-fabricado. A sua produção baseia-se num conceito dual de parte da construção ser pré-fabricada produzida por um processo industrializado (referido como "Moby's Core") e existir uma personalização e montagem final do modelo realizado em estaleiro (referido como "Moby's Shell").

Um modelo de avaliação do ciclo de vida e a análise do inventário foram realizadas para avaliar a energia e o GEE incorporado nos materiais usados na sua construção; transporte (de trabalhadores, módulos e materiais) e durante a fase de utilização. O consumo de energia e as emissões de GEE para o transportedos módulos e dos trabalhadores para diferentes locais de implantação foram contabilizadas de forma a verificar a influência da localização final sobre os resultados. Por fim, uma ferramenta de simulação dinâmica térmica foi usada para avaliar o consumo de energia na fase de utilização.

As seguintes alternativas foram estudadas para o protótipo de base: (i) opções comerciais propostas pela empresa de produção, que incluem quatro diferentes tipologias / layouts e três linhas de materiais de acabamento; e (ii) alternativas propostas no âmbito desta pesquisa para analisar o desempenho ambiental do protótipo, isto é, diferentes estruturas e materiais de isolamento. Estas variações foram analisadas e os resultados foram comparados.

Os resultados mais importantes foram identificados ao nível dos materiais, sendo relevante o impacto de “Core” (79% de EE e GEE) em relação ao “Shell” (21% de EE e GEE), enfatizando a necessidade de redefinição estrutural do processo de pré-fabricação e o impacto relativamente reduzido dos materiais de acabamento no todo .

Relativamente ao transporte, verificou-se que este tem uma grande influência durante as fases de construção e montagem, variando entre 8% da energia incorporada (EE) e 13% das emissões de Gases de Efeito Estufa (GEE) (para o cenário de Aveiro) e 44% de EE

e 52% de GEE (para o cenário do Rio de Janeiro). No entanto os impactos nem sempre aumentam proporcionalmente com a distância, pois o meio de transporte influencia significativamente os resultados. Quando incluinda nesta análise a fase de utilização, o transporte representa apenas 2% da EE e ECeq global podendo ser apenas de 1% de ECeq, no pior cenário de emissões de GEE associadas ao consumo de energia na fase de utilização (com um fator de emissão de energia de 609 gCO_2 / kWh apresentado para o ano de 2005).

Comparando os resultados para as diferentes tipologias verificou-se que o aumento da tipologia desta casa modular leva a uma redução dos impactos por unidade funcional: energia incorporada (EE) e GEE (ECeq) i) por área (EE/m^2 e ECeq/m^2), ii) por número estimado de habitantes (EE/hab e ECeq/hab) e iii) por tipologia (EE/ nr quartos e ECeq/nr quartos). Além disso, neste caso em estudo verificou-se que o aumento do custo das casas modulares (melhoria da gama das linhas de acabamentos) leva a impactos incorporados nos materiais superiores (devido a materiais com consumo de energia superior na sua produção e a camadas extras adicionadas à envolvente exterior).

Os materiais de isolamento incluídos nas paredes exteriores não influenciam significativamente os resultados fazendo-os variar em apenas um ou dois pontos percentuais. Os materiais estruturais influenciam o perfil ambiental do caso de estudo porque a estrutura primária, a parede exterior, o pavimento e a cobertura nos quais se encontram estes elementos estruturais totalizam 56% do total EE. Neste sentido, o Light Steel Framing (LSF) provou ser o material preferencial.

Os resultados de GEE incorporado no protótipo de variam entre 20,5-24,4 tCO_2 e de energia incorporada entre 390-424 GJ. Isso equivale a 367-436 $kgCO_2$ e 7,0-7,6 GJ de energia primária por m^2 sendo que esta amplitude de valores deve-se a materiais estruturais alternativos analisados nos diferetes cenários. Estes resultados enquadram-se na variação de valores de EE e ECeq apresentados por outros estudos para idênticos métodos de construção**.**

Palavras-chave

Edifício prefabricado

Avaliação do ciclo de vida

Eficiência energética dos edifícios

Avaliação da energia e do GEE incorporado

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LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
BIM	Building Information Modelling
CO_2	Carbon dioxide
EC	Embodied Carbon
ECeq	Embodied Carbon Equivalent
EE	Embodied Energy
ENSLIC	Energy Saving Through Promotion of Life-cycle Assessment in Buildings
EPBD	Energy Performance of Buildings Directive
ETICS	External Thermal Insulation Composite Systems
GHG / GEE	Greenhouse Gas / Gases com efeito de estufa
ISO	International Organization for Standardization
LCA	Life-cycle Assessment
LSF	Light Steel Framing
MC	Mass customization
MDF	Medium-Density Fibreboard
XPS	Rigid Extruded Polystyrene Foam

1. Introduction and motivation

"The building sector, including housing, constitutes 30–40% of the society's total energy demand and approximately 44% of the total material use. Consequently, the building sector has to be prioritized to be able to reach a sustainable society within a reasonable period of time." Erlandsson et. al., 2003

The student's motivation in developing this research comes from the desire to learn more about prefabricated modular construction and contribute to improve its environmental performance. To this end it is proposed to analyse, evaluate, redesign and re-evaluate a pre-existing prefabricated modular prototype, named "Moby". The student had previously worked on this project as an architect and was part of the design team during his professional career.

This professional motivation comes from a personal determination that always led the student to intervene in the territory, designing buildings and parts of the city, while maintaining an environmental awareness that compels him to analyse the environmental impacts inherent to what is proposed. It was this motivation that first led the student to enrol in the advanced studies program Energy for Sustainability. During this advanced course the student had contact with subjects on built environment energy and emissions. From this overview the student has identified Life-cycle Assessment, methodology presented during Industrial Ecology course, as an analysis tool and a methodology that first came from the industrial production sector and that is now being increasingly applied to buildings. Being this is a prefabricated house (this is being this a partially industrialized product) results may be disseminated and replicated by the repeated production of buildings.

In addition to the professional and personal motivation previously identified, the student recognizes in the dwelling sector a presented need of: on one hand, making more proficient and professional the construction process, from design stage all through production and ending up in the building's use and maintenance; on the other hand, the need to export (even more) the Architecture, Engineering and Construction (AEC) sector, whether through projects, products, know-how or manpower. Both of these issues were previously recognized by prefabricated producers that are a small but growing niche of the Portuguese construction industry. Prefabrication in construction is one of the answers to both of the sector goals: on one hand it means a continuous improvement in the production of a building, modules and building's components or parts; on the other hand it represents an opportunity to export an end product of the construction sector, being this product an entire buildings, modules or parts of a building.

It is well known that although the construction sector is a major manufacturing sector in Portugal, with plenty of accumulated know-how and tradition, there is a communication gap between designers and workers, since this sector served, for a long time, as a professional occupation for all who lacked any training. This difference is evidenced in the reduced number of CAD-CAM processes. So maybe it is understandable the difficulty felt in prefabrication implementation in AEC since it requires rigor and skilled and specialized workers, a non-typical type of labour in the Portuguese construction sector.

On the other hand, in relation to prefab housing market, Portugal is a preferred market for large scale housing demand, by the fast developing countries, either by its cultural proximity, with the Portuguese speaking countries, or by a geographical proximity, such as with North Africa or Middle East countries. There are current commissions to Portuguese contractors some of which at a public level such as "Petro Casas", a contract made between the Portugal and Venezuela government; and others as private orders, such as "Houses for Mozambique" a competition to which various Portuguese contractors have answered.

Prefabrication is here presented as one answer to some of the sector crises. However it is recognized that prefabrication in construction is not something new or something unusual. Prefabrication in different proportions and in various application scales is a recurrent and almost constant process in construction. The buildings are made of elements, parts, compositions, between other elements buildings have being all more or less prefabricated. Buildings have frames, glasses, bricks, concrete blocks, sanitary equipment, insulation panels, ceilings plasterboard, faucets, among others prefabricated elements. Sometimes even entire rooms of a building are prefabricated, such as toilets in many hotels, that are produced in plant and simply assembled on construction site (as a time and money saving process). So even when one talk about "traditional" or "current" building process it is implied a certain degree of prefabrication, of building's components, constituent or parts. So it needs to be defined the difference between the construction process under study, a modular prefabricated building and a "current" process. One can say that the difference is inherently associated with the construction process as well as the amount of prefabricated elements in relation to the whole. However it is here stated that the main difference lies on the construction process and its phases. Whereas the current construction process sequence is: i) materials extraction; ii) construction elements production in different plants; iii) materials transportation to building site and, finally, iv) in site construction. In a prefabricated building process there is a prior stage to construction and a consequential extra transportation phase, which is called "prefabrication" (of modules, panels or parts) and that is developed in a specific construction production plant.

In conclusion, as previously affirmed prefabricated buildings or building parts are neither new nor unusual. On one hand, prefabricated buildings exist for some decades and had a great expression during the post war as a necessary response to the rapid reconstruction urge and as a natural consequence of the industrial revolution (even though in some cases with some delay). On the other hand, as previously affirmed, it is necessary to define the degree of prefabrication as it may be applied to parts and components included in all buildings, since construction exists.

With the advent of CAD / CAM tools (that is not a trend but is an increasingly present reality) the prefabrication sector will be driven (or towed) to a new dimension and prefab units, modules or constituent elements will gain more relevance within the building sector.

1.1. Goal and scope definition

The aim of this thesis is to study and evaluate a prefabricated modular house. On that basis, it was analysed an existing prefabricated modular home with all commercial alternatives presented to the market upon its release (various layouts/typologies and different finishing lines). Other alternatives proposing its redesign, in order to reduce the prototype impacts, were suggested by the student as part of this work (namely alternative structures and insulation materials).

The prototype analysis included not only EE and ECeq of the materials used on its production, but also the energy and GHG emissions related to transportation and use phase. The assessment of the impacts inherent to the transportation of materials, modules and workers, on a construction process based on prefabrication was of utmost importance since this constructive process added another non-existent phase in the traditional process: transportation from the factory to construction place.

Finally, because the use phase is a very important phase in the life-cycle of buildings (as lifespan of buildings is long), we have calculated the use phase impacts by the thermal simulation of the prototype.

1.2. Methodology

Life-cycle Assessment (LCA) is an environmental assessment tool that started to be employed in the 60's (Kashereen et al., 2009). According to Monahan (Monahan and Powell, 2011) "one of the principle techniques to enable the quantification and comparison of the environmental impacts of a product is life cycle assessment (LCA)." This is an assessment methodology that has increasingly been applied to buildings, in order to analysis its environmental profile and support its performance improvement. Various papers present research about buildings developed using LCA methodology applied to building (Bribián et al. 2009, Erlandsson et Borg 2003, Hacker et al 2008, Monteiro et Freire 2012,Peuportier 2001, Sivaraman 2011 and Thormark 2002). Lately some papers present LCA methodology applied to modular, prefabricated or MMC (modern methods of construction) buildings (Aye et al 2012, Pons et Wadel, 2011, Quale et al. 2012, Mao et al.2013 and Monahan et Powell 2011)

Energy Plus[1] software was used to calculate the energy required during the use phase. A dynamic thermal simulation tool has been used so introducing complexity to the study. However the dynamic thermal analysis of different scenarios are left to be performed latter being out of the scope of the present study. In this work only GHG emissions and energy consumption were study. Demolition phase was excluded from this analysis.

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[1] Software available in DOE., U. (n.d.). Energy efficiency and renewable energy, building technologies program and software tools. Website: http://www.eere.energy.gov/buildings/energy_tools/energyplus/. USA Department of Energy.

Each model was studied using different function units: energy and GHG per square meter (EE/m^2 and $ECeq/m^2$); energy and GHG per estimated number of habitants (EE/hab and ECeq/hab); and energy and GHG per number of bedrooms (EE/no of bedrooms and ECeq/t no of bedrooms).

In order to calculate the EE and ECeq related to the transportation, on the one hand, it was calculated emissions and energy of materials and modules transportation and, on the other hand, workers transportation. The following elements were taken into consideration for this calculation: the transportation of materials to the plant is constant to all location since the plant of modules manufacturing remains the same, modules transportation from the factory to the construction site, materials transportation up to construction site, workers transportation to the factory and workers transportation from plant to building yard.

Materials transportation to plant and to building site was considered by a heavy truck for all the four site locations in Portuguese territory. The transportation of modules from plant to site was calculated by truck crane. Workers' transportation was considered by private cars, from home to factory, and by a minivan from factory to construction site. This analysis tried to reproduce the base case study, i.e. the modes of transportation used including prototype construction.

Embodied Energy (EE) and GHG Emissions (EC) were calculated using the Inventory of Carbon and Energy (ICE) Version 2[2]. The ICE database lists a large range of materials and has been referred in various published works.

1.3. Context

1.3.1 Prefabrication process

Prefabrication of objects, elements or systems already existed before the industrial revolution (by the repeated artisanal production of parts or artefacts through moulds and models). However, it was with the industrialization of the production process that prefabrication gained its true dimension by producing standard components in large

[2] Inventory of Carbon & Energy (ICE) Version 2.0 developed by Sustainable Energy Research Team (SERT) Department of Mechanical Engineering University of Bath, UK and available in: http://web.mit.edu/2.813/www/readings/ICEv2.pdf.old

numbers, which are after assembled in a separate place. The basis of prefabrication is standardization which offers a number of advantages:

- Accelerates construction, reducing response time;
- Avoids "reinventing the wheel";
- Allows costs reduction over lifetime (from production, through use and providing materials recycling/reuse):
- Offers a more consistent quality;
- Allows to relocate part of production away from manufacture or use site;
- Improves the health and safety of producers and consumers;
- Allows waste reduction;
- Turns production more sustainable;
- Can reduce production cost and therefore market price.

Standardization is the basis for industrialization of the entire construction process, by allowing the partial replacement of human action by mechanical reproduction of elements and with a precision and production time reduction unparalleled by the traditional production process.

The prefabrication construction is characterized as a process that incorporates industrially produced elements, being that only small parts of the building (prefabricated elements) or most of the building itself (prefabricated construction and / or modular construction). Part of the production tends to be forward to a time prior to construction (reducing failures in production and meeting deadlines). So the construction process tends to be translocated from the construction yard (a place with a higher construction cost and simultaneously more unpredictable and dangerous) to the factory, through prefabrication.

However, it is difficult to draw the boundary between the traditional construction process and the prefabricated building: it will be difficult to find a building completely built in a factory – at least the connection between the parties, foundation works and the infrastructure connection to the field will be held on site – or one that does not contain any prefabricated elements – many of the elements that comprise traditional construction are prefabricated such as bricks, toilets, windows, or other element. In the end, it could be considered the “Igloo” and the “Lodge” as a building fully realized in construction site and the “Trailer” as a totally prefabricated building example (being this actually a mixture of a house with a car, and so totally finished at the factory gate). The universe of building’s prefabrication is situated in the vast space between these two opposites, sometimes closer to one and sometimes closer to the other, taking advantages and leveraging potentialities from this building process.

As referred by Bausman and Lu (Bausman and Lu 2008) prefabricated construction techniques may be divide by the relative representation it has in the total construction, or by the intervention concept in the following categories:

- **Prior assembly** refers to a process where the various elements of construction (prefabricated components and / or equipment) are previously produced and associated somewhere else (usually refers to a system and not a product). Those may be such as structural, heating or ventilation system that are pre-assembled.
- **Hybrid systems** include prebuilt spaces or modules that may be, for example, a toilet module completely finished in factory with all the interior finishes, the electrical elements, plumbing systems, between other systems.
- **Construction system by panels** consists in the creation of a prefabricated building system based on frames (panelised structures) or in the building envelope. After being built, these parts are transported to construction site, assembled and fixed. Typically the construction of these panels includes the final coating, insulation, finishing, doors and windows.
- **Modular buildings** refers to modules or totally constructed buildings and assembled in factory and transported to site where modules or buildings are link together and plug in to site. These modules are finished and only need the union and sealing of the modules in construction place.

Although being unknown (in this work) the percentage of prefabricated buildings in Europe, it is stated that in the United States this round 23% of the whole construction industry, according Bausman and Lu (Bausman and Lu 2008) and in their comparative study about construction techniques out of construction yard. This fraction refers mostly to prefabricated concrete components especially at the structural level (columns, beams, trusses). In the same study it is expressed the market sensitivity to prefabricated building being presented some conclusions:

- Professionals (architects, engineers and builders) who have already tried prefabricated construction have a more positive view over this process than those who have not yet had contact with this type of construction;
- Prefabricated buildings users or inhabitants have a more positive idea of prefabrication itself stating that such techniques increases the safety, quality and management efficiency; reduces the cost and does not limit the design options in the design, contrary to the remaining population living in traditional buildings;
- The limitations mentioned by designers (architects and engineers) are due to design options limitation, owner's perspective and specific design software required, being these more on the housing sector level than on the commercial sector.

Finally, in this same study (Bausman and Lu, 2008) were presented some of the measures that may encourage this process within the construction sector. This measures intended to increase the use of prefabrication techniques: the promotion of research and development by companies and organizations on offsite construction technologies; increasing the knowledge and expertise of technicians, workers and contractors; collaboration between all stakeholders in order to pre-plan the project going beyond the idea that the prefabricated construction will limit the flexibility of changes in site; encouraged institutions and associations supporting this type of construction.

1.3.2 Prefabricated buildings

Prefabrication is a process in which components are produced and pre-installed in a specialized plant to be then assembled into the final site. This process is based on large scale production in order to divide the initial investment and production costs by the highest possible number of products. The aim of prefabrication in the construction sector is to make architecture affordable to most of the population. This implies simplifying the process of conceiving and constructing buildings.

Prefabrication has been presented by several authors (Chen 2010, Chiang 2006, Da Silveira 2001, Noguchi 2005, Richard 2005) as a way to increase efficiency, competitiveness and profit in the construction sector, by reducing waste, materials, energy and emissions. Within prefabrication research theme, Richard (Richard, 2005) presents the progress of buildings industry to full industrialization as a way to decrease price though improving quality. Therefore converting special and usually expensive products, as a dwelling, reasonably accessible to people. Five levels of industrialization process are presented: prefabrication, mechanization, automation, robotic, and, finally, reproduction. The first four levels of prefabrication replicate the traditional construction process although there is the substitution of man labour by machines. The fifth level presented, named reproduction process, is a revolutionary approach and can deeply simplify the industrialization process.

Prefabrication	A product produced before or in another plane. In building industry implies a pre-construction of components or modules, similar to traditional construction, in a plant and a later assemblage on construction site
Mechanization	A process that includes machinery use to reduce man labour. Usually accompany prefabrication process.
Automation	The mechanization process takes over the manufacture process. Usually man labour is reduced to production supervision and maintenance.
Robotic	The same tool performs different production activities. Together with informatics design (CAD) and production toll (CAM - computer-aided manufacturing) makes possible mass customization (individualization of the products in mass production)
Reproduction	Simplifies the multiplication of complex goods in generating a simpler process. It intends to shortcut processes inherent in manufacturing process. It’s done through research and development.

Table 1 Degrees of Industrialization (in Richard, 2005)

The author describes a three level methodology to implement reproduction: i) creating the product to respond to performance requirement; ii) drawing a process that simplifies the production set; iii) proposing a design that comprehends process and product relations. The industrialization of housing construction is presented as a case study. The dwelling is divided into two different types of spaces: the “*served spaces*” (open spaces that include the living, the dining, bedroom and family room); and the “*serving spaces*”, (kitchen, bathroom, laundry, staircases, elevator and mechanical duct). “*The service core can be to the building what engine is to the car; the same engine can power a sports car or a family sedan, the same service core accommodates a townhouse or a condominium*” (Richard, 2005).

Other conceptualization of a prefabricated dwelling is presented in Benros’ study (Benros et al., 2008) in which is established a design system to mass customization houses aiming to decrease houses cost through large scale production while ensuring the inhabitants’ satisfaction by house individualization. It is also established a MC housing design system: “*a model for the mass production of houses that encompasses three* *systems: a design system, a building system, and a computer system"*. The project developed under this study was originated in Ove Arup[3] company while trying to overcome problems related with a high complexity building based on metal components.

Though prefabrication is a repetition process, Noguchi (Noguchi et al., 2005) emphasized the necessity to a market reaction to costumers' desire of personalization in mass produced houses, even in low and mid income segments in Mexico's mass production housing experience. This differentiation can be achieved throughout the concept of mass customization (MC), presented by Da Silveira (Da Silveira at al., 2001). Building's prefabrication can be realized in different degrees of prefabrication. According to Mao (Mao et al., 2013): i) semi-fabrication (some elements are prefabricated and others are traditionally done on site), ii) comprehensive prefabrication (all elements are done on factory and after assembly onsite) and iii) volumetric modular (the building is done on plant, by modules or as a whole).

Japan's governmental program to implement prefabrication in construction is presented by Chiang (Chiang et al., 2006) and Chen's work (Chen at al., 2010). This last work introduces prefabrication as a way to increase buildings sustainability doing a multi-attribute study multicriteria analysis. Monahan (Monahan et al., 2011) also presented a "cradle to use study" in an economic low energy house and Mao (Mao et al., 2013) presented a comparative study between "Offsite construction" and "Standard construction" in a collective dwelling project. Although only parts of the building were prefabricated (facades, stairs and precast corridors slabs) it was witnessed a 3% decrease of CO_2 emission, a small reduction due to the small level of prefabrication. Also assessing multi residential buildings, Aye (Aye et al., 2012) presented a study comparing three constructive solution: conventional concrete, prefabricated steel, and prefabricated timber.

The previous state-of-the-art frames the proposed research. It justifies the need to develop a more complete assessments of pre-fabricated buildings, including buildings as a whole, during its entire life-cycle (from materials extraction to demolition phase),

[3] Company founded in 1946 with an initial focus on structural engineering. Website: http://www.arup.com/

assessing different types of building (wood, concrete, steel) and intervention strategies (new construction or refurbishment). However, the flexibility of the study must be assured, so that the developed methodology can be replicated and widely used aiming at a more efficient sector and a more sustainable built environment.

1.3.3 Prefab buildings worldwide

It can be said that prefabrication in the United States dates back to at least to the "Gold Rush Era" during which the settlers took prefabricated materials to quickly build their homes in West American. In the beginning of the twentieth century the home kits became popular. These could be picked up in the train stations, in sets of thousands pieces, being then assembled by anyone who had some skills and tools. In fact, between 1908 and 1940 Sears Roebuck sold 75,000 prefabricated houses that could be chosen from different classes: "Good", "Better" and "Best", which allowed some customization. The Lustron Homes, a company created in 1948 that went bankrupt in 1950, managed to sell 3,000 prefabricated houses during these two years of existence.

In Britain, after the Second World War, 150,000 houses were built. Created to accommodate the war homeless, these "palaces for the people" sought to respond to people's needs and were built to last only 15 years. However, although they have been subject to demolition attempts, some still persist after 60 years of existence.

1.3.4 Prefab buildings in Portugal

It is difficult to trace prefabricated houses history in Portugal. With a somehow heavy construction tradition based in stone and later in concrete materials, and in the absence of wars or natural disasters that required the rapid resettlement of the population, prefabricated houses have never had great expression in national territory, being almost reduced to second homes being divided between “Trailers” and “Bungalows”. Portuguese traditional prefabricated houses are the wooden houses. Firstly imported from the Nordic countries (with a long tradition in wood building) and later produced in Portugal (although design and some components continue to be imported). It can be pointed out some commercial examples such as *Rusticasa*[4], existing since 1978, or *Logdomus*[5]. Being a traditional example (at the architectural design level), these have a

[4] Rusticasa website: http://www.rusticasa.pt/
[5] Logdoms website: http://www.logdomus.pt/

presence on the market for three or four decades, always continuing to sell the same products.

However, in the last decade in Portugal, prefabricated housing market has presented some innovations and a huge difference both in design and in market size. The *Modular System*[6] design, led by company *Equiporto*, had a modular concept house made up from wood elements. After that, the company has presented a different prefab house in metal structures and concrete. This house is being trade nationally and has already been adapted to serve other functions than housing. The *Casa Inteligente* (Smart Home), designed by Cannata and Fernandes, is an experimental module built in 2002 for Concreta Fair held at Exponor. Since its launch it has not been commercialized. Protoconcep design, presented by a company with the same name, is a prefabricated wooden housing with unique design. The houses are built in factory and constituent parts are subsequently disassembled and reassembled at construction site.

Finally, Moby[7] house developed by CNLL and one of which models is here presented as base case study. This modular house was initially launched in 2005 in Oportoshow. After that it has not been on the market but was relaunched a second version in 2011. It is made up of similar modules, completely built in factory being after transported by truck crane to building site, being then assembled, connected and finished. Due to this exclusive nature, and the lake of scale in national market, the cost of these prefabricated houses is similar to traditional construction cost.

1.3.5 Life-cycle assessment of Buildings

Life-cycle Assessment (LCA) is a methodology that has been applied in multiple studies since 1960, though only thirty years later the first studies about buildings` LCA were published. Khasreen et al., 2009 published a review over life-cycle assessment (LCA) and environmental impacts of buildings in which the author underlines the importance of LCA as a supporting decision tool. In the same year Bribian (Bribián et al., 2009) proposes LCA as a complement to buildings energy certification, highlighting the need to include embodied carbon and energy in EPBD [8] (Energy Performance of

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[6] Modular System website: http://www.modular-system.com/
[7] Moby website: http://www.cnll.pt/moby/
[8] EPBD, Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings," Off. J. Eur. Communities, pp. L1/65–L1/71, 2003.

Buildings Directive) and not only operational energy. Szalay (Szalay 2005) also highlights limitations in the energy legislation that considers only energy consumed by buildings in use phase neglecting embodied energy of materials. Furthermore, in a review paper Dixit (Dixit et al., 2012) fundaments the need of revising LCA ISO standard (ISO 14040-3) especially about buildings' embodied energy section. Finally, Ortiz (Ortiz et al., 2009) refers various studies on Life-cycle assessment applied to the construction sector and reports the sector raising concern over the need to improve sustainability indicators performance: social, economic and environmental.

Most of researches conducted over the environmental impacts of buildings focus mainly on buildings' parts or construction elements (wall, structure, etc.) or at a specific stage of the process (construction or use phase). Monteiro (Monteiro et al., 2012) presents a comprehensive Life-cycle of a dwelling, with two operation patterns and seven exterior wall solutions scenario. Haapio (Haapio et al., 2008) has focused on structure and investigated how different structural solutions and materials influence building´s LCA results throughout by calculating impacts of 78 single-family residential buildings within different scenarios. This restricted LCA is due to buildings' complexity and as the process has multiple constraints and stakeholders it turns out difficult to perform a comprehensive study, covering the building as an whole and including the complete Life-cycle of the building: from materials extraction to the end of the life of a building.

Although neglecting demolition phase some studies attempt to perform a more comprehensive study. In 2008 Hacker et al. (Hacker et al., 2008) presented a case study covering construction and use phase with four different buildings technologies' scenarios: lightweight, medium weight, medium-heavy weight and heavyweight. It was concluded that a decrease on the overall CO_2 can be achieved by focusing on operational phase. Thormark (Thormark, 2002) research focused on low energy consumption buildings in Sweden and emphasizes the importance of embodied energy in the materials during construction phase for this type of building referring also the implication of the reuse and recycling of materials and components. In this study the embodied energy of buildings had a higher relative weight, as energy required for operation stage was reduced.

Peuportier (Peuportier et al., 2001) applied LCA to perform a comparative validation of three different houses in France: a standard construction, a solar construction and a wood panels building. One decade later (Peuportier et al., 2013) included thermal simulation to analyse the influence of occupant in buildings performance. Rossi (Rossi et al., 2012) presented a similar study in which is not the building that changes but its location, assessing the same building in three different locations (Belgium, Sweden and Portugal) in order to understand how site might influence buildings performance. Finally, Verbeeck (Verbeeck at al., 2010) presented a Life-cycle inventory research with partially equivalent goals of the present work program: to optimize buildings in terms of energy, environment and cost. About rehabilitation Siveraman (Siveraman, 2011) introduces the evaluation of retrofitting strategies in heritage buildings.

In a macro context, and having a vast number of case studies in each, two papers were presented being part of co-financed European projects: Nemry (Nemry et al., 2010) published results of the Environmental Improvement Potentials of Buildings (IMPRO-Building) project from the analysis of 72-type of existing buildings divided in three typologies (single-family house, multi-family house and high-rise buildings) and three climatic zones (southern, central and northern Europe). This publication summarizes a study commissioned by European Union about potential and cost of different alternatives to reduce environmental impacts of residential buildings in the EU. On the following year, Malmqvist (Malmqvist et al., 2011) published a simplified method to realize a LCA of buildings during design phase to support decisions and increase buildings sustainability. This study presents results from Energy Saving Through Promotion of Life-cycle Analysis in Buildings (ENSLIC) project.

1.3.6 Life-cycle assessment of prefabricated or modular buildings

Lately some LCA studies have focus in prefabricated, modular or MMC construction methods. Hacker (Hacker 2008) studied the embodied energy and carbon and operation energy and carbon of four different constructions structures: Lightweight a timber frame with brick exterior; Medium weight a traditional brick and block exterior wall, with lightweight ceilings and partitions; Medium-heavy equal to medium weight but with block partitions and concrete hollow-core ceiling on ground floor and, finally a Heavy with heavyweight block inner leaf and partitions, with hollow-core concrete ceiling on the ground and first floor. One of the main conclusion was that although the calculated initial ECO2 was higher in the heavier weight that difference were offset early in the lifecycle due to the savings in operational CO2 emissions. Monahan and Powell (Monahan and Powell, 2011) focused on three different case studies: MMC (modern method of construction) with a timber frame larch cladding, MMC with a timber frame brick cladding and the last scenario in masonry.

Pons (Pons et al., 2011) studied prefabricated schools buildings in Catalonia comparing concrete, timber and steel prefabricated constructive technologies and a non-prefabricated one. Results of CO2 emissions, energy, waste and materials recyclability are presented for each of the buildings presented and to each of the life-cycle phase. In prefab buildings one extra phase is added: preassemble phase, buildings preconstruction realized in plant before onsite assembly.

Quale (Quale et al. 2012) compared a modular and a conventional house excluding use phase, as buildings performance is considered to be equal. This study concluded that GHG emissions are approximately 40% higher in conventional construction. Finally, Mao (Mao 2013) compared two different buildings: one semi-prefab and another conventional. Embodied emissions of building materials, transportation of building materials, transportation of construction waste and soil, transportation of prefabricated components, operation of equipment, and construction techniques were analysed. Results show that the semi-prefabrication method produces less GHG emissions per square meter compared with the conventional construction.

2. Case study presentation - Moby

The building under study is a prefabricated modular construction which is a commercial product developed by the company CNLL Ltd. This modular prefab house is the result of a research and development (R&D) project in which the student has worked in. In the development of this building there was not any concern about the environmental profile of the building since it was out the scope of the research project. The aim of this R&D project was the development of modular solutions and prefabrication application in the construction sector.

2.1. Case study characterization

The case study here presented is a modular prefab house, commercially referred to as "Moby", constructed in two different stages: first 2.5m x 7.5m x 3.6m modules are fabricated in factory, being after transported to site and there assembled and finished. This is based in a dual concept of a prefab industrialized core (referred as “Moby’s

Core”) and an onsite personalized assemblage and finishing (referred as “Moby’s Shell”). The primary and secondary structure of the modules is made of steel as well as site foundations of this case study. Sandwich panels with different compositions are used in the external wall, floor and roof. Plaster board is used in the interior side of the exterior walls, in celling and in the interior layer of the walls. Some acoustic and thermal insulation is applied in all the exterior envelop of the house. Finishing alternative materials are presented.

The modules can be freely associated creating countless final layout possibilities. However, the production company proposes four final layouts (from one bedroom to four bedroom models). In addition to these models, the user may choose different finishing from three lines sets: basic, standard and deluxe (up to 12 base models).

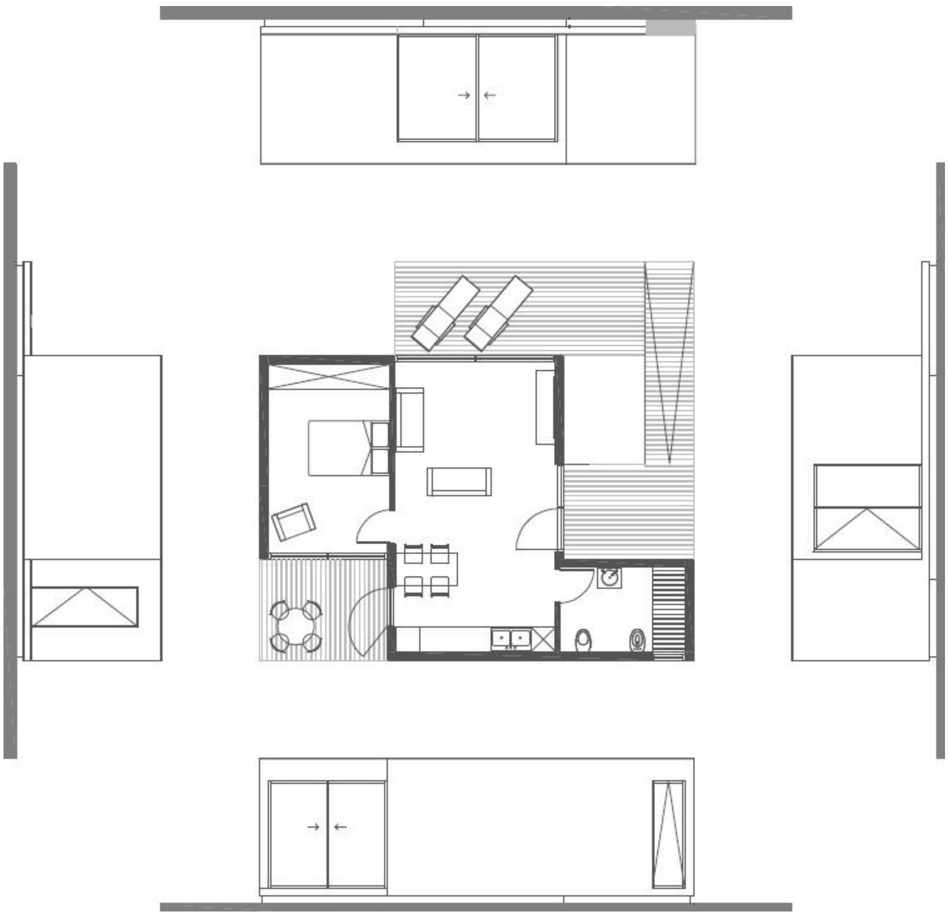


Figure 1 Floorplan and elevation of the case study

Although being a prefabricated house it is proposed a concept that enables individual assemblage as costumers may use the number of modules in accordance to their needs and chosen layout, as well as personalization by the use of local materials during the finishing stage. However numerous models layouts of almost any size is possible, in the scope of this work, only four final assemblies are stablished, representing the most typical housing typologies: from one bed-room models to a four bed-room one. In addition three pre select finishing lines were considered as commercially proposed by the company during the prototype presentation. Typologies and finishing sets here presented have only a design purpose and are market oriented. No environmental concerns were taken into account during Moby’s design phase.

Figure 2 Pictures from Moby’s production and transportation

2.2. Materials

The case study is a pre-fabricated modular building without of environmental issues incorporated in design. The prototype under study was presented in 2011 and is composed by three prefabricated metal structure modules. The core is executed in plant and transported to construction site where it is assembled and finished with local materials and according to different users/customers’ preferences.

The case study inventory was organized by each one of the buildings constituent parts. The core was divided in base/ground foundations, modules’ primary structure, exterior wall composition, floor composition, roof composition and infrastructures (water and gas supply systems, electrical service, and rain drainage system).

The shell was divided into exterior wall finishes, interiors walls, floor finishing, interior openings (doors), exterior openings (windows) and other elements as baseboard and cornices, sanitary equipment and fixed furniture (wardrobe, kitchen and bathroom cabinet). The following table attempts to systematize the elements of each of the production stage: Moby = Core (offsite construction) + Shell (onsite assembly).

Core (offsite construction)	**Shell (onsite assembly)**
Fixed (the same within each model)	Variable (according to context and user preferences)
• Base – Foundation – Ground basement • Primary structure of modules • Exterior wall composition • Floor composition • Roof composition • Facilities / infrastructure – Water supply – Gas supply – Electricity – Rain water drainage – Grey water drainage (sewage)	• Exterior wall – Exterior finishing – Interior finishing • Interior wall • Floor finishing • Celling finishing • Interior openings - doors – Doors • Exterior openings - windows – Frame – Glass – Shading – Framing • Others elements – Baseboard and cornice – Bathroom equipment – Kitchen cabinet – Countertop – Lightings

Table 2 Inventory structure

2.3. Inventory

Most of the detailed information over the construction process was collected in the design office as the student was part of the R&D project team during the prototype design and construction. During this data collection process were used technical design drawings, implementation detailed drafts, shop drawings, bill of quantities and photographic surveys (of the production of modules and the prototype final assemblage).

The missing data (not held by project team because some were a result of production choices or alterations) was searched on the market, from different producers, through technical catalogues, installation standards or product sheets, trying to replicate constructions' "good practices". At the first approach, even the smallest elements were measured such as screws and ceilings fasteners. For this purpose, square meter estimations and materials' over consumption concept were used (available in applicators' catalogues).

The inventory reproduces prototype building process conducted from January until March of 2011. The modules were built at the factory and according to the specifications of the designer company. The three modules were transported by trucks from the plant (near Espinho) to Aveiro, since the prototype was publicly presented during the March fair in this city. The temporary display (during the fair) led to the use of temporary foundations, a structure simply resting on the ground, after its regularization. This structure was composed by "I-shape" profiles simply resting on the ground and a lifting structure that allowed a ventilated loft under the volume. Around the prototype there was an outside deck that was not taken into consideration in this study.

The inventory was built reflecting the separation in production, the Core and the Shell, because it was intended to analyse both parts separately and so identifying improvement opportunities: during prefabrication (of the core) or during assembly and finishing (relative to the shell).

The Core inventory was divided in the parts that constituted the prototype core fabrication and site assemblage. The base foundation was constituted by continuous structure "I-shape" section profiles (beams) that received each module and anchor bolts link between "I-shape" section profiles (beams and columns) the principal structure of the modules, and ground basement with metallic structure "I-shape" section profiles, footing and anchor bolts link between "I-shape" section profiles and footing. After, it was measure the corner reinforced structure with a "O-shape" profile (on the top of the modules), corner reinforced structure "C-shape" section profile (at modules bottom) and anchor bolts that links "O-shape" and "C-shape" profiles. Next, the exterior wall is composed by "sandwich" panel, internal secondary "O-shape" section profile, peripheral "U-shape" section profile structure, Rockwool and, finally, a plasterboard internal layer composed by vertical profiles and 13mm thick plasterboards. The floor consists of MDF panels, Rockwool, sandwich panels, internal "O-shape" section profile and peripheral "U-shape" section structure. Next the celling is composed by sandwich panels, peripheral "U-shape" section structure, Internal "O-shape" section profile structure, Rockwool and, finally, on the interior a plasterboard suspended celling with vertical cords. At last, the infrastructure was calculated, including the water supply system and grey water sewage, gas supply system, electrical service and rain water drainage system.

All these elements and materials represent Moby's basis. The modules main structure was calculated independently and multiplied by three (as three modules were used in this prototype) in order to calculate materials used per module. All other elements were calculated individually as a regular measurement process. Detailed schedules listing the complete material inventory are following presented.

Materials core inventory

MOBY'S CORE INVENTARY	material	weight (kg)	EE (MJ)	ECeq ($kgCO_2e$)
Base			49.907,156	3.586,548
Base Foundation				
Continuous structure "I" section profiles (beams) that receives each module and the external deck (150 x 90 x 3)	galvanized steel	1.410,360	41.605,620	2.989,963
Anchor bolts link between "I" section profiles (beams and columns) and the principal structure of the modules	galvanized steel	23,040	679,680	48,845
ground basement				
Punctual metallic structure "I" section profiles (column) (150 x 90 x 3)	galvanized steel	154,560	4.559,520	327,667
Footing (400 x 400 x 5)	galvanized steel	100,608	2.967,936	213,289
Anchor bolts link between "I" section profiles and footing	galvanized steel	3,200	94,400	6,784
Primary structure of modules			18.940,416	1.361,142
Corner reinforced structure "O" section profile (up horizontal edges) 20 x 65x 3	galvanized steel	85,200	2.513,400	180,624
Corner reinforced structure "C" section profile (down horizontal edges) 80 x 10 x 3	galvanized steel	54,000	1.593,000	114,480
Corner reinforced structure "O" section profile (vertical edges) 80 x 40 x 3	galvanized steel	66,176	1.952,192	140,293
Anchor bolts (link between "O" and "C" profiles)	galvanized steel	8,640	254,880	18,317
Total / module		642,048	6.313,472	453,714
(No of modules)	(3)		(18.940,416)	(1.361,142)
Exterior wall composition			118.817,392	5.647,104
Sandwich panel composed by double PVC face and EPS core (4mm thickness)	pvc	496,800	38.352,960	1.540,080
	pur	217,350	22.061,025	925,911
	pvc	397,440	30.682,368	1.232,064
	stainless steel	14,283	809,846	87,840
Internal structure "O" section profile (46 x 31,5 x 3)	galvanized steel	330,785	9.758,158	701,264
	galvanized steel	1,050	30,975	2,226
Peripheral structure "U" section bended profile (46 x 19 x 3)	galvanized steel	341,542	10.075,477	724,068
	galvanized steel	5,760	169,920	12,211
Rockwool with 30mm (30kg/m3)	rockwool	66,681	1.120,241	74,683
Plasterboard wall composed by vertical profiles and 13mm plasterboards	galvanized steel	31,859	939,832	67,540
	plasterboard	703,855	4.751,021	274,503
	galvanized steel	2,223	65,570	4,712
Floor composition			81.226,187	4.368,841
MDF panels	mdf	575,956	6.335,519	178,546
	galvanized steel	1,530	45,135	3,244
Rockwool with 60mm (30kg/m3)	rockwool	91,800	1.542,240	102,816
	aluminium	13,770	2.134,350	126,409
Galvanized ribbed sheet	aluminium	120,960	18.748,800	1.110,413
	bitumen with minerals	107,520	5.483,520	52,685
	galvanized steel	440,294	12.988,685	933,424
	bitumen	107,520	5.483,520	52,685
	aluminium	120,960	18.748,800	1.110,413
	galvanized steel	2,688	79,296	5,699
Internal structure "O" section profile (46x 31,5 x 3)	galvanized steel	163,575	4.825,463	346,779
	galvanized steel	1,050	30,975	2,226
Peripheral structure "U" section bended profile (46 x 19 x 3)	galvanized steel	160,590	4.737,405	340,451
	galvanized steel	1,440	42,480	3,053

Celling composition			57.262,192	3.005,716
Sandwich panel composed by superior galvanized face, inferior PVC layer and polyurethane core (50mm)	galvanized steel	276,188	8.147,531	585,518
	pur	118,125	11.989,688	503,213
	pvc	270,000	20.844,000	837,000
	galvanized steel	1,688	49,781	3,578
	galvanized steel	25,800	761,100	54,696
Peripheral structure "U" section bended profile (46 x 19 x 3)	galvanized steel	160,590	4.737,405	340,451
	galvanized steel	1,440	42,480	3,053
Internal structure "O" section profile (46 x 31,5 x 3)	galvanized steel	69,000	2.035,500	146,280
	galvanized steel	1,050	30,975	2,226
Rockwool with 6mm thick (30kg/m3)	rockwool	91,800	1.542,240	102,816
Plasterboard celling composed by vertical cords and 13mm plasterboards	galvanized steel	39,044	1.151,798	82,773
	plasterboard	862,600	5.822,550	336,414
	galvanized steel	1,816	53,572	3,850
	galvanized steel	1,816	53,572	3,850
Infrastructure			6.478,815	312,732
Water supply system and grey water sewage			386,197	12,339
Water supply and sewage	polyethylene (ldpe)	1,364	113,307	3,463
	polyethylene (ldpe)	1,612	133,990	4,095
	polyethylene (ldpe)	1,437	119,373	3,649
	bronze	0,283	19,527	1,132
	bronze	0,376	25,944	1,504
Gas supply system			180,180	11,626
Gas supply	copper	4,290	180,180	11,626
Electrical service			90,182	4,399
Electricity	pvc	0,085	5,738	0,275
	pvc	0,085	5,738	0,275
	pvc	0,092	6,185	0,296
	copper	0,120	5,022	0,324
	pvc	1,000	67,500	3,230
Rain water drainage system			5.822,256	284,368
Rain water drainage	zinc	10,494	557,256	32,428
	pvc	78,000	5.265,000	251,940

Table 3 Materials core inventory

Materials shell inventory

MOBY'S SHELL INVENTARY	material	weight (kg)	EE (MJ)	ECeq ($kgCO_2e$)
Exterior wall finishing			23.256,45	1.220,51
ETICS (external thermal insulation composite system) with 60 mm thick do EPS	painting	150,075	8.854,43	381,19
	plaster	465,75	838,35	60,55
	cement	465,75	2.095,88	344,66
	fiberglass	16,56	463,68	25,50
	eps (expanded polystyrene)	124,20	11.004,12	408,62
Interior wall			7.225,39	401,64
Interior bathroom finishing			289,10	12,45
Bathroom hydrophobic painting	hydro repellent. paint	4,90	289,10	12,45
Interior wall			6.936,29	389,19
Plasterboard wall composed by vertical profiles and 15mm plasterboards	plasterboard	158,70	1.071,23	61,89
	galvanized steel	5,93	169,12	12,05
	plasterboard	158,70	1.071,23	61,89
	rockwool	124,20	2.086,56	139,10
	galvanized steel	6,21	176,99	12,61
	paint	40,02	2.361,18	101,65
Floor finishing			6.546,01	196,14
laminated wood flooring	varnish	3,33	166,69	18,44
	timber	44,88	448,79	13,91
	laminated timber	307,74	3.692,88	95,40
polyethylene foam	polyethylene	26,93	2.237,65	68,40
interior openings - doors			330,84	11,85
Doors with wood sheet finishing and alveolar interior	plywood	3,83	57,42	1,72
	laminated veneer lumber	19,31	183,45	6,37
	timber sheet	5,66	56,61	1,75
Door hand	brass	0,76	33,35	2,00
exterior openings - windows			39.626,91	2.328,41
Frame	extruded aluminium	#REF!	22.599,41	1.332,48
Double glass compounded by a 6mm tempered glass and 8 mm laminated glass	glass tempered	367,50	5.512,50	334,43
	glass laminated	490,00	11.515,00	661,50
Other element			12.245,59	597,71
Baseboard and cornice			120,12	3,72
Baseboard (40 mm x 20mm)	timber	12,01	120,12	3,72
Sanitary equipment			1.480,00	102,50
Sanitary equipment	ceramic	14,50	145,00	10,15
	brass	2,20	96,80	5,81
	ceramic	47,30	473,00	33,11
	ceramic	45,00	450,00	31,50
	brass	0,300	13,20	0,79
	ceramic	30,20	302,00	21,14
Fixed furniture			10.645,47	491,49
Bedroom cabinet	mdf	100,80	1.108,80	39,31
	mdf	129,36	1.422,96	50,45
	mdf	226,80	2.494,80	88,45
	nickel plated steel	0,81	132,84	10,04
	brass	0,25	11,00	0,66
	brass	3,60000	158,40	9,50
	bedroom cabinet total		5.328,80	198,42
Bathroom cabinet	mdf	15,68	172,48	6,12
	mdf	21,70	238,70	8,46
	mdf	2,52	27,72	0,98
	brass	0,72	31,68	1,90
	bathroom cabinet total		470,58	17,46
Kitchen cabinet	mdf	115,43	1.269,73	45,02
	mdf	95,55	1.051,05	37,26
	brass	0,85	37,40	2,24
	brass	4,32	190,08	11,40

	nickel plated steel	2,59	425,09	32,14
	stainless steel	11,32	641,84	69,62
	brass	2,60	114,40	6,86
	granite	101,50	1.116,50	71,05
	kitchen cabinet total		4.846,09	275,60

Table 4 Materials shell inventory

The shell inventory brings together the finishing materials and customization options that were used in the prototype fabrication and construction. The external wall finishing used on the prototype was ETICS (external thermal insulation composite system); the interior walls were made in plasterboard with vertical profiles; the floor finishing is a laminated wood flooring with a polyethylene foam; the interior doors were prefab plywood doors with a timber sheet, and the exterior windows were constituted by aluminium frame and double glazed glass (as window layout and size was a customization option it is included in Shell inventory). Finally some other elements were considered such as baseboard, sanitary equipment, and fixed furniture (cabinet, closet, counter board).

2.4. Results

Table 5 presents the weight, the embodied energy and GHG emissions results for each of Moby's components. In this analysis the separation between the Core and Shell was considered, and it was also considered each of the elements or parts individually.

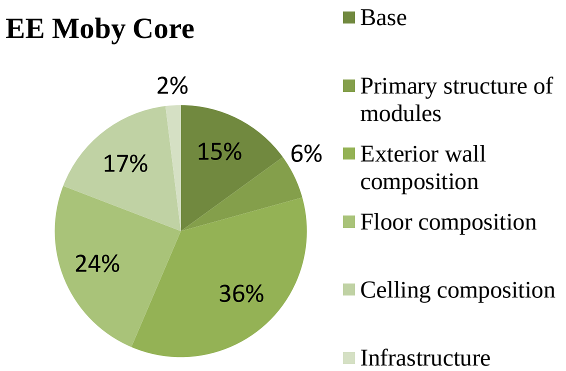
MOBY's CORE	WEIGHT (kg)	% core	% total	EE (MJ)	% core	% total	ECeq ($kgCO_2eq$)	% core	% total
Base	1.433	16%	11%	49.907	15%	12%	3.587	20%	16%
Primary structure	900	10%	7%	18.940	6%	4%	1.361	7%	6%
Exterior wall	2.610	29%	20%	118.817	36%	28%	5.647	31%	25%
Floor	1.910	22%	15%	81.226	24%	19%	4.369	24%	19%
Celling	1.921	22%	15%	57.262	17%	14%	3.006	16%	13%
Infrastructure	99	1%	1%	6.479	2%	2%	313	2%	1%
Total Core	8.873	100%	68%	332.632	100%	79%	18.282	100%	79%

MOBY's SHELL	WEIGHT (kg)	% shell	% total	EE (MJ)	% shell	% total	ECeq ($kgCO_2eq$)	% shell	% total
Exterior wall finishing	1.222	30%	9%	23.256	26%	6%	1.221	26%	5%
Interior wall	499	12%	4%	7.225	8%	2%	402	8%	2%
Floor finishing	383	9%	3%	6.546	7%	2%	196	4%	1%
Doors	30	1%	0%	331	0%	0%	12	0%	0%
Windows	1.004	24%	8%	39.627	44%	9%	2.328	49%	10%
Baseboard and cornice	12	0%	0%	120	0%	0%	4	0%	0%
Sanitary equipment	140	3%	1%	1.480	2%	0%	103	2%	0%
Fixed furniture	836	20%	6%	10.645	12%	3%	491	10%	2%
Total Shell	4.126	100%	32%	89.231	100%	21%	4.756	100%	21%

	WEIGHT (kg)		EE (MJ)		ECeq (ECkgCO2eq)	
Total Moby	12.999		421.863		23.038	

Table 5 Results of materials

From the analysis of the results it can be affirmed that the more representative element within the core is the Exterior Wall that stands for 36% of EE and 31% of ECeq. After that are the Floor Composition (24% EE and ECeq) and the Roof Composition (16% EE, 17% ECeq). These three elements represent about 3/4 of the total energy and GHG emissions of the core.



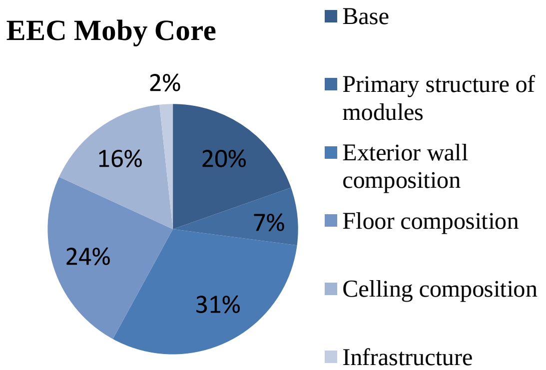
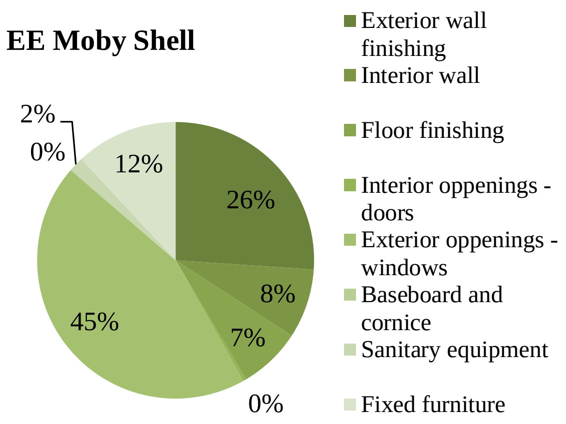


Figure 3 Embodied energy and GHG of Moby´s Core

On the other hand, the most significant element of the Shell is the Exterior Opening (windows) representing 44% of EE and 49% of ECeq. Next are the Exterior Wall Finishing (26% EE and ECeq) and the Fixed Furniture (12% ECeq and 10% ECeq).



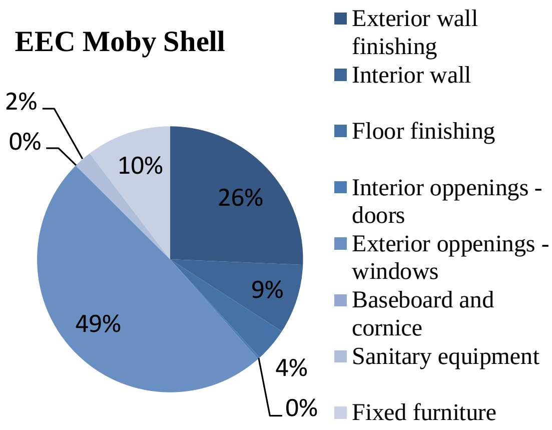


Figure 4 Embodied energy and GHG of Moby´s Shell

It is also important to analyse the results for materials of Moby as a whole. Thus, overall, the most relevant element is terms of energy and GHG emissions is the Exterior Wall Composition (28% of total EE and 25% of ECeq) followed by Floor Composition (19% of total EE and ECeq) and Roof Composition (14% of total EE and 13% for ECeq). All these three elements are part of the Core of Moby. This is an important result to be addressed in its eco-design towards a more sustainable solution.

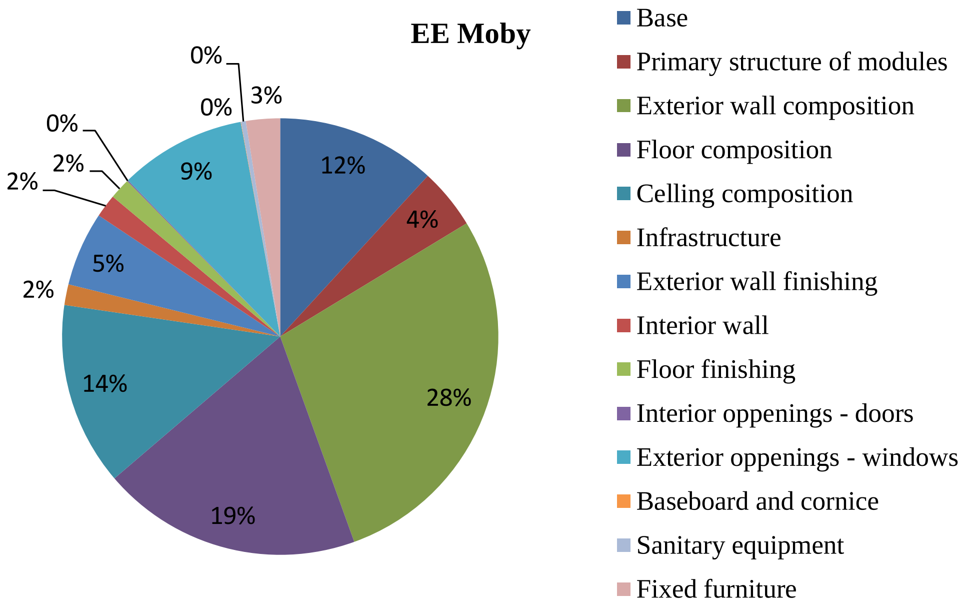


Figure 5 Embodied energy of Moby

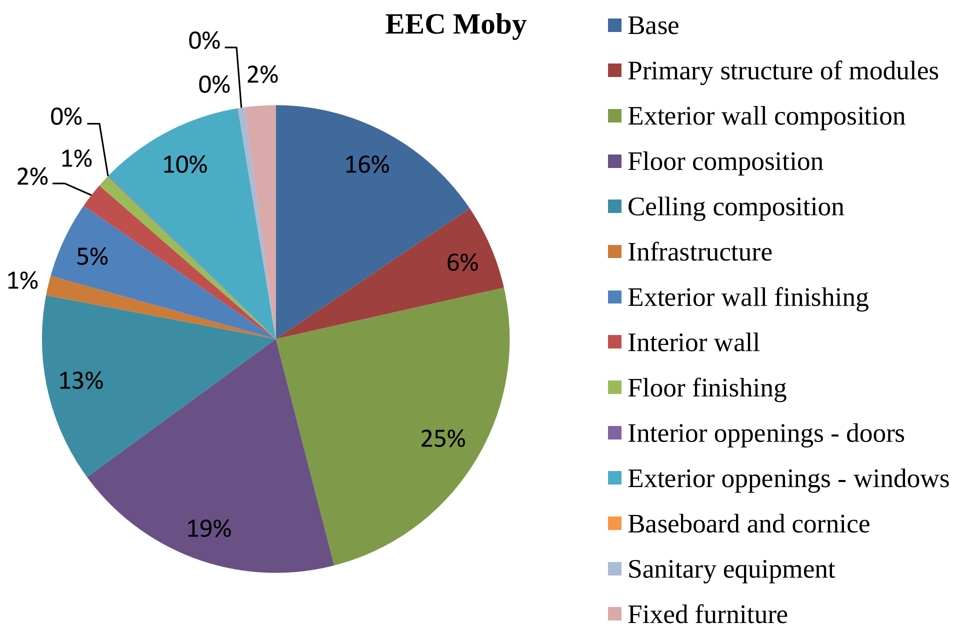


Figure 6 GHG of Moby

Finally it is important to know the aggregated result of Shell and Core in the whole. Thus EE and ECeq correspond to 21% and 79% of the total, Shell and Core respectively. The Core definitely the most relevant part of prototype in terms of embodied Energy and Carbon during materials production and construction phase. This result is rather significant as the Core is repeatable and produced in plant (and may be optimized) while the Shell is changeable in order to adapt to inhabitants and final location.

When compared to other case studies in the literature, the total mass of Moby fits within the range of the published values found in literature review. Aye (Aye et. Al, 2012) presents for the mass of the steel module a value of 0.22 t/m^2. In the present study we found a very similar value of 0.23 t/m^2.

In comparison with values present in literature, r the incorporated energy of materials Aye presents a value equal to 14.4 GJ/m^2, while in Moby we found a value of 7.5 GJ/m^2. Such a difference should be further analysed in the future.

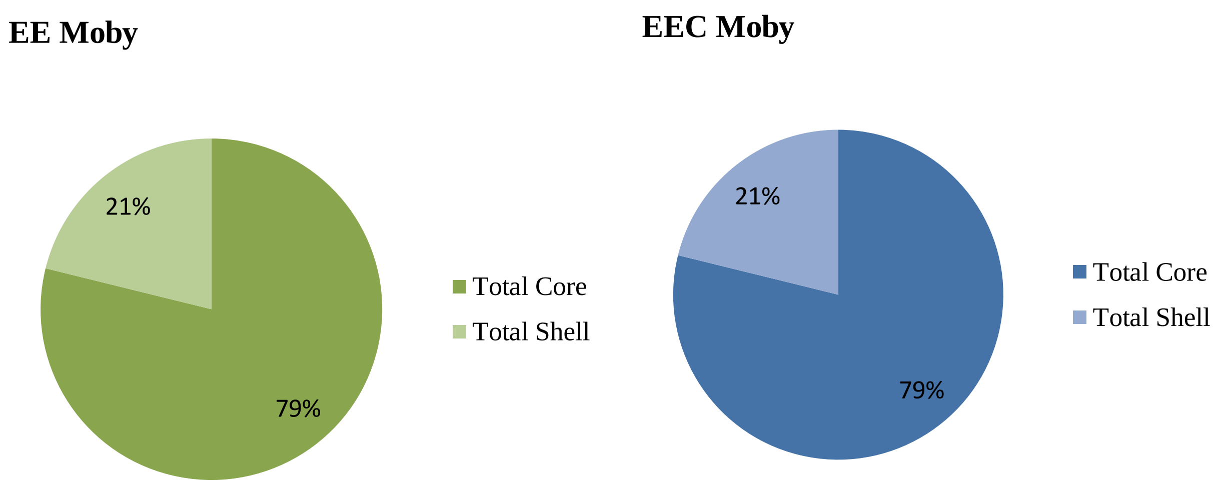


Figure 7 Embodied energy and GHG of Moby Shell and Core

The aggregated results show the importance of the Core emissions and energy relating Moby's total, and therefore the importance of Core fabrication in plant. As this is part of an industrialized procedure, the Core can and must be redesigned, aiming at improving Moby's environmental performance. The materials used in Core must equally be carefully selected. In this work, it was proposed and analysed alternative materials in the prefabrication of the core. This study is presented in Chapter 3 "Core alternative".

2.6. Finishing lines: Basic, Standard and Deluxe

2.6.1. Description

Apart from the numerous options available, namely by different modules combination that allow creating different typologies, there were commercially presented three customization option set. Each set has different finishes named as: Basic, Standard, and Deluxe. All these three options sets were measured and analysed.

As differences were just in the finishing materials, only the Shell results were altered. The differences in models materials were (from *Basic to Deluxe*) in Exterior Wall Composition simply painted in *Basic*, the ETIC in *Standard* and the wooden panels in *Deluxe*; interior Bathroom Wall Finishing the ceramic in *Basic* and in *Standard* and the marble in *Deluxe*; Floor Finishing the ceramic and vinyl floor in *Basic*, and ceramic and laminated wood in *Standard* and the wood, ceramic and granite in *Deluxe*, and, finally, Kitchens Countertop that was in MDF in *Basic*, in granite in *Standard*, and in Corian in *Deluxe*.

2.6.2. Results

The results are presented in the following table and show an increasing tendency in each of the finishing's materials line, in direct correlation with the prototype cost.

BASIC	EE (MJ)	ECeq ($kgCO_2e$)	**STANDARD**	EE (MJ)	ECeq ($kgCO_2e$)	**DELUXE**	EE (MJ)	ECeq ($kgCO_2e$)
Core	332.632	18.282	Core	332.632	18.282	Core	332.632	18.282
Shell	90.412	4.627	Shell	92.711	5.063	Shell	94.554	5.356
	423.045	22.909		425.343	23.345		427.186	23.638

Table 6 Results of different finishing lines sets

These are due to two main causes: on the one hand, in some cases more materials were added to the prototype (e.g. in the case of the exterior wall an additional layer is added); on the other hand more processed materials were used (as in the case of the counter top in the *Deluxe* model which is in Corian). So, in the present case studies, the models are more expensive, have more materials and energy embodied in the prototype.

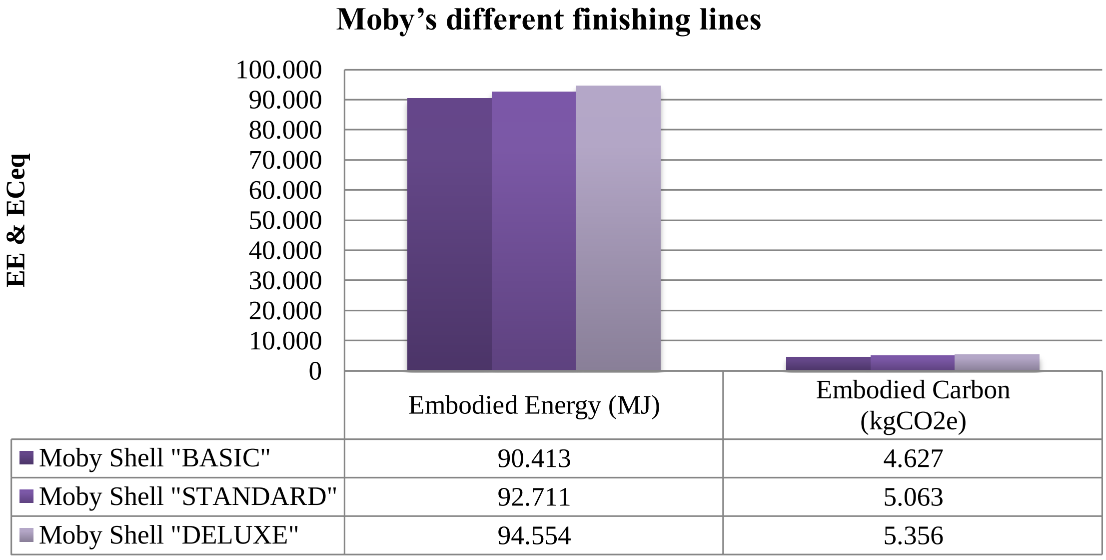


Figure 8 Different finishing lines results

2.6.3. Discussion

The following table shows the percentage change between the different finishing lines, i.e. the variation of EE and ECeq from *Basic* to *Standard* line and after that, from *Standard* to *Deluxe* line. The *Basic* to the *Standard* line variation is higher, since more layers were added to the *Basic* model. This increment is of 3% in the embodied energy and 9% in the embodied GHG. After, results from *Standard* to *Deluxe* suffer an increment rate of 2% in EE and of 6% in the ECeq.

basic -> standard	EE (MJ)	ECeq ($kgCO_2e$)
Exterior wall finishing	+8%	+44%
Interior wall	-1%	-2%
Floor finishing	-2%	+2%
Other element	+7%	+11%
	+3%	+9%

standard -> deluxe	EE (MJ)	ECeq ($kgCO_2e$)
Exterior wall finishing	+12%	-16%
Interior wall	+26%	+29%
Floor finishing	-29%	-63%
Other element	-1%	+91%
	+2%	+6%

Table 7 Different finishing lines results variation

Therefore, from this analysis of present case studies, it may be referred that the highest the price of the house the bigger the embodied energy and the corresponding GHG emissions as extra layers were added to basic model. However, it should be calculated the energy used during the use phase, as this higher embodied energy and GHG in materials can also represent energy savings during the use phase to the same level of comfort. A more extensive Life-cycle assessment including use phase should be performed in order to account to energy and GHG during use phase and to quantify the energy needed in each scenario. In a "cradle to grave" assessment the ranking of each solution energy use and GHG emission might be different in the same comfort performance level scenario as the insulation levels of models are not guaranteed to be the same.

2.7. Typologies variation: from one-bedroom house to a four bedroom house

2.7.1. Description

In order to analyse the influence of models size, four different typologies were analysed: a one-bedroom house with 56m^2 (the prototype), a two-bedroom house with 75m^2, a three-bedroom house with 94m^2 and, finally, a four-bedroom house with 113m^2 of gross floor area.

Figure 9 Studied typologies: from one-bedroom to four-bedroom models

A simplified method was used in this analysis: based on the initial prototype it was calculated the ECeq and EE were calculated per unit: in modules' main structure and per square meter in the remaining elements (floor, roofing, exterior wall, interior wall, exteriors and interiors openings, infrastructure, finishing and other elements). Next, total EE and ECeq were calculated for each model. The results are presented in the next table.

	one-bedroom model		**two-bedroom model**		**three-bedroom model**		**four-bedroom model**	
	EE (MJ)	ECeq ($kgCO_2$)	EE (MJ)	ECeq ($kgCO_2$)	EE (MJ)	ECeq ($kgCO_2$)	EE (MJ)	ECeq ($kgCO_2$)
foundations	49.907	3.587	66.543	4.782	83.179	5.978	99.814	7.173
modules	18.940	1.361	25.254	1.815	31.567	2.269	37.881	2.722
floor	87.772	4.565	117.030	6.087	146.287	7.608	175.544	9.130
roof	57.262	3.006	76.350	4.008	95.437	5.010	114.524	6.011
external walls	142.074	6.868	163.261	7.892	177.908	8.600	194.427	9.398
internal walls	7.225	402	25.694	1.428	37.810	2.102	47.220	2.625
windows	39.627	2.328	53.571	3.148	60.583	3.560	73.503	4.319
doors	331	12	662	24	993	36	993	36
infrastructure	6.479	313	8.638	417	10.798	521	12.958	625
sanitary equipment	1.480	103	1.480	103	2.960	205	2.960	205
bathroom cabinet	471	17	471	17	941	35	941	35
bedroom cabinet	5.329	198	10.658	397	15.986	595	21.315	794
kitchen cabinet	4.846	276	4.846	276	4.846	276	4.846	276
baseboard	120	4	161	5	201	6	241	7
TOTAL	**421.863**	**23.038**	**554.617**	**30.397**	**669.496**	**36.799**	**787.166**	**43.356**
total/m2	7.533	411	9.904	543	11.955	657	14.057	774

Table 8 Different typologies inventory

2.7.2. Results

Increasing the number of rooms (and global area) will also increase the embodied energy and associated GHG. However, as it would be expected, this perceptual increase tends to diminish with the growth of the house. This tendency is the subject of our next analysis.

	total EE (MJ)		total ECeq (kgCO2)	
one bedroom	421.863		22.441	
two bedrooms	554.617	31%	29.600	32%
three bedrooms	669.496	21%	35.682	21%
four bedrooms	787.166	18%	42.040	18%

Table 9 Different typologies results

Different functional units were considered in the analysis: house area, corrected number of inhabitants and number of rooms. It was decided to correct the number habitants because in the thermal regulation it is establish two inhabitants for the first room and one extra per room, a number that seemed excessive. The corrected number of inhabitants used included inhabitants fractions (half of an inhabitant) something only possible in the hypothetical field and in this numerical analysis of this case study.

The results are summarized in the table 10. In all cases the increasing number of rooms represents a decrease in the embodied energy and GHG per functional unit: square meter, habitants or number of bedroom. This was an expected conclusion as it expresses the dilution of more equipped common areas with higher impacts, or “service areas” (kitchen and bathrooms) as defined by Richard (Richard, 2005) since the impacts are shared between habitants and/or allocated to a higher area. However decreasing tendency is different when using different functional units. When using area as the functional unit the decrease in embodied energy and GHG is in the order of 1-4% from a model to the bigger one. The decrease of embodied energy and GHG per habitant vary from 12% to 6%, while using the estimated number of inhabitants functional unit decreasing the percentage variation as the model increases. Finally, using number of bedroom as function unit the decrease is higher than 30% among smaller typologies being 12% of the larger ones.

Per AREA	Area (m^2)		EE/m2 (MJ)		EEC/m^2 ($kgCO_2$)	
one bedroom	56,25 m^2		7.499,79		398,94	
two bedroom	75,00 m^2	+33%	7.394,89	-1%	394,66	-1%
three bedrooms	93,75 m^2	+25%	7.141,29	-3%	380,61	-4%
four bedrooms	112,50 m^2	+20%	6.997,03	-2%	373,69	-2%

Per INHABITANTS	no of inhabitants (unit)		EE/hab (MJ)		EEC/hab ($kgCO_2$)	
one bedroom	1,00 units		421.863,35		22.440,64	
two bedroom	1,50 units	+50%	369.744,54	-12%	19.733,09	-12%
three bedrooms	2,00 units	+33%	334.747,76	-9%	17.841,01	-10%
four bedrooms	2,50 units	+25%	314.866,50	-6%	16.815,91	-6%

Per NUMBER OF ROOMS	no bedrooms (unit)		EE/no bedrooms (MJ)		EEC/no bedrooms ($kgCO_2$)	
one bedroom	1 units		421.863		22.441	
two bedroom	2 units	+100%	277.308	-34%	14.800	-34%
three bedrooms	3 units	+50%	223.165	-20%	11.894	-20%
four bedrooms	4 units	+33%	196.791,	-12%	10.510	-12%

Table 10 Embodied energy and embodied GHG results variation using different function units

These tables show that despite of the increase of the area or the number of inhabitants not a direct and proportional increase of impacts by function unit is verified as impacts tend to decrease per functional unit. By varying the functional unit, this trend also varies, being more or less expressive, though maintaining this decreasing tendency.

Independent results by functional unit are shown in the figures below. In the interest of simplification, only the graphics representing EE in each of the functional units used is showed. Graphics presenting ECeq results would present a similar tendency.

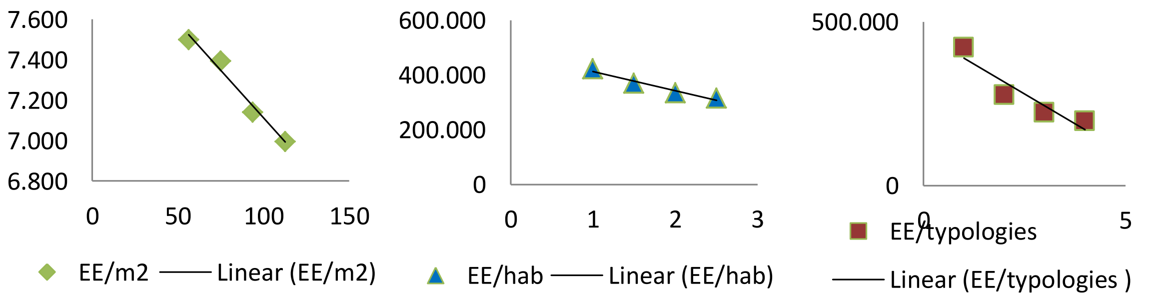
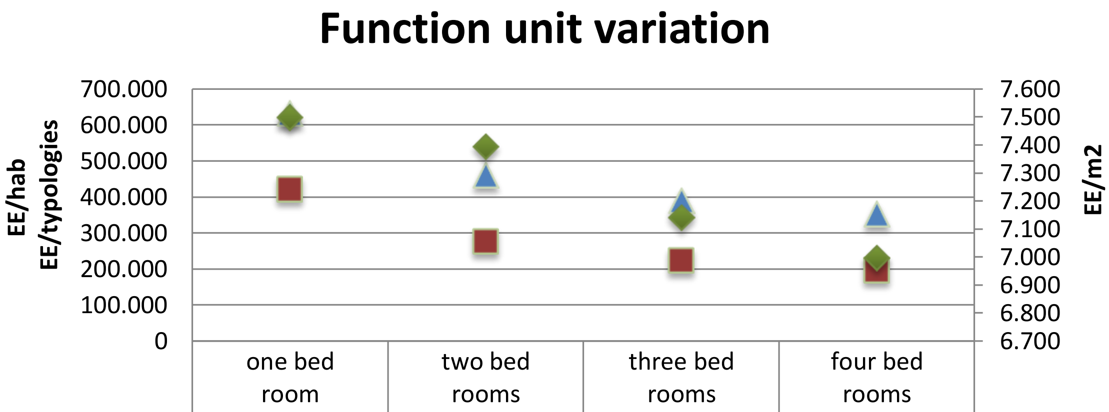


Figure 10 Embodied energy results presented per different function units: square meter, number of inhabitants and number of rooms variation

2.7.3. Discussion

The figure 11 shows the results of the three functional units. It is worth mentioning to note that the values for inhabitants and typologies are similar (as the number of rooms accompanies the number of inhabitants). It is also worth noting the influence that the choice of the functional unit might have in results.



	one bed room	two bed rooms	three bed rooms	four bed rooms
EE/hab	210.932	184.872	167.374	157.433
EE/typologies	421.863	277.308	223.165	196.792
EE/m2	7.500	7.395	7.141	6.997

Table 11 Function units embodied energy results

2.8. Distance to site

2.8.1. Description

It was intended to study the influence of the construction site distance on the cumulative results of production and transportation thus expanding the EE and ECeq analysis from "cradle to gate" to "cradle to site". Consequently, one real location plus seven hypothetical sites were analysed: four in national territory: Aveiro (where the prototype was built), Coimbra, Lisbon and Faro; and four international sites: Paris, Luanda, Casablanca and Rio de Janeiro. These last four places were defined in order to the representativeness of some of the Portuguese Architecture, Engineering and Construction (AEC) industry target market: a city in a country in central Europe, a city in the African coast, one city in the Mediterranean and, finally, another city over the Atlantic Ocean. Moreover these countries represent target markets for the Portuguese prefabricated buildings industry due to proximity (North Africa), because they are part of the same common market (European Community) or because they share the language and culture (in this study Angola and Brazil but other Portuguese-speaking countries may be included).

For the international locations it was considered the means of transportation that best suited the distance and the site location, trying to get closer to the reality. Within Europe (Paris) it was considered the transportation of workers for the construction site by air. All the remaining means of transportation are the same of the national settings. In the other three alternatives – Luanda, Casablanca and Rio de Janeiro – it was considered the modules' transportation from the factory to the port by crane truck and then by a freight vessel from there to the destination country. As international locations are hypothetical the distance from the port to the construction site was unable to be set. Therefore it was considered a fixed distance of 80 km for locals materials transportation to site, related to shell materials, chosen locally by end users.

In general, for national locations, the number of trips and percentage of occupation of each mode of transportation for calculation purposed were taken the following considerations: i) the transportation of materials to the plant was calculated in heavy truck with an occupancy factor of 25% and considering the return trip; ii) the transportation of the modules (both from factory to building site and from factory to port) was considered by crane truck with 15% occupancy, with return journey; iii) workers' transportation to factory was considered by individual car, four trips per day for each one of the eight workers at an average of 20 km away of home during 44 working-days (this is two months, the time it took to build the prototype) plus ten days with only two trips per day (time of assemblage); and, finally, iv) workers transportation to construction site in a minivan with nine seats and considering two trips per day for a period of ten days.

The international locations, excepting Paris where the transportation of the modules was considered directly by land, were calculated the transportation of the modules to the port of Leixões by crane truck (at a occupancy rate of 15% with return) and from there to the destination port by boat. The transportation of workers to construction site has been considered by a commercial plane with only one round trip, considering only 3 workers. The other workers would be hired locally.

ESPINHO -> AVEIRO (50 km)	No trips (units)	Distance (km)	Mode of transportation	EE (MJ)	ECeq ($kgCO_2e$)
Materials transportation to factory	8	50	heavy truck	4.250	323
Modules transportation from factory to site	6	50	crane truck	6.375	485
Materials transportation to site	4	80	heavy truck	3.400	258
Workers transportation to factory	412	20	car	21.012	1.597
Workers transportation to site	6	50	mini van	1.020	78
Total				**36.057**	**2.740**

ESPINHO -> COIMBRA (100 km)	No trips (units)	Distance (km)	Mode of transportation	EE (MJ)	ECeq ($kgCO_2e$)
Materials transportation to factory	8	50	heavy truck	4.250	323
Modules transportation from factory to site	6	100	crane truck	12.750	969
Materials transportation to site	4	80	heavy truck	3.400	258
Workers transportation to factory	412	20	car	21.012	1.597
Workers transportation to site	6	100	mini van	2.040	155
Total				**43.452**	**3.302**

ESPINHO -> LISBOA (300 km)	No trips (units)	Distance (km)	Mode of transportation	EE (MJ)	ECeq ($kgCO_2e$)
Materials transportation to factory	8	50	heavy truck	4.250	323
Modules transportation from factory to site	6	300	crane truck	38.250	2.907
Materials transportation to site	4	80	heavy truck	3.400	258
Workers transportation to factory	412	20	car	21.012	1.597
Workers transportation to site	2	300	mini van	3.740	284
Total				**70.652**	**5.370**

ESPINHO -> FARO (500 km)	No trips (units)	Distance (km)	Mode of transportation	EE (MJ)	ECeq (kgCO2e)
Materials transportation to factory	8	50	heavy truck	4.250	323
Modules transportation from factory to site	6	500	crane truck	63.750	4.845
Materials transportation to site	4	80	heavy truck	3.400	258
Workers transportation to factory	412	20	car	28.016	2.129
Workers transportation to site	2	500	mini van	6.375	485
Total				**105.791**	**8.040**

Table 12 Transportation EE and GHG inventory to four Portuguese sites

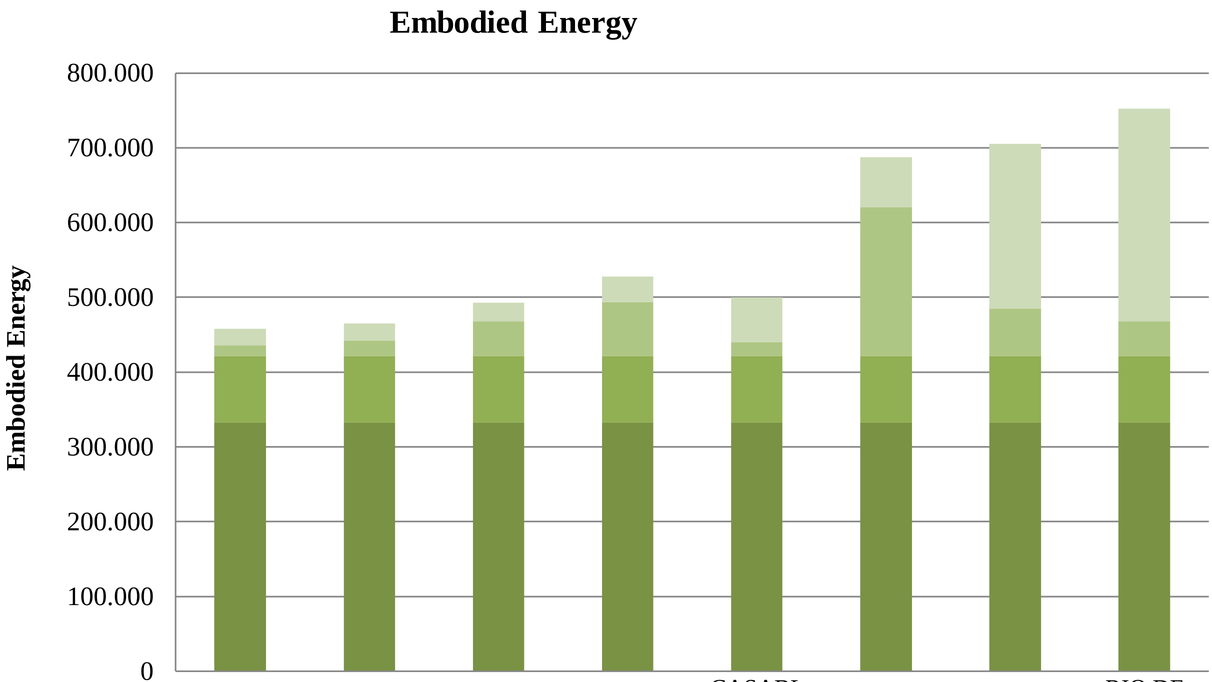
ESPINHO -> PARIS (1.500 km)	No trips (units)	Distance (km)	Mode of transportation	EE (MJ)	ECeq (kgCO2e)
Materials transportation to factory	8	50	heavy truck	4.250	323
Modules transportation from factory to site	6	1.500	crane truck	191.250	14.535
Materials transportation to site	4	80	heavy truck	3.400	258
Workers transportation to factory	412	20	car	28.016	2.129
Workers transportation to site	6	1.500	plane	38.491	2.925
Total				**265.407**	**20.171**
ESPINHO -> LUANDA (6.000 km)	**No trips (units)**	**Distance (km)**	**Mode of transportation**	**EE (MJ)**	**ECeq (kgCO2e)**
Materials transportation to factory	8	50	heavy truck	4.250	323
Modules transportation from factory to port	6	50	crane truck	6.375	485
Modules transportation from factory to site	1	6.000	cargo ship	23.958	1.917
Materials transportation to site	4	80	heavy truck	3.400	258
Workers transportation to factory	412	20	car	28.016	2.129
Workers transportation to site	6	6.000	plane	192.453	14.626
Total				**283.567**	**19.738**
ESPINHO -> CASABLANCA (1.000 km)	**No trips (units)**	**Distance (km)**	**Mode of transportation**	**EE (MJ)**	**ECeq (kgCO2e)**
Materials transportation to factory	8	50	heavy truck	4.250	323
Modules transportation from factory to port	6	50	crane truck	6.375	485
Modules transportation from port to site	6	1.000	cargo ship	3.993	319
Materials transportation to site	4	80	heavy truck	3.400	258
Workers transportation to factory	412	20	car	28.016	2.129
Workers transportation to site	6	1.000	plane	32.075	2.438
Total				**78.109**	**5.952**
ESPINHO -> RIO DE JANEIRO (8.000 km)	**No trips (units)**	**Distance (km)**	**Mode of transportation**	**EE (MJ)**	**ECeq (kgCO2e)**
Materials transportation to factory	8	50	heavy truck	4.250	323
Modules transportation from factory to port	6	50	crane truck	6.375	485
Modules transportation from port to site	6	8.000	cargo ship	31.944	2.556
Materials transportation to site	4	80	heavy truck	3.400	258
Workers transportation to factory	412	20	car	28.016	2.129
Workers transportation to site	6	8.000	plane	256.604	19.502
Total				**330.588**	**25.252**

Table 13 Transportation EE and GHG inventory to four international sites

2.8.2. Results

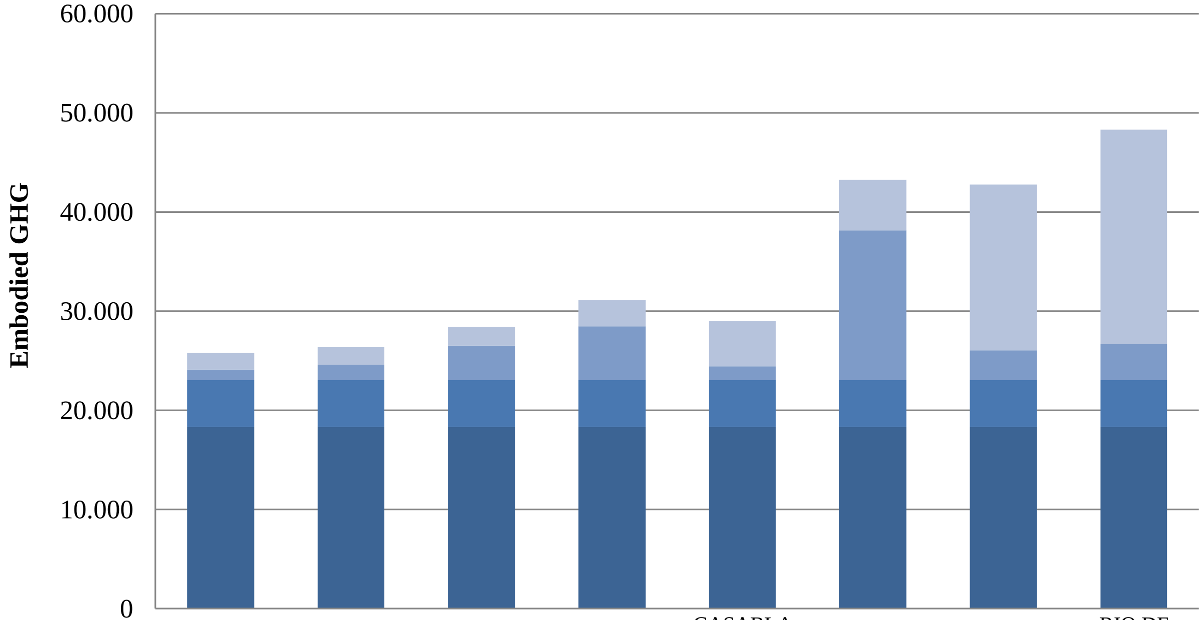
The following graphics show the cumulative results of EE and ECeq production of Moby production with transportation (materials, modules and workers). One can foresee that building site location can greatly influence the end result noticing that not always a longer distance represents a higher GHG emissions and energy value, and that the means of transportation (emissions and energy associated with each one of the transportation modes) can greatly influence results.

The table and graphic below show the results of EE and ECeq for each scenario, from the closest site to the farthest, being considered the following distances: Aveiro 50 km, Coimbra 100 Km, Lisbon 300 Km, Faro 900 km, Casablanca 1000 km, Paris 1200 km, Luanda 6000 km and, finally, Rio de Janeiro 8000 km. In the national territory since it was always used the same means of transportation, there is a direct relation between EE, ECeq and distance to the construction site. However, for international locations, despite the increasing distance, emissions do not always grow proportionally. In Luanda's scenario, despite a distance approximately five times higher than Paris, the presented value is slightly lower. Moreover, in Paris case study it was verified that the results associated with the transportation of the modules made by land are quite significant. In contrast, in Luanda and Rio de Janeiro scenarios, it is the workers' transportation that is undoubtedly the most significant part in transportation related energy consumption and GHG emission analysis due to workers transportation by air.



	AVEIRO (50km)	COIMBRA (100km)	LISBOA (300km)	FARO (900km)	CASABLANCA (1.000km)	PARIS (1.200km)	LUANDA (6.000km)	RIO DE JANEIRO (8.000km)
Workers transport	22.032	23.052	24.752	34.391	60.091	66.507	220.469	284.620
Materials and modules transport	14.025	20.400	45.900	71.400	18.018	198.900	63.099	45.969
Materials in Shell	89.231	89.231	89.231	89.231	89.231	89.231	89.231	89.231
Materials in Core	332.632	332.632	332.632	332.632	332.632	332.632	332.632	332.632

Figure 11 Embodied energy related to transportation



	AVEIRO (50km)	COIMBRA (100km)	LISBOA (300km)	FARO (900km)	CASABLANCA (1.000km)	PARIS (1.200km)	LUANDA (6.000km)	RIO DE JANEIRO (8.000km)
Workers transport	1.674	1.752	1.881	2.614	4.567	5.054	16.756	21.631
Materials and modules transport	1.066	1.550	3.488	5.426	1.385	15.116	2.983	3.621
Materials in Shell	4.756	4.756	4.756	4.756	4.756	4.756	4.756	4.756
Materials in Core	18.282	18.282	18.282	18.282	18.282	18.282	18.282	18.282

Figure 12 Embodied GHG related to transportation

Discussion

The results of this analysis proves the great influence that the final construction location and distance from production plant can have in building environmental performance especially in prefabricated modular construction. Besides the distance, the mode of transportation may also be of great importance since some have high energy consumption per transported weight or volume. For example, the air transportation despite being used only to the transportation of the skilled workers to the local final assemblage represents high energy consumption for most of the international places.

2.9. Dynamic thermal simulation

2.9.1. Dynamic thermal simulation model presentation

The dynamic thermal simulation was performed in order to evaluate the prototype during use phase, using the base scenario, i.e., the 56 m^2 one-bedroom house under study.

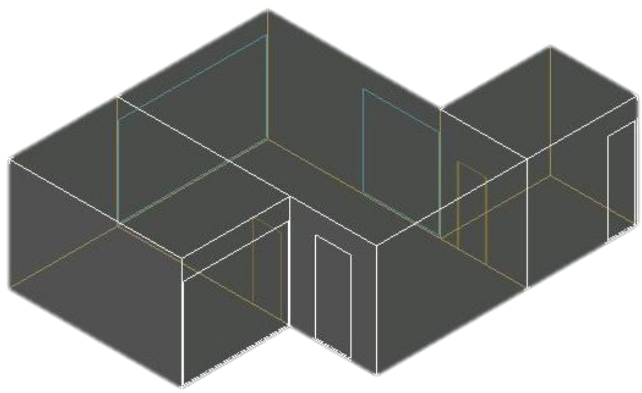


Figure 13 Energy Plus model

The prototype was modeled and analyzed using the 8.2 version of EnergyPlus software. Two users and three occupation profiles were considered: week, weekend, and holidays. A 50 years lifetime was considered, a value presented in literature review (Bribian, Aye, among others). The geometry was built in Sketchup being later imported into Energy Plus program by a *.idf format file.

Since it was only intended to compare construction solutions, it was used a simplified acclimatization model named "Ideal Loads Air Systems" in which it is considered the electric supply (equivalence) and thermal supply with 100% efficiency. Most of the climate data used was taken from the US Department of Energy website[9]. For the other locations not present in the previous website, it was used the LNEG climate data calculation tool[10].

2.9.2. Results

The use phase has a large impact on the building performance assessment. Even in a scenario in which the Life-cycle service considered was of only 30 years the difference in the use phase impacts would only be 10% lower (varying from 72% of the over whole impacts, considering 30 years lifespan, to 81% here presented). For a neutral acclimatization scenario it is expected a power consumption of 39,8 GJ per year. As previously explained, in this simulation it was considered a simple “Ideal Loads System”, a kind of "District Heating" power supply in which the efficiency of the system is considered to be 100%, i.e. there is no loss of energy on supply and transformation. Nevertheless, after 50 years of use, it is estimated a total energy consumption and equivalent GHG emissions of almost three times more than the embodied energy in materials and transportation during construction and assemblage phases, a value far too significant.

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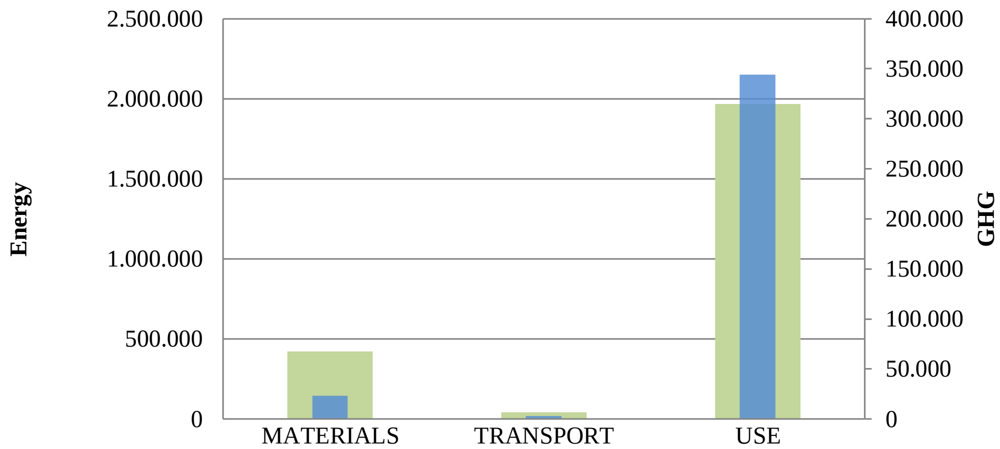
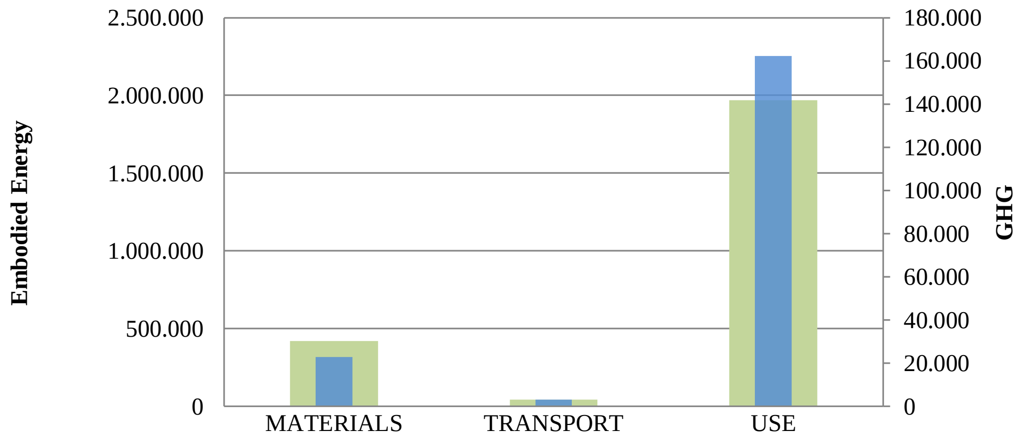
9 Available in: http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=6_europe_wmo_region_6/country=PRT/cname=Portugal

10 Available in: http://www.lneg.pt/servicos/328/2263/



	MATERIALS	TRANSPORT	USE
Embodied Energy (MJ)	421.863,35	43.452,00	1.968.400,00
Embodied Carbon (kgCO2e)	23.038,35	3.302,35	344.042,86

Figure 14 Results of energy and GHG of materials, transportation and use (year ref 2005)



	MATERIALS	TRANSPORT	USE
Embodied Energy (MJ)	421.863,35	43.452,00	1.968.400,00
Embodied Carbon (kgCO2e)	23.038,35	3.302,35	162.135,14

Figure 15 Results of energy and GHG of materials, transportation and use (year ref 2010)

2.9.3. Discussion

To calculate the GHG value associated with the operation energy required during the use phase, two different emission factor were considered: 609 kg CO_2eq (from 2005 year) and 287 kg CO_2eq (from 2010 year) being respectively the highest and the lowest values for life-cycle impacts per kWh of the annual Portuguese electricity generation mix for 2003–2012 (Garcia et al. 2014). This is a relatively low range when compared to the values presented by Bribian (Bribian et al. 2009) in which is set a value of 649 gCO_2/kWh for conventional peninsular electricity.

Another research presented by Bribian focuses on a traditional construction house, with approximately 220m^2 and located in Zaragoza. This case study presents for the use phase and for a year period a value of 15kgCO_2/m^2 for GHG emissions a value 36% lower than Moby's (24kgCO_2/m^2). Relating energy consumption it presents a value of 71.1kWh/m^2 in present case study value is 40% corresponding to 122.87kWh/m^2.

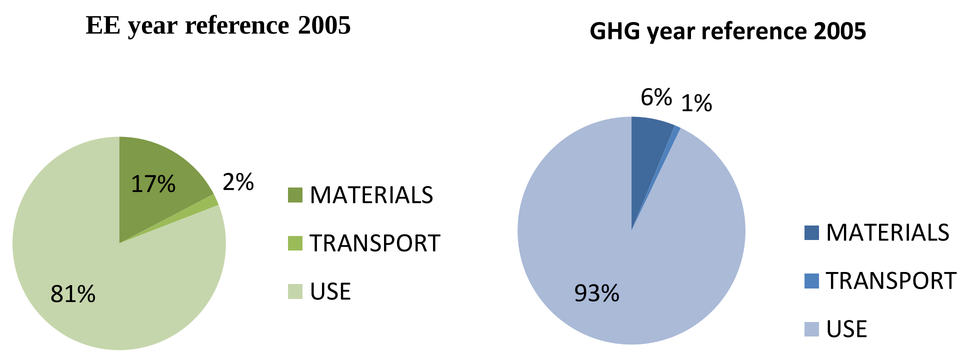


Figure 16 Energy and GHG of materials, transportation and use (year reference 2005)

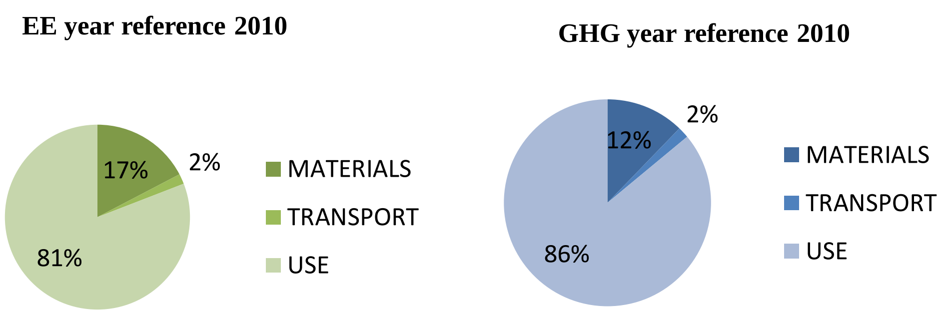


Figure 17 Energy and GHG of materials, transportation and use (year reference 2010)

3. Core alternative

3.1. Core alternative presentation

In Chapter 2 the core was identified as being the part of the prototype responsible for the biggest energy consumption and GHG emissions (79% of both EE and GHG). Within this section it was intend to analyse alternative materials to modules structure. However it was not intended to change the essence of the project, i.e. alternatives should not alter the prefabricated and modularity concept of the building. Therefore, three alternatives to structural materials were proposed and compared to the initial structure: Concrete, Wood and Light Steel Framing (LSF).

It was intended to ensure a similar resistance between different structural alternatives. As the building is simple with only one floor and a maximum of 3.6 meters width portico, lighten structures were used with small sections. Foundations were removed from this analysis as the kind of foundations used in each Moby was, on the one hand, very varied and depending on the soil and on designer's decision and because they were independent from the structural system. Therefore, the comparison between similar models with different structural solutions was made without considering any foundation variation from base case study.

Figure 18 Wooden, concrete and light steel framing prefabricated construction examples

3.1.1. Concrete

The concrete structure was considered a continuous wall structure with 12 cm thick. The same thickness has been considered for the floor and the roof. Being this a “tunnel type” structure it has a double function of structural resistance and closure, no other additional closure elements are required.

3.1.2. Wood

A quadrangular-shape section pillars of 15cm side and spaced approximately 60cm between elements was considered and. The beams on the floor and on the roof have a rectangular section of 11cm by 15cm with a similar spacing distance. Finally, the secondary vertical and horizontal structure composed by elements with 8cm by 5cm section. OSB panels were considered for closure of the exterior wall, floor and roof, as well as to give more rigidity to all the structure.

3.1.3. Light steel framing

Finally, a structure in light steel framing system (LSF) was simulated. To calculate the LSF structure it was not considered the sections of pillars and beams, but the weight per length of each profile (selected from catalogue[11]). Since all elements were in galvanized steel, for each vertical corner, top and bottom edge were chosen more robust profiles. A lighter profile was selected for the horizontal and vertical secondary substructure.

3.2. Results

As presented in the table 14, the change of structural material influences results. The weight of the structure is the parameter that changes the most, being foreseen that in the case of the concrete structure it can be four times the weight of the base case and reduced to almost 80% in LSF structure solution. Regarding the aspects under study, the solution in timber and in LSF are the most advantageous being the last the lightest and

with less embodied energy and GHG of all the studied alternatives.

	BASE CASE STUDY		**CONCRETE**	% of case study	**WOOD**	% of case study	**LSF**	% of case study
Weight (Kg)	***12.999***		*59.340*	*456%*	*16.375*	*126%*	*10.485*	*81%*
Embodied Energy (Mj)	**421.887**		400.254	95%	424.414	101%	390.282	93%
Embodied GHG (kgCO2eq)	**23.042**		24.422	106%	20.511	89%	20.528	89%

Table 14 Different structural materials results

3.3. Discussion

A comparative analysis of alternative structural systems composed of different materials should be subject to a more careful study. This analysis should include at least two aspects arising from the change in the structure: i) consider the variation in the modules transportation with different resistance, weight and volume transported, and ii) consider changing the energy consumed and associated GHG emission for acclimatization during

[11] Available in: http://lightsteelframing.pt/info-tecnica/downloads/

the use phase. Although being a preliminary analysis, this study shows the variability of results out coming from different structural systems and materials.

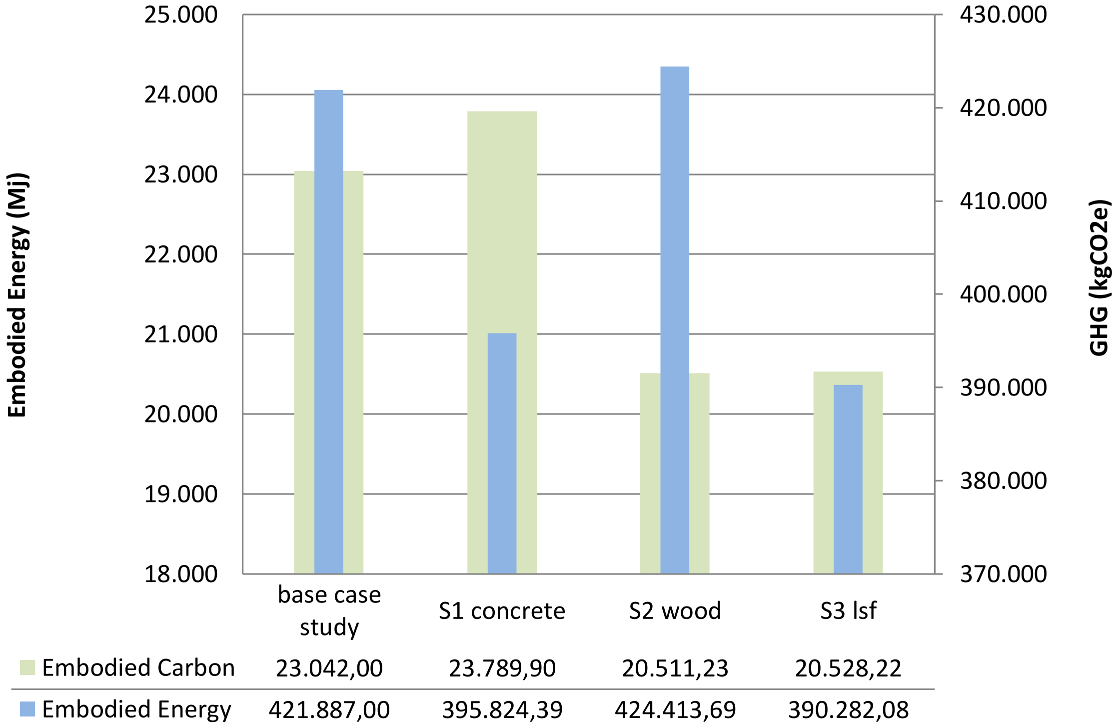


Figure 19 Embodied energy and GHG of different structural materials

4. Insulation alternative

4.1. Insulation alternative presentation

As in the previous chapter, in which different structural materials were studied, in this section were simulated three different scenarios with three alternative materials for thermal insulation: rigid extruded polystyrene foam (XPS), Rockwool and Cork. These three insulation materials were compared with the base case study insulation, the ETICS system.

Figure 20 XPS, Rockwool and Cork insulation examples

4.1.1. XPS

The rigid extruded polystyrene foam (XPS) was chosen as a first alternative, since it is often used in the construction in Portugal. It was considered plates with about 6cm thick as this is a typical thickness for this type of insulation, and for our typical climate.

4.1.2. Rockwool

The rockwool is a material from the mineral insulation products family. In conjunction with XPS it is one of the most applied insulation materials in Portugal. It was used for the calculations a standard measure of 6cm thickness, distributed in rolled sheets.

4.1.3. Cork

Finally, cork was chosen from the so called "greener materials" and because it is a material produced in Portugal and transformed near Moby's plant. Various new application of cork in the building's industry are now under development. Thus, it was intended to analyse cork as one of the scenarios for the thermal insulation of Moby. For the scope of this study, cork boards with 8cm thickness were considered.

4.2. Results

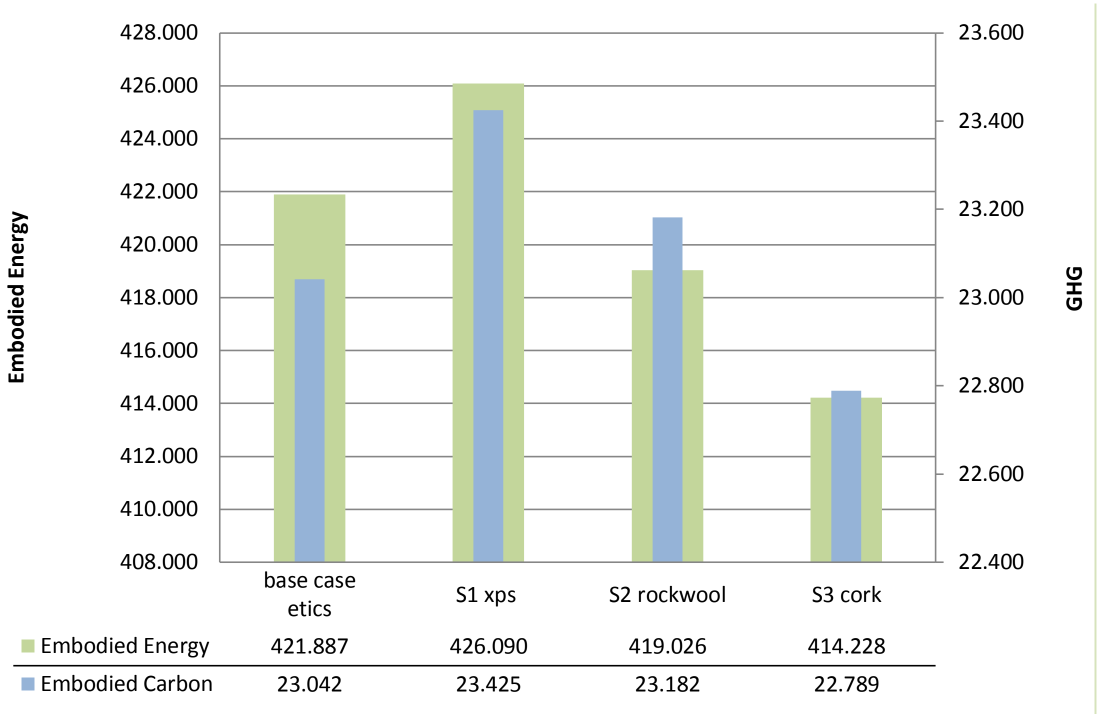


Figure 21 Embodied energy and GHG of different insulation materials

4.3. Discussion

From all the studied insulation materials cork performs the best as an insulation material which could optimize the environmental performance of the Shell. Being the most natural material, i.e. less transformed, this was an expectable result. However, despite the picture presented above that seems to point at a wide variation between four scenarios, the change in the insulation material would only reduce by about 1%. The total EE and ECeq of Moby (Core + Shell). This is due to the small relative weight of the Shell on the whole (about 20%) and due to the reduced importance of the thermal insulation within all of the materials that compose the Shell. As previous stated a further research should be performed in order to include use phase the comparison of different insulation materials.

5. Conclusions & future developments

5.1. Results and comparison with results in literature

Results from Moby´s assessment during construction phase are summarized in table 15. Differences between materials durability and maintenance works for each structural alternatives were not considered in present analyses.

Moby a prefab modular house	**case study description**	**EE/m²** (MJ/m^2)	**ECeq/m²** ($kgCO2/m^2$)	**note**
base case study	metal structure & ETICS insulation	7.534	412	
structural alternatives	concrete structure	7.147	436	
	wood structure	7.579	366	
	LSF structure	**6.969**	**367**	embodied energy and GHG related to construction phase
insulation alternatives	XPS	7.609	418	
	rockwool	7.483	414	
	cork	7.397	407	

Table 15 Embodied Energy and GHG per area for each of the studied structural materials

Prototype results fit into the range of results presented in literature of other studies with similar case studies or construction methods: modular presented by Quale et al., semi-prefabrication by Mao et al.; Modern Method of Construction (MMC) and Lightweight by Hacker et al. Results are summarized in table 16.

Name of the paper	author	journal	case study description	EE/m² (MJ/m²)	ECeq/m² (kgCO2/m²)	note
Construction Matters Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States	J. Quale et al.	Journal of Industrial Ecology (2012) Vol 16 nr 2 2012	modular average	-	613	only material production
			on site average	-	780	
Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects	C. Mao et al.	Energy and Buildings 66 (2013) 165–176	semi-prefabrication	-	**336**	in the construction phase
			conventional construction	-	368	
An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework	J. Monahan, J.C. Powell	Energy and Buildings 43 (2011) 179–188	Scenario 1: MMC timber frame larch cladding	5.700	405	embodied primary energy to construct
			Scenario 2 MMC timber frame brick cladding	7.700	535	
			Scenario 3: masonry	8.200	612	
Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change	Hacker et al.	Energy and Buildings 40 (2008) 375–384	Lightweight (timber frame with brick exterior).	-	492	ECO2 (t) at completion for the four case study weights
			Medium weight (traditional brick and block exterior wall, with lightweight ceilings and partitions).	-	508	
			Medium-heavy (as medium weight but with block partitions and concrete hollow-core ceiling on ground floor).	-	538	
			Heavy (heavyweight block inner leaf and partitions, with hollow-core concrete ceiling on the ground and first floor).	-	569	

Table 16 Overview of literature specific on housing construction results for embodied energy and carbon

5.2. Discussion

"To evolve in order to improve as industry is a natural way in the construction sector."[12] (Couto e Couto, 2007)

From the mapping of the state of the art, can be pointed out some of the advantage in the use of prefabrication in construction: reducing labour cost, achieved through scale economy and specialization that maximize efficiency by allocating production activities and the continuous process improvement; material cost reducing because of the big production scale one can negotiate the best price and study the best use of materials; increased quality, by material choosing, control of production and technical specifications; reducing waste by a higher control over materials and construction performance. On the opposite, a series of factors constrains prefabrication: limitations in design due to standardization; restricted group of specialized contractors and workers; economic competitiveness achieved only from a particular production scale; cultural, legal and social barriers, represented by legislators, regulators and users that prevents the growth of this industry feeling apprehensive in face of the unknown and local production (and their own jobs) displacement to distant factories. However, pros and cons should be analysed based on the environmental and economic benefits that should be measured and properly weighed in order to support the implementation and expansion actions towards a more prefabricated construction sector, whether public or spontaneous, at the governance political level, or in individual efforts within the private sector. Based on this, our research focuses on the environmental aspects of the construction process.

All the assessment, validation and innovation about construction are more interesting if there is a possibility replication and repeating results. The studied and evaluated solutions only have impact if inserted into a prefabrication and repeat system, where the created solutions are tested and validated through prototype analysis and whose added value (economic, environmental and social) is revealed by its constant repetition. It is not important to "invent the wheel" if it is only used once. As Life-cycle analysis tools are too costly and time consuming to be applied in individual cases, each time a unique, unrepeatable construction. Prefabrication in construction allow the pre-evaluation of

[12] Traduced from the Portuguese quote "*Evoluir no sentido de aperfeiçoar-se como indústria é um caminho natural do sector da construção civi*l."

buildings that will be latter influenced by building's final location but whose previous analysis will allow a more rapid and flexible final evaluation and optimization of the construction.

As buildings have a long use period the use phase has a strong importance in LCA deeply influencing results, even though it is stated in some studies the improvement of buildings performance will increase the relative weight of construction phase.

5.3. Conclusions

From the studied developed about Moby´s production process and from some of the analysed scenarios the following conclusions can be drawn:

- As the core of the prototype represents almost 80% of total embodied energy and GHG the most effective action in order to improve Moby's performance at construction stage is to redesign its core;

- From the three different finishing line sets analysis that are part of the Shell it can be concluded that as shell's materials' impacts are small so finishing can be altered without deeply influence Moby's performance;

- In the present case study, the most expensive models are the most energy intensive ones during construction phase. However, use phase ought to be included, in order to analyse if energy and cost investment made during the construction represent gains during the use phase.

- Contrary to the shell's customization distance to site is of great importance in the final impacts of the prototype. Distance to site and the means of transportation used during materials, modules and workers transportation will deeply influence final results.

- Embodied energy and embodied GHG during construction phase of present case study fits construction house values from the comparison of values presented in literature review. Moby's embodied energy and GHG values vary from 7.0-7,6 GJ/m^2 and 366-436 kgCO_2/m^2, respectively, and results presented in the literature (Hacker et al.2008, Mao et al. 2013, Monahan and Powell 2011, Quale et al. 2012) vary from 5,7-8,2 GJ/m^2 of embodied energy and 336-780 CO_2/m^2 of embodied GHG (results presented in table 16).

• Operation energy and respective GHG emission during use phase are higher than values presented in literature explicitly by Hacker research (Hacker et. al 2008). Moby´s operational energy is 703 MJ per m^2 and related GHG 58-122 $kgCO_2$ per m^2 (variation due to emission factor variation, 2005 and 2010 reference years, being the highest and lowest). Values presented by Bribian (Bribian et al 2009) are 255 MJ/m^2 of primary energy consumption per year and 15 $kgCO_2/m^2$ per year. This operation energy and GHG increase in lightweight buildings is referred by Hacker et al. (Hacker et al. 2008) in the analysis between lightweight to heavyweight construction. One of the conclusions of that study is that although being initial embodied CO_2 is higher in the heavier weight cases difference were counterpoise early in the lifecycle due to the reduction in operational CO_2 emissions.

5.4. Future development

Competitiveness in the construction sector, due to the decrease in demand, impels this sector to modernize: to improve its efficiency and working conditions while reducing costs. Prefabrication is presented as a possible way to achieve that, through automation, standardization, routines and modelling; the construction process can be more efficient based on the continuous improvement of the process that being repeated enhances learning, and a continuing process of improvement. Thus errors are avoided as well as negative experiments and the most advantageous solutions are repeated and constantly improved. The process and the quality of the final product (which is very difficult to do in traditional construction) is controlled, and a more specialized sector is created. These features might positively affect this sector currently in financial crises and push it through global market.

In this context, the student intends to continue this research in order to overcome some of the limitations of the presented study that have been identified all through this written work. Some thoughts for future development will be here enumerated that may take this study to a completely new level, turning this research more robust and complete, surpassing its limitations.

In order to make the model more flexible and responsive to the context conditions, a more accurate and defined dynamic thermal simulation ought to be performed to each of the different scenarios presented in this study. This assessment may include all the others alternatives that might be considered interesting in the future. To do this correctly it would be necessary to correctly dimension the HVAC system as well as all the other networks such as lighting, hot water, electric equipment; to better analyse each scenario and alternative.

Another future development involves increasing of the number of the studied case studies both in terms of modular prefabricated buildings as well as in the traditional construction. With a wider sampling, study would have different result sets that would allow a better comparison between constructive typologies correctly grounded in a vast data base and so, conclusions could be driven. In the present research only one single case was studied. Even though results were compared with data obtained from different research found in the literature, the degree of the reliability of the conclusions may be compromised.

Finally, in order to make previous presented points feasible and data more operative, it is intended to integrate BIM methodology in buildings LCA. Building Information Modelling (BIM) is a working methodology based on a digital model and associated database that allows data sharing and exchange between different stakeholders through a shared or common digital model. The integration of BIM methodology would make the building inventory construction more simplified and constantly updated, turning the assessment more flexible and reliable.

In conclusion, developing a buildings' evaluation methodology, encompassing the full complexity of the buildings (structure, finishing, openings, insulation, equipment, networks, etc.) and that would take into account the whole life cycle, from extraction of materials until the end of life is envisioned. This methodology is intended to be flexible and easy to use, so that it could evaluate construction during design phase being this assessment the basis for its continuous improvement. Thus it is envisioned a building assessment methodology that integrates LCA, BIM and Building's Dynamic Simulation tools. That envisioned assessment methodology is not a building's posthumous evaluation but, on the contrary, is a design support tool by gathering and treating data that will serve as a base point to decision making. Thus making data available and comprehensive to designers, builders, owners, rulers and all the others stakeholders that have interest in improving the built environment in which we all live in.

6. References

Antón, A., Díaz, J. (2014) "Integration of Life-cycle assessment in a BIM environment", Original Research Article Procedia Engineering, Volume 85 (2014) 26-32.

Aye, L.; Ngo, T.; Crawford, R.; Gammampila, R.; Mendis, P. (2012) "Life-cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules", Energy and Buildings. Vol. 47 (2012) 159-168.

Basbagill, J.; Flager, F.; Lepech, M.; Fischer, M. (2013) "Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts", Building and Environment 60 (2013) 81-92.

Benros, D., Duarte, J.P. (2008) "An integrated system for providing mass customized housing", Automation in Construction 18 (2009) 310–320

Borg, M., (2001). "Environmental assessment of materials, components and buildings - Buildings specific considerations, open-loop recycling, variations in assessment results and the usage phase of buildings", Doctoral thesis, Stockholm 2001. ISBN 91-7283-159-6.

Bribián, I. Z., Usón, A. A., & Scarpellini, S. (2009). "Life-cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification", Building and Environment, 44, (2009) 2510–2520.

Chen, Y.; Okudan, G.; Riley, D. (2010) "Decision support for construction method selection in concrete buildings: prefabrication adoption and optimization" Automation in Construction 19 (2010) 665-675.

Chiang, Y-H.; Chan, E.; Lok, H-L (2006). "Prefabrication and barriers to entry – a case study of public housing and institutional buildings in Hong Kong", Habitat International 30 (2006) 482–499.

Da Silveira, G., Borenstein, D., Fogliatto, F. (2001) "Mass customization: Literature review and research directions", Int. J. Production Economics 72 (2001) 1-13.

Dimoundi, A., Tompa, C. (2008) "Energy and environmental indicators related construction". Reource, conservation and recycling 53 (2008) 80-95.

Dixit, M.; Fernández-Solís, J.; Lavy, S.; Culp, C. (2012) "Need for an embodied energy measurement protocol for buildings: A review paper" Renewable and Sustainable Energy Reviews 16 (2013) 3730-3743.

Erlandsson, M., Borg, M., (2003). “Generic LCA-methodology applicable for buildings, constructions and operation services—today practice and development needs”, Building and Environment 38 (2003) 919 – 938.

Garcia, R., Marques, P., Freire, F. (2014). “Life-cycle assessment of electricity in Portugal”, Applied Energy 134 (2014) 563-572.

Haapio, A., & Viitaniemi, P. (2008). “A critical review of building environmental assessment tools”, Environmental Impact Assessment Review, 28(7), 469-482.

Hacker, J. N., De Saulles, T. P., Minson, A. J., & Holmes, M. J. (2008). “Embodied and operational carbon dioxide emissions”, Energy and Buildings 40 (2008) 375–384

Huberman, H., Pearlmutter, D., (2007). “A life-cycle energy analysis of building materials in the Negev desert.” Energy and Buildings 40 (2008) 837-848.

Jaillon, L., Poon, C.S., (2009) “The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector”, Automation in Construction 18 (2009) 239–248.

Jalaei, F., Jrade, A., (2014) “An automated BIM model to conceptually design, analyse, simulate, and assess sustainable building projects”, Journal of Information Technology in Construction - ITcon Vol. 19 (2014) 494-519.

Kellenberge, D., Althaus, H. (2008). “Relevance of simplifications in LCA of building components”, Building and Environment 44 (2009) 818–825.

Khasreen, M., Banfill, P., Menzies, G. (2009) “Life-Cycle Assessment and the Environmental Impact of Buildings: A Review”, Sustainability (2009) 1, 674-701.

Li, Z., (2006) “A new Life-cycle impact assessment approach for buildings”, Building and Environment 41 (2006) 1414-1422.

MA Zhiliang; ZHAO Yili (2008) "Model of Next generation energy-efficient design software for buildings", Tsinghua science and technology Vol 13, S1(2008), 298-304.

Malmqvist , T.; Glaumann, M.; Scarpellini, S.; Zabalza, I.; Aranda, A.; Llera, E.; Díaz, S. (2011) "Life-cycle assessment in buildings: The ENSLIC simplified method and guidelines", Energy 36 (2011) 1900-1907.

Mao, C.; Shen, Q.; Shen, L.; Tang, L. (2013) "Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects", Energy and Buildings 66 (2013) 165-176.

Monahan, J., Powell, J. (2011) "An embodied carbon and energy analysis of moderns methods of construction in housing: A case study using lifecycle assessment framework", energy and buildings 43 (2011) 179-188.

Monteiro, H. Freire F. (2012)."Life-Cycle Assessment of a house with alternative exterior walls: comparison of three impact assessment methods". Journal Energy and Buildings, vol. 47, pp.572-583.

Nemry, F., Uihlein, A., Colodel, C. M., Wetzel, C., Braune, A., Wittstock, B., et al. (2010). "Options to reduce the environmental impacts of residential buildings in the European Union—Potential and costs", Energy and Buildings (2010).

Noguchi, M., Velasco, C. (2005). "A 'mass custom design' approach to upgrading conventional housing development in Mexico", Habitat International 29 (2005) 325–336.

Ortiz, O., Castells, F., & Sonnemann, G. (2009). "Sustainability in the construction industry: A review of recent developments based on LCA", Construction and Building Materials, 23(1), 28-39.

Peuportier, B. (2001). "Life-cycle assessment applied to the comparative evaluation of single family houses in the French context", Energy and Buildings, 33(5) (2001) 443-450.

Peuportier, B.; Thiers, S.; Guiavarch, A. (2013). "Eco-design of buildings using thermal simulation and Life-cycle assessment", Journal of Cleaner Production 39 (2013) 73-78.

Pons, O.; Wadel, G.(2011) "Environmental impacts of prefabricated school buildings in Catalonia", Habitat International. Vol. 35-4 (2011) 553-563.

Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G., Zimmerman, J.B. (2012). "Construction matters: Comparing environmental impacts of building modular and conventional homes in the United States", Journal of Industrial Ecology 16(2), 243-253.

Richard, R.-B. (2005). “Industrialized building systems: reproduction before automation and robotics.” Automation in Construction 14 (2005) 442–451.

Rossi, B.; Marique, A.; Glaumann, M.; Reiter, S. (2012). "Life-cycle assessment of residential buildings in three different European locations, basic tool." Building and Environment 51 (2012) 395-401.

Silva, J. Mendes; Ramos, A., (2011). “Directives towards a sustainable urban rehabilitation process in old cities”, International Journal of Sustainable Development (IJSD) Volume 14 - Issue 1/2 – 2011.

Sivaraman, D. (2011). “An integrated Life-cycle assessment model: Energy and greenhouse gas performance of residential heritage buildings, and the influence of retrofit strategies in the state of Victoria in Australia”, Energy and Buildings (2011).

Szalay, A. (2005). “What is missing from the concept of the new European Building Directive?” Building and Environment 42 (2007) 1761-1769.

Thormark, C., (2002). “A low energy building in a Life-cycle – its embodied energy, energy need for operation and recycling potential”, Building and Environment, 37, (2002) 429-435.

Tillman, A-M. (2000). “Significance of decision-making for LCA methodology”, Environmental Impact Assessment Review 20 (2000) 113–123 .

Tommerup H., Rose, J., Svendsen S. (2007). “Energy-efficient houses built according to the energy performance requirements introduced in Denmark in 2006”, Energy and Buildings 39 (2007) 1123–1130.

Tsai, W-H; Lin, S-J; Liu, J-Y; Lin, W-R; Lee, K-C. (2011) “Incorporating Life-cycle assessments into building project decision-making: An energy consumption and CO2 emission perspective”, Energy 36 (2011) 3022-3029.

Verbeeck, G., Hens, H. (2010) “Life-cycle inventory of buildings: a contribution analysis”, Building and Environment 45 (2010) 94-967.