Environmental footprint of modular building solution Using LCA approach

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Abstract – *Construction sector is the major resource exploiter, being responsible for the consumption of 40% of natural materials, for the production of 40% of the waste generated in each country and the use of 40% of energy, which in Europe is related with buildings operation. Therefore it is necessary to assess the impacts and contributions of buildings life cycle, instead of focusing the environmental analysis in just one indicator, allowing a wider vision for sustainability. This study was intended to approach the environmental footprint, for a construction solution produced in Portugal, project FRED204, comparing the results obtained with other case studies related to different construction typologies. It was performed an analyses with a wider approach, that uses distinct indicators, integrating the environmental footprint with LCA analysis, implemented through SimaPro Software.*

From the results obtained it is important to mention the good environmental performance of project FRED204, with lower CF values among the other construction typologies considered. The implementation of more sustainable solutions on the construction sector, as modular solutions, drives through a compromise where environment, economy and human well-being are addressed and not compromised.

Keywords – Sustainable Construction, Modular Construction, Environmental Footprint, Life Cycle Assessment, Environmental impact, Ecological Indicators

1. INTRODUCTION

Mankind has always pursued lifestyles and enrolled in activities which expose the environment to a number of different impacts. The increasing population numbers leads to an outstanding resource consumption and, if on one hand, we are facing a society on a technological rise, were comfort standards are improving, on the other, the resources available are decreasing.

Bearing in mind that the construction sector is one of the largest exploiters of resources (Spence & Mulligan, 1995) their impacts cannot be excluded, arising throughout the life cycle of buildings (Zuo & Zhao, 2014).

In the European Union, this sector is responsible for the use of 40% of the natural material resources, for about 40% of the total consumption of primary energy (Erlandsson & Borg, 2003) and, moreover, for the production of 40% of the waste in each country (Solís-Guzmán et al., 2013). There is a demanding need to adopt measures to minimize energy expenditure and construction impacts on the environment (Desideri et al., 2013), but considering that, on average, people spend about 90% of their time indoors (Tirone, 2007), is also needed to take special care in construction methods and materials used on design.

Given its importance in terms of impacts caused in environment and its accelerated development, the construction sector is a target segment (Proietti et al., 2013), and it is necessary to try to reduce negative impacts, compensate the irreversible ones and enhance the positive ones. Therefore, it is important to stimulate the demand for new practices, methods and/or technologies which result in lower environmental impacts, ensure a closer relationship with the environment and provides suitable comfort levels, but that at the same time, do not neglect the protection and defense of natural resources throughout time.

In this context the demand for modular building solutions is one of the challenges on the agenda, which should be encouraged and promoted. The use of these solutions is increasing, with evident advantages in functional terms, being an emerging concept that responds to the environmental and economic needs.

According to Lucas & Amado (2013) it is necessary to move towards a new paradigm that integrates the principles of sustainability. The perception of environmental footprint allows the knowledge of what are the impacts associated with each construction solutions and further understand the improvement opportunities, which are two key areas to move towards a sustainable development, where, as mention earlier, the construction sector has a key role. Therefore, there is an urgent need for approaches that assess the cause-effect relation of these anthropogenic pressures on the environment, such as the environmental footprint.

Regarding this need, the European Commission has been promoting ways to increase resource productivity and to decouple economic growth from both resource use and environmental impacts, taking a life cycle perspective. Thus, the Product and Organization Environmental Footprint project was initiated with the aim of developing a harmonized European methodology for Environmental Footprint studies that can accommodate a broader suite of relevant environmental performance criteria using a life cycle approach (EC, 2013).

Considering that standardization remains a key tool to measure and demonstrate processes improvement (Desideri et al., 2013), this study aims to pursue the future needs in terms of methodological approach, namely, a general method to measure and communicate the potential environmental impact of a product life cycle, integrating the calculation of footprints on the basis of an evaluation of life cycle (Product Environmental Footprint).

In general, the "footprint" is a quantitative measure that describes the appropriation of natural resources by man (Hoekstra, 2008), illustrating how human activities may impose different loads and impacts on global sustainability.

The environmental footprint enables a quantifiable analysis in relation to the efficiency of: 1) production processes, 2) resource consumption limits and 3) global distribution of natural resources. This analysis allows the discussion raise and drives the development of answers that help to deal with the sustainable use of natural resources around the world (Senbel et al., 2003).

The search for the environmental footprint of modular solutions are therefore important in order to better understand their implementation and impacts on the environmental, being the object of this study.

2. STATE-OF-ART

In order to understand the dimension and the impact from anthropogenic activities on environment, it is possible to perform an analysis based on the systematization of the footprint.

Examples of footprint concepts application are related to 1) the space required to withstand or absorb the impact of anthropogenic activities (Ecological Footprint), 2) emission of greenhouse gases (Carbon Footprint) and 3) water consumption (Water Footprint) associated with these activities.

2.1 *Ecological Footprint*

Developed by W. Rees e Matis Wackernagel, in 1996, ecological footprint (EF), it is a methodology which allows the activities and its flows characterization, to determine the system requirements in terms of space, to support feeding needs, wood, energy and infrastructures. It translates into the biologically productive area necessary to support the required resources and absorb the generated waste by an individual, a community, an activity or building, within a year (Pinheiro, 2006).

2.2 *Carbon Footprint*

The Popularity of the concept carbon footprint (CF) increased in last years, responding to the rising concern of public opinion regarding environmental issues and climate change, it became one of the main environmental indicators (Galli et al., 2012). Despite its popularity it is still not clear a solid definition for this concept, although it could be understood as the amount of CO_2 and other greenhouse gases (GHG) emitted, directly or indirectly, through the process or product life cycle (UK POST, 2011).

2.3 *Water Footprint*

Water is a scarcer and essential resource for a quality life and economic development of the population. The demand on this resource is increasing, becoming urgent the need for reservoirs preservation and an efficient use of this resource. Similar to other resources, it become necessary the development of an indicator to evaluate water consumption. In 2002, the water footprint (WF) concept emerged introduced by Professor A. Y. Hoekstra (Hoekstra, 2003). The concept of WF considers the water used directly and indirectly, represented by total volumes of water consumed or water polluted by time or by functional unit (Čuček et al., 2012).

This has brought the concept of footprint family defining a set of indicators capable of analyzing human pressure on the environment. Despite the similarities between these three concepts that integrate footprint family, their origin and purpose are different and respond to different demands on environmental studies.

2.4 *LCA could be a base?*

The LCA stands out currently as an excellence tool for the analysis and selection of alternatives, particularly from an environmental perspective (Proietti et al., 2013), and its use, over the past few decades, has been increasing.

One of the first official definitions of LCA emerged in 1991 by SETAC (Society of Environmental Toxicology and Chemistry) according to which the LCA was seen as an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. (Pinheiro, 2006).

It is considered that the fundamental concept of LCA is based on the perspective of life cycle, emerging with the awareness that any product, process or activity produces impacts on the environment, since the raw materials essential to their existence were extracted, until after its useful life, they are then returned to nature or reintegrated in the production cycle (Ferrão, 2009).

The LCA is used to compare materials and products, in order to understand which of the alternatives has less impact (Kibert, 2003).

Therefore, LCA allows 1) the comparison of different products, 2) optimization of the environmental performance of products, by identifying improvement opportunities in processes which are included in their life cycle, and also processes which are included in their life cycle, and also 3) the support in decision-making (Ferrão, 2009).

The guidelines for the LCA analysis are the ISO 14000 series standards on the environmental management systems. According to the ISO 14040 and 14044, an LCA study is divided into four main areas:

- Goal and scope definition;
- Life Cycle Inventory;
- Life Cycle Impact Assessment;
- Life Cycle Impact Interpretation.

Buildings can also be characterized according to this approach, which allows a comparison of the environmental impact associated to different buildings (Sartori & Hestnes, 2007).

However, such analysis has been developed mainly for single products design and compared to these products, buildings are totally different. It's important to note that they have a relatively long life, are often subject to change, may have multiple functions, are integrated with infrastructures and they may not have clearly defined boundaries (Desideri et al., 2013). Therefore, the LCA of a building is not a simple process as for many other consumption goods. None the less, the LCA approach is important and necessary to improve the environmental performance of the construction sector and thus to reduce the environmental global load (Zabalza et al., 2009). Given its importance and possibilities to evaluate the environmental impacts of buildings, the LCA is a powerful tool and could be a base to integrate other indicators, namely the footprints mentioned earlier. Over the years, several case studies using the LCA approach were being carried out. On Table 1, are presented some of them.

3. OBJECTIVES AND METHODOLOGIES

The aim of this study was to address ways of evaluating an environmental footprint studying a concrete case of a modular unit manufactured in Portugal. These results will also be compared with other case studies on other types of buildings.

In order to achieve these purposes, the characteristics of the different building materials was assessed, potential improvements were identified and some suggestions were provided, contemplating the materials selection. Furthermore, a variety of environmental performance indicators was used, in order to realize their usefulness in terms of decision-making. Therefore, it is required to identify the critical points related to the environmental performance of the chosen building typology, suggesting areas to improve, in order to achieve the lowest possible impact and, simultaneously, getting more recognition for environmental protection.

This case study ends with the characterization of the modular solution considered, regarding its systematization and positioning of its environmental performance, in a complete and documented manner, based on the analysis of its environmental footprint.

To achieve the proposed objectives, the methodology covers, on a first phase, the study of concepts Life Cycle Assessment (LCA) and environmental footprints. Afterwards it continued with the review of the state of art of different instruments to support the LCA and family footprints, and selection of specific calculation methodologies and life cycle assessment methods.

First it was selected an assessment tool to be used, SimaPro. In this software tool a set of impact assessment methods and databases are available and were analyzed to realize which adjusts better to achieve the goals of this study.

It is important to highlight that, in the present case study, rather than the common approach, in which data are

Table 1
Case studies using LCA approach

Reference	Scope	Functional Unit	System Boundaries	Location	Building typology
(Aye et al., 2012)	Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules	Whole building	Embodied and operational energy and GHG emissions	Australia	Prefabricated building (Multi-residential)
(Proietti et al., 2013)	Life cycle assessment of a passive house in a seismic temperate zone	1 m^2 of living area per a period of 1 year	All life cycle phases: acquisition and production of materials, on-site construction and use/maintenance, demolition and material disposal	Italy	Passive house (residential)
(Dahlstrøm et al., 2012)	Life cycle assessment of a single-family residence built to either conventional or passive house standard	1 m^2 useful floor area	Entire building life cycle: construction, maintenance, operation of the ventilation and heating system, operational energy and water consumption, and end of life treatment	Norway	Conventional and Passive house (residential)
(Desideri et al., 2013)	Design of a multipurpose “zero energy consumption” building according to European Directive 2010/31/EU: Life cycle assessment	Whole building	Entire building life cycle	Italy	Multipurpose building
(Rincón et al., 2013)	Evaluate the environmental impacts of different constructive systems of the building envelope using MFA and LCA	1 m^2 useful floor area	Manufacturing, operational and disposal phases	Spain	Experimental buildings with different constructive systems
(Monahan & Powell, 2011)	An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework	External, thermal envelope of a 3 bedroom, semidetached house with a total foot print area of $45m^2$ and a total internal volume of $220.5m^3$	Cradle to site	United Kingdom	Residential buildings

processed in a Microsoft Excel® spreadsheet, the data is introduced in SimaPro and, using the assessment methods and available databases, the indicators are estimated.
In addition, this work addressed the Environmental Product Declaration (EPD) to be used as a tool to obtain data on specific materials, as well as a comparison tool for products and services through their demonstrated environmental performance.
Subsequently, the case study was selected and, to apply the methodology, data was gathered, namely of the used materials, assessing its environmental footprint using the assessment tools previously mentioned.
After the results were obtained, a critical assessment was realized regarding the environmental performance of the modular solution considered, and a comparison to other types of buildings were made and were analyzed opportunities for improvement.
Finally, the considered approach was discussed, showing the limitations and potentialities, even suggesting some recommendations for future work.

4. CASE STUDY

The FRED204 project (Fig. 1), located in Portugal, was built in March 2014. It was idealized and developed by a national company, MYMODHOUSE, and emerged of the necessity to develop and execute sustainable projects, with high quality levels and low maintenance, using innovative and emergent techniques and materials. It consists on a modular construction, carried out using reused shipping containers, organized in a creative way and architecturally well structured. In a few words, it is defined as a project focused in architectural simplicity, functionality, versatility and concerned about future generations.
The main objective of this project is the creation of livability and comfort conditions similar, or even higher, as in traditional houses, but in a sustainable way. It is a building intended to accommodate a single-family, a T1 typology, with around $45m^2$ of useful area.

4.1 *Building structure*

The structural base of the building is created by the reuse of shipping containers, rehabilitated as recommended by the architecture.

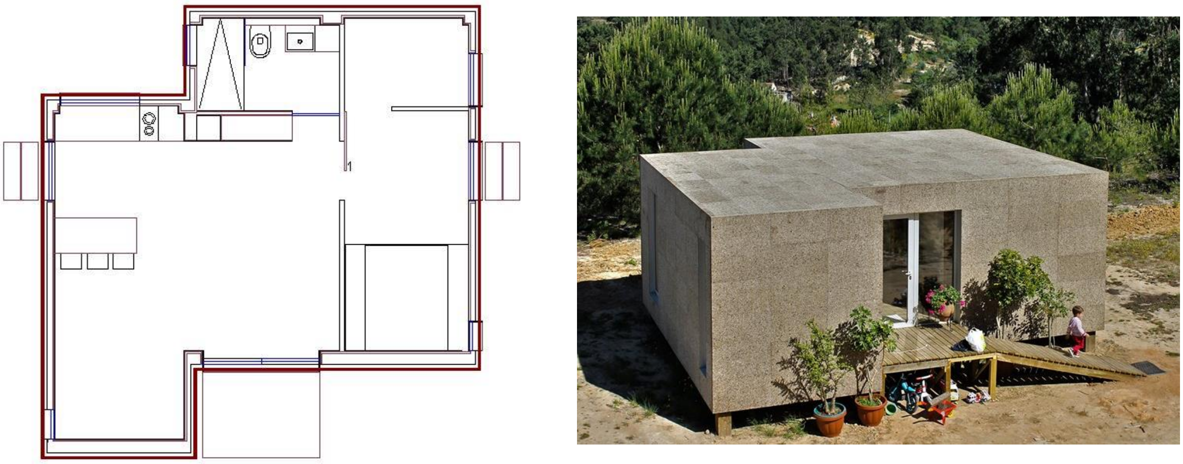

Fig. 1 Plant (left) and photograph (right) of the studied building, FRED204.

The laying base of these modules is composed by a wooden mesh placed under pine wood stakes. This structural mesh under the stakes is used because it allows the same level of comfort, a better energy efficiency, an absence of infiltration by capillarity and a significant financial saving.
Also, as a complement regarding the structural base is used the LSF system (Light Steel Framing), which allows overcome the volumetric limitations of maritime containers, when necessary. This system, besides being a sustainable structural solution, have several advantages, namely: 1) the decrease of time-consumption in the construction process, 2) the reduction of the structure weight up to 10 times, when comparing to the traditional systems, 3) a higher thermal and acoustic efficiency, 4) facilitates the maintenance processes and 5) results in a more competitive price.

4.2 *External Covering*

The external covering (walls and roofs) is mainly composed by Expanded Insulation Corkboard. This solution was chosen because it is a natural material and, after 45 years of use, maintains the original characteristics. This option, besides being ecological, also allows solutions for thermal and acoustic isolation from the exterior. Its copulation to the containers was carried out with resource to a special glue, free of volatile organic compounds.

4.3 *Internal Covering*

On the rooms, different solutions were used. In the bedroom, the wall covering has pine wood, originated from sustainable forests. In the bathroom was used a ceramic glued to the gypsum plasterboard; and on the living room and kitchen the option was OSB (Oriented Strand Board). All the ceilings were covered with gypsum plasterboard. Also regarding the internal covering, the paint applied in ceilings and walls was free of volatile organic compounds.

4.4 *Internal floor covering*

Except for the bathroom, in all the other pavement area was used laminated oak wood, placed directly in the containers floor. In the bathroom, was used a ceramic pavement.

4.5 *Insulation*

The thermal control is done by the exterior cork covering, due to its great thermal and acoustic performance. On the other hand, the thermal control in the floor is promoted by the application of expanded polyurethane foam from soy at the bottom of containers, performed on the outside of the container.

4.6 *Doors and windows*

Regarding windows and outside doors, the doorways are in anodized aluminum frames with double glass and thermal cutting. On the other hand, the inner doors are composed of oak wood.

5. RESULTS

5.1 LIFE CYCLE MODELING

5.1.1 Goal and Scope Definition

The application of the LCA methodology aims to analyze the impacts associated with the materials of the modular solution in study and, afterwards, to compare the obtained results with other building typologies.
Based on the results obtained, by comparison with other case studies and with the instruments to support LCA (eg. EPD), will be presented opportunities for improvement, enabling the reduction of impacts associated with the project life cycle.
The functional unit considered in the study is 45m^2 of useful floor area of a residential building, type T1, with a life cycle of 45 years. The area considered for the functional unit is the total area of the modular solution. Afterwards, the results

are presented, in a square meters base, to enable the comparison with other similar studies.

Definition of the system boundary establishes the unitary processes to include in this analysis. Therefore, it was considered only “Product Stage” (stages A1-A3), composed by three sub-stages: extraction of raw material, transport and manufacture. Consequently, the LCA will be based in the “cradle to gate” approach.

Additionally, the transport of materials to the construction site (stage A4) was also analyzed to understand the influence of this parameter in the final impacts of the project.

5.1.2 Life Cycle Inventory

First step was to collect the data related to the type of materials and their quantities from the company promoting the project, MYMODHOUSE, presented on Table 2. This data includes quantity, the transportation distance between the production and implementation sites (gate-to-site transportation), and product origin. It is important to refer that not all the materials of the modular solution were considered, it was only included those that was justified by its quantity or characteristics.

Afterwards, the unitary processes of the materials included in the life cycle stages were calculated based on the generic data, using the databases available on SimaPro.

About these unitary processes, all the materials are transported by truck, with the exception of pine wood and laminated oak wood, originated from Finland and transported by transoceanic ship.

Next, in order to understand which are the predominant materials in the modular solution, an analysis to the different types of materials was made, based on quantity applied on the solution (Fig. 2).

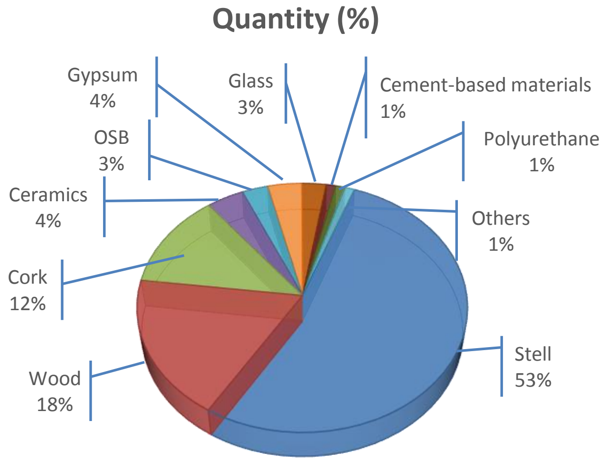

Fig. 2 Composition of the building by type of material, in terms of weight

As expected, the dominant material is steel (53%), because it is the main structure of the project. Followed by wood, with 18%, representing also a large quantity, explained by its use in the wood mesh as structural base of the building. Furthermore, it reflects the use of wood in the floors and walls inside, in some rooms. Lastly, cork (12%) also stands in the list of materials more used.

The assumptions used in this data analysis can significantly influence the final results of LCA. It is important to mention that are only considered the impacts relating to the product stage, choosing to exclude the installation and use stage due to its low relevance to the study objectives and also to the difficulty in obtain that data.

Also, due to the use of generic data, it was not always possible to select the exact material in the software, using, in alternative, the most similar options to represent the materials in question.

Table 2

List of materials used in the case study, amounts and respective transport distance from the production site to the place of implementation of the building

	Material	Quantity (kg)	Transport (km)	Production site
Structure	Steel	6000	280	Porto Leixões - Portugal
	LSF - Steel	450	70	Sintra - Portugal
	Pine wood	1219	90	Leiria - Portugal
External Wall	Cork slab	1512	75	Torres Novas - Portugal
	Glue	48	2000	Milan - Italy
Internal Wall	Ceramic tiles	418	210	Aveiro - Portugal
	OSB	339	2170	Netherlands
	Pine wood	715	4100	Finland
	Gypsum plasterboard	440	2170	Netherlands
	Alkyd paint	42	85	Setúbal - Portugal
Floor	Laminated oak wood	235	4100	Finland
	Ceramic tiles	66	210	Aveiro - Portugal
Windows/External Doors	Aluminum	25	270	Porto - Portugal
	Glass	315	100	Marinha Grande - Portugal
Internal Doors	Oak wood	38	70	Sintra - Portugal
Other Materials	Adhesive mortar	50	85	Setúbal - Portugal
	Cement mortar	75	85	Setúbal - Portugal
	Asphalt membrane	8	2800	Berlin - Germany
	Expanded polyurethane foam	122	2000	Milan - Italy

5.1.3 Life Cycle Impact Assessment

After the inventory stage, the data is treated in the SimaPro software and evaluated with the chosen impact assessment methods and their defined categories.

From the several methods for the assessment available by SimaPro software have been chosen CML-IA baseline and Eco-indicator 99.

CML-IA baseline includes the characterization stage and the evaluation is carried out on six LCIA indicators associated with the midpoint environmental impact categories considered (Table 3). The impact categories were chosen according to the CEN/TC 350 EN 15643-2 standard.

When using the Eco-indicator 99 method, the inventory data is divided into three damage categories, i.e. endpoints, namely Human Health, whose damage is expressed in DALY (disability adjusted life years), Ecosystem Quality, assessed in PDFm^2year (potentially disappeared fraction of species in a certain area over a period of time) and Resources, estimated in MJ surplus energy.

Note that all results in this section are presented accordingly to the functional unit, the useful floor area of the modular solution (45m^2). Regarding the raw materials and transport associated to their production was used generic data from the databases available in the SimaPro software. The transport processes are accounted in terms of tkm, which translate the relation between the quantity and distance. Regarding the electrical energy associated with the process, was considered the "electricity, medium voltage" option in SimaPro, available for Portugal and expressed in kWh.

The LCA analysis of the project FRED204 has been evaluated considering different settings namely through two main scenarios:

1. *Scenario 1*: base scenario that includes the stages A1-A3 of the life cycle, where some simulations were made, regarding to the use of reused shipping containers. This scenario includes:
   - **Simulation 1A**: It was attempted to represent the reality in relation to FRED204 project and also what is considered to be the most common scenario, when you are dealing with a project with reuse shipping containers. Accordingly, it was chosen for an analysis were the impacts related to the steel production process were not reckoned.
   - **Simulation 1B**: It was considered a situation in which, the containers are reused, but are in poor condition and it is necessary to consider their production process. In this case, the analysis includes the impacts associated with the steel production process, from used materials.
   - **Simulation 1C**: In this situation were considered the impacts associated with the shipping container degradation. Given the currency devaluation associated with the purchase of reused containers, compared with the price of the new containers, it was set that, in the present situation, the impacts would be proportional to the devaluation. The devaluation is around 83%, consequently the impacts associated to the steel production process for the container included in this simulation was only 17%, corresponding to a production need of 1020 kg of steel, from iron derived from scrap metal.

2. *Scenario 2*: It refers to the stages A1-A3 of the life cycle, also including the A4 stage, in order to evaluate the influence of gate-to-site transportation, in the global impacts associated to the building. This scenario includes:
   - **Simulation 2A**: Consider the same assumptions as in simulation 1A, including also stage A4, related with the transport of materials, on which is also considered the transport of the reused containers from the purchase site to the construction site.

Table 3
Indicator of each midpoint environmental impact category, based on CML-IA baseline

Category indicator (abbreviation)	Units
Abiotic Depletion Potential (ADP)	kg Sb eq
Global Warming Potential (GWP)	kg CO_2 eq
Ozone Depletion Potential (ODP)	kg CFC-11 eq
Photochemical Ozone Creation Potential (POCP)	kg C_2H_4 eq
Acidification Potential (AP)	kg SO_2 eq
Eutrophication Potential (EP)	kg PO_4^{3-} eq

The results of the different simulations considered for both impact assessment methods are presented below.

Scenario 1

CML-IA baseline

The results obtained for the simulation 1A, regarding the relative contribution of components of the building, for each impact category are presented on Fig. 3. In this simulation, the building components that show greater influence in terms of impacts are the internal walls and structure. Those impacts are associated with ceramics, for internal wall covering, and LSF system, for building structure.

On the other hand, the impacts associated with the windows/external doors also have some relevance, related with the glass production process.

The relative contribution of each component of the building for the majority of the impact categories is similar, exception made to the POCP, where the contribution of the external wall stands out, associated with the use of cork.

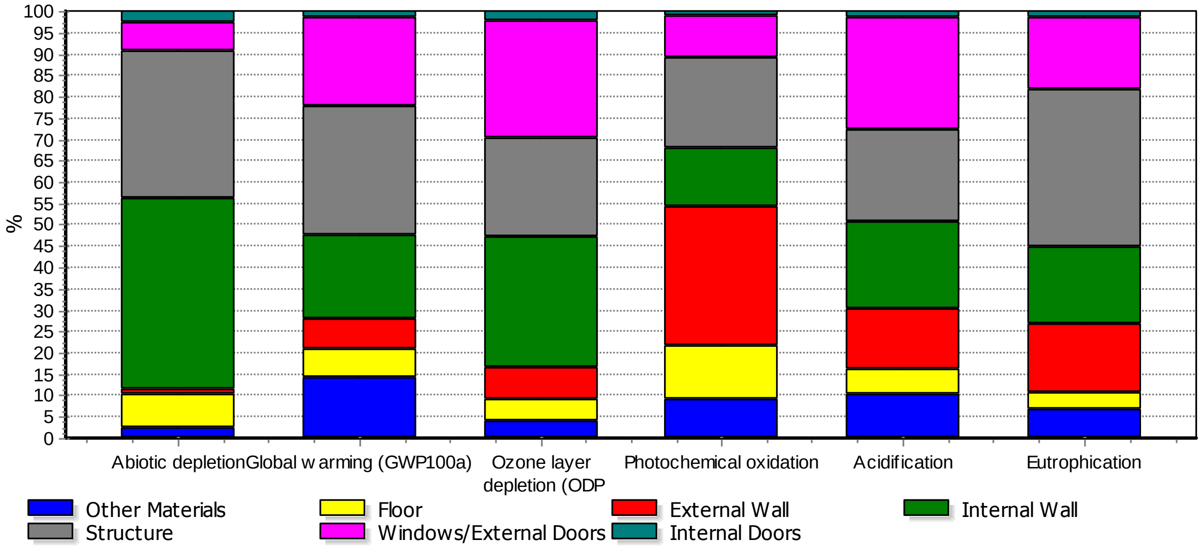

Fig. 3 Simulation 1A: Relative contribution of building components for the selected impact categories

In simulation 1B, the impacts associated with the building structure dominate all the impact categories, having suffered a large increase from the previous simulation. For example, regarding the GWP impact category, the value corresponding to the impact categories shifted from 1256.03 to 2966.03 kg CO_2 eq, representing an increase of 136%.

Simulation 1C shows a lower increase, when compared with simulation 1B. Regarding the steel production process, due to the registered value by the structure on the GWP impact category on simulation 1A, is shown an increase of 23% on simulation 1C.

<u>Eco-indicator 99</u>

Fig. 4 presents the results related to simulation 1A. Regarding the damage categories, it can be observed a dominance by three components referred before: the internal walls, the external walls and the structure. However, the internal walls have a negative contribute to the damage category related to the Ecosystem Quality, these translates into positive impacts regarding the avoided impacts by the use of these materials.

Overall, in this category, the negative impacts associated to some components of the building are compensated by the positive impacts of other components, obtaining a global impact associated with the Ecosystem Quality category of -837.77 PDF*m2y.

This result expresses the loss of species over a certain area, during a certain time, which could be avoided.

Once again, the negative environmental impact from the component related to the external wall is due to the cork used in its covering. On the other hand, the paint used on

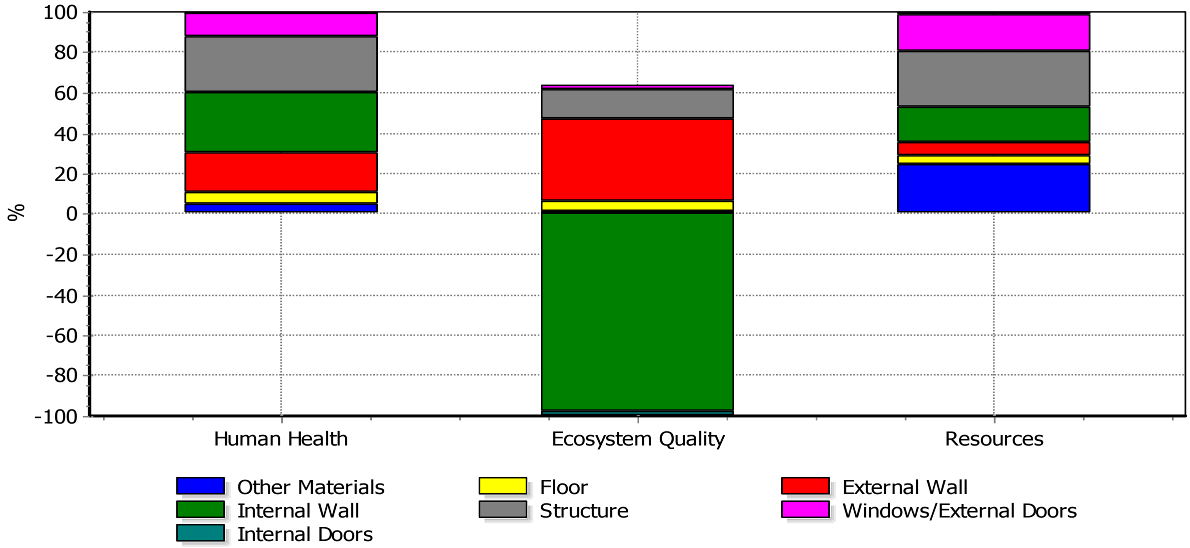

Fig. 4 Simulation 1A: Relative contribution of building components for each damage category

the internal walls is responsible for the positive impacts, meaning avoided impacts. This happens because, in practice, the production of soy based paint considers as an inflow the absorption of CO_2, compensating the possible environmental damaging outflows and their negative impacts.

Regarding the simulation 1B, it is important to highlight the damage associated with the structure, in any category of damage, representing the component with most impacts.

On simulation 1C, the impacts of the shipping container associated with each category decreased in relation to the previous simulation.

Scenario 2

CML-IA baseline

In order to compare the difference between considering the transport of the materials from the production site to the construction site (stage A4) or not, it was represented, in the same graph (Fig. 5), the impacts associated with simulation 1A (without transport) and simulation 2A (with transport).

When the transportation processes are included in the analysis, the impacts increase in every category. In this case, the processes associated with transport are responsible for an increase of 5 to 15% of the registered impacts in almost every category selected, with ODP and GWP impact categories represent an increase higher than 15%.

Eco-indicator 99

As expected, through the Eco-indicator 99, the obtained results show that the transportation processes impacts have some expression related to the damage categories, with a higher contribution in the Resources damage category.

5.2 FOOTPRINT CALCULATION

Besides LCA, the results related to the footprint family indicators associated with the FRED204 project were also analyzed.

The methods of impact evaluation available were explored on SimaPro and then proceeded to the calculation of EF, CF and WF.

In order to perform a coherent analysis, it was used the LCA analysis scenarios, simulation and parameters (namely the scope, the functional unit, system boundaries, data and assumptions).

5.2.1 Ecological Footprint

Nowadays, the EF is defined as the sum of the direct land occupation and indirect land occupation related with the CO_2 emissions from fossil energy use. However, the Ecological Footprint method available in SimaPro, through which was calculated EF, also considers the parameter related to the indirect land occupation regarding nuclear energy use. The units to present the EF could be different. It is usually measured in global hectares (gha), instead of m^2y, as presented in this study.

Scenario 1

On Fig. 6 is presented the EF parameters for simulation 1A. For each parameter there is a different component from the building that represents a major impact. Regarding indirect land occupation, associated to fossil fuel consumption, the component with higher EF is the structure. Based on LCA results, this outcome was expected, and it is related with steel production process for LSF system. Meanwhile, polyurethane inserted on "other materials" component is the one with higher EF, associated with consumption of nuclear energy. At least, for land occupation the component that contributes the most is external wall.

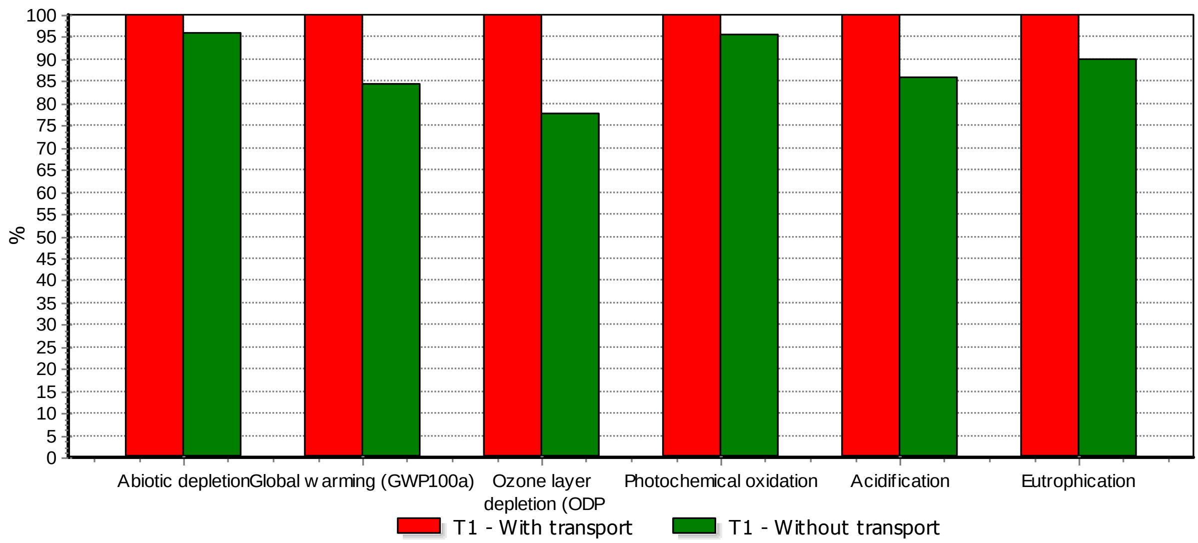

Fig. 5 Comparison of results between two situations: with and without transport

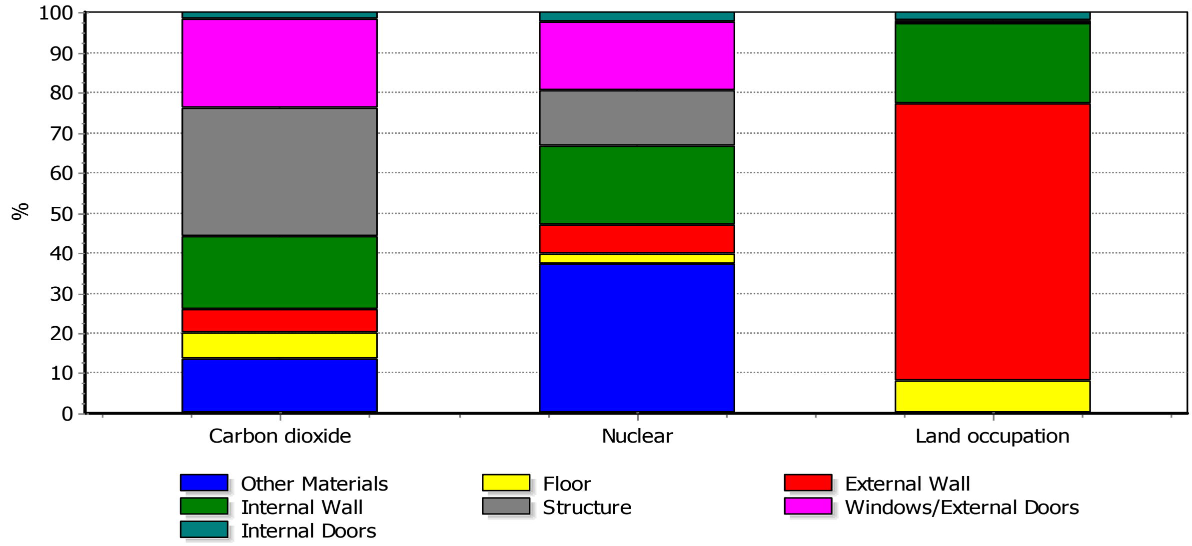

Fig. 6 Simulation 1A: Relative contribution of each component of the building to the parameters associated with EF

On Table 4 are presented the total results of the performed simulations. It is possible to conclude that simulation 1A has the lowest total EF. This result was expected, because this simulation does not consider, both direct and indirect land occupation, associated with steel production processes for the shipping containers. This last fact is important because once considerate shipping containers on simulation 1B the total EF increases 18%. Regarding simulation 1C, the total EF increase is less pronounced (only 3%), when compared with simulation 1B.

Scenario 2

Comparing simulation 2A with simulation 1A, when introducing transportation processes into simulation 2A, there are no significant alterations on relative contributions of each building component on the EF parameters. Nevertheless, analyzing Table 5 it is possible to observe that both EF related to nuclear and fossil energy consumption increases, 9 and 20% respectively. This increase is associated with materials transportation.
Therefore, it is possible to conclude that the transport processes have influence on CO_2 emissions, resulting in the need for increased forest area for absorption of fossil carbon dioxide emissions associated with the transport of materials. Globally, including gate-to-site transportation is observed an increase of 8% on total EF.

Table 4
Comparison of results from different simulations associated with EF

	Simulation		
	1A	**1B**	**1C**
Carbon dioxide (m2y)	9654.73	13853.30	10368.49
Nuclear (m^2y)	691.44	1004.08	744.59
Land occupation (m^2y)	16512.61	16735.15	16550.44
Total EF (m^2y)	26858.77	31592.53	27663.51

Table 5
Comparison of results between two situations: with and without transport

	Scenario 1 Simulation 1A	**Scenario 2 Simulation 2A**
Carbon dioxide (m2y)	9654.73	11559.81
Nuclear (m2y)	691.44	755.04
Land occupation (m2y)	16512.61	16632.56
Total EF (m2y)	26858.77	28947.40

5.2.2 Carbon Footprint

It was established to use IPCC GWP 100a to estimate CF. Values obtained for GWP impact category determined with impact assessment method CML-IA baseline on LCA, are determined by the pretended methodology, therefore those values were used to access CF.

Scenario 1

Analyzing Table 6 it is observed that considering the need to produce new shipping containers (simulation 1B) the CF increases around 43%, whereas comparing simulation 1C with simulation 1A the increase is 7%.

Scenario 2

On simulation 2A the CF increase, when comparing with simulation 1A, is 19%, which indicates that transportation has a significant contribution for CO_2 and GHG emissions.

Table 6
Comparison of CF results considering the values of the different simulations

	Simulation		
	1A	**1B**	**1C**
CF (kg CO_2 eq)	4057.20	5767.19	4347.90

5.2.3 Water Footprint

For WF calculation it was used ReCiPe method from SimaPro using water depletion impact category (m^3). This category considers different water flows stipulated for the WF analysis, namely water from lakes, rivers, turbine and refrigeration use and groundwater.

Scenario 1

On Fig. 7 it is possible to observe that the main contributors for WF on simulation 1A are the structure and windows/external doors. It is important to refer that even without steel production for the shipping containers the structure stands out representing more than 56% from the WF associated to the building.

When comparing the different simulations (Table 7) it was noted an increase of 32% from simulation 1A to 1B and an increase of 5% from simulation 1A to 1C.

Scenario 2

On simulation 2A, including transportation, the overall WF values increased, but their relative contribution do not changed significantly.

Globally in this simulation it was recorded a 3% increase on water consumption (m^3).

Table 7
Comparison of WF results considering the values of the different simulations

	Simulation		
	1A	**1B**	**1C**
PH (m^3)	14465.88	19025.84	15241.08

6. DISCUSSION OF RESULTS

Overlooking this study the structure is the component to which are associated more impacts, due to steel production processes related to the shipping containers and LSF system. Regarding LSF system it is important to mention it is still a valid option, when comparing its impacts with other alternatives, like concrete. The impacts associated to the shipping containers used on project FRED204 are not relevant, because the shipping containers are reutilized, therefore no impacts should be considered from them on global performance of this modular solution.

Focusing on LCA analysis it was possible to identify other component with significant associated impacts, namely the internal wall, due to is covering materials. Therefore, it is important to analyze with more detail this component presenting on Table 8 the results from CF for each material. It is possible to conclude that ceramics are the material with higher CF and consequently its substitution should be considered. A possible alternative is the use of ceramics with an elevated percentage of recycled materials to reduce the CO_2 and GHG emissions associated with the current ceramics. Another alternative is the use of "Porcelain Ceramic Slab"[1] presented on german EPD system, with a CF value of 6.33 kg CO_2 eq/m^2, about half from the current one.

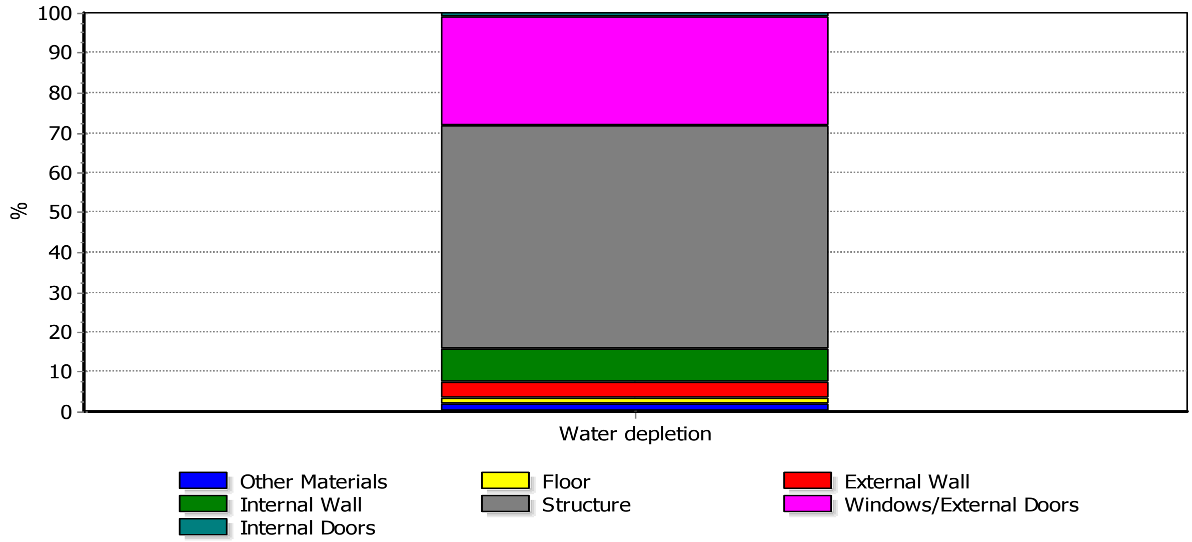

Fig. 7 Simulation 1A: Relative contribution of each component of the building to the WF

[1] EPD available on: http://construction-environment.com/download/C24ecb187X1398b7fd130X513f/EPD_KSK_2012511_E.pdf

On other perspective, according with the results obtain on EF, polyurethane used in exterior insulation on the bottom of the shipping containers represents an elevated contribution for EF related to the nuclear energy consumption. Also this material presents a CF value greater than cork, more 9,9 kg CO_2 eq/m^2, which represents an increase of 8% of total CF associated with the modular solution.

Therefore and considering thermic and acoustic insulation properties of these materials, it should be considered the substitution of polyurethane for Expanded Insulation Corkboard. Cork is a very sustainable material and its production process is free of chemicals and with low energy consumption, nevertheless it presents an elevated contribution to land occupation associated to total EF of the building. The high EF associated to cork can be justified by 1) the high quantity of material needed 2) inlet flows assumptions on the generic processes from Ecoinvent database, where is considered that to produce 1 m^3 of cork it is needed 4240 m^2y of land occupation. This elevated land occupation should lead to a negative result on global CO_2 and GHG emissions, because it was expected that CO_2 absorption on cork plantations compensate the CO_2 and GHG emitted on the extraction and production processes of Expanded Insulation Corkboard, which was not observed.
Regarding CF value for cork, it was obtained 0.20 kg CO_2 eq/kg cork, which compared with producer reference value (-4 kg CO_2 eq/kg cork) is higher than expected, but not incongruous when compared with values from literature (Zabalza et al., 2011), namely 0.81 kg CO_2 eq/kg cork.
On scenario 2, when including the stage A4, associated with gate-to-site transportation, it is relevant to highlight some results.

Table 8
Comparison of CF results associated with each material used in the covering of the internal wall

	Pine wood	Ceramic tiles	OSB	Gypsum plasterboard
PC (kg CO_2 eq/m^2)	0.38	12.13	5.32	1.59

The LCA the categories more affected by the impact associated with transportation are ODP and GWP, consequence of the CO_2 and GHG emissions from the materials transportation. On the other hand, the damage categories with major influence is Resources due to the surplus energy needed to support fossil fuels consumption.
As expect, when analyzing the footprint family the main differences was verified in CF, with a 19% increase, when relating with simulation without transportation.
Due to the global impacts of transportation a sensibility analysis was performed, in order to evaluate the impact of using alternative suppliers, within a 100 km distance (Fig. 8). With this approach is possible to reduce the impacts in most categories from 5 to 15%, and, on ODP, this reduction could achieve 20%.
Due to the major impact of transportation on CF, three different situations were considered: simulation with real distances, simulation with 100 km distance and simulation without materials transport (Fig. 9). Reducing the real gate-to-site transportation to 100 km distance, transport impacts becomes insignificant, representing only 4% on overall CF.
The environmental footprint of project FRED204 is now determined and reflects the environmental performance on the aspects considered. Therefore is now possible to compare, evaluate and establish this modular solution within the reference values, regarding to other case studies

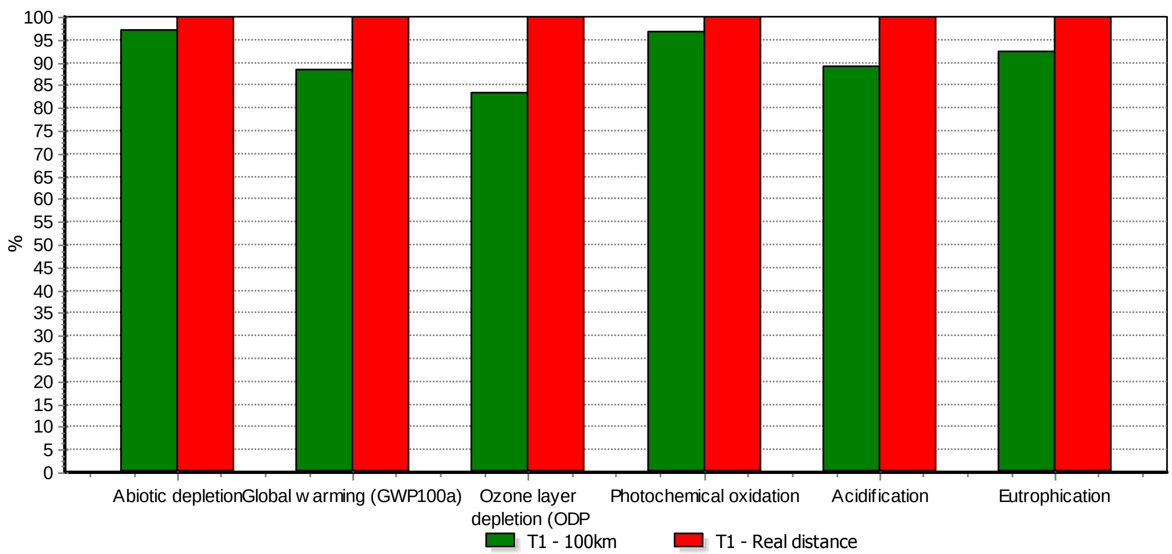

Fig. 8 Comparison of results between two situations: transport considering 100km distance and transport considering real distance

and other constructions typologies. Each case study has its one set of parameters, and could diverge on climate, country, building typology, functional unit, assumptions and data collected. To enable this comparison all data was converted to 1m^2 of useful floor area, instead of the functional unit considered. Also it is important to mention that case studies comparison was made based only on CF values, because no other case studies was available with the same scope of this analysis (stage A1-A3).

On Table 9 it was possible to observe a higher environmental performance of projected FRED204, with CF results significantly lower than all the other case studies considered, with CF reductions from 24 to 58%. It is interesting to realize that both modular solution and pre-fabricated construction are the alternatives with lower CF values, which enlightens the solution to follow for a more sustainable future. Accordingly to this it is crucial to continue to pursue evolution and consider new construction solutions, focusing on continuous improvement on materials, solutions to present, and also comfort.

Table 9
Comparison reference values available in the literature, given the results obtained for the project FRED204

Construction typology	kg CO_2 eq/m^2	Location	Reference
Modular (FRED204)	90	Portugal	-
Traditional	180	Norway	(Dahlstrøm et al., 2012)
Wood	218	Sweden	(Dodoo & Gustavsson, 2013)
Prefabricated	112	Norway	(Sørnes, 2010)
Traditional	196	Spain	(Ortiz et al., 2009)

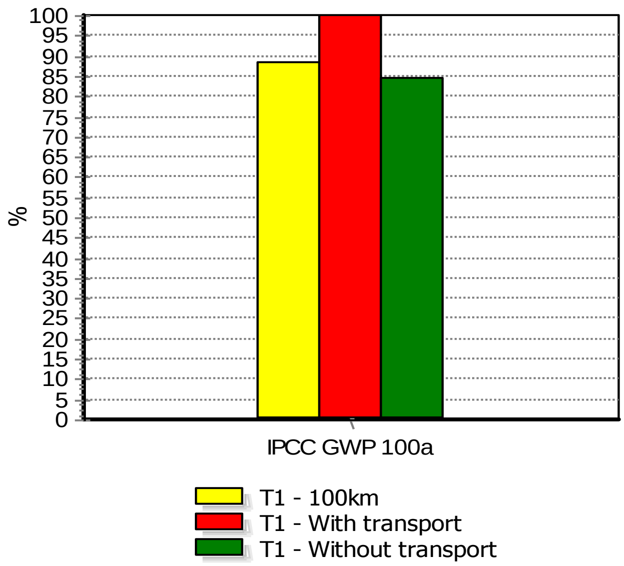

Fig. 9 Comparison of different scenarios regarding the distance of transport for CF

7. CONCLUSION

The approach used on this case study allowed to determine the environmental footprint for the project FRED204, using SimaPro software as the assessment tool, instead of the usual Microsoft Excel® approach or other specific model.

From the results obtained is it possible to conclude that this tool is an option to consider, enabling an integrated approach using different indicators, namely the LCA as a base to evaluate the EF, CF and WF.

On this approach it is possible and important the use of distinct methodologies that provide quantitative results of environmental performance (intermediate indicators) and allowing a clear communication of the results obtained (endpoint indicators). Also the considered footprints present a potential communication tool that should be further explored, once they are known concepts by public opinion, well understood and accepted.

The particularity of project FRED204 relies on the reutilization of shipping containers as a structural base, therefore, it was necessary to perform different simulations in order to characterize their environmental performance. The obtained results prove that this component is the most relevant, attributing them a significant contribution on the environmental friendly aspects of the project. To support the good environmental performance is the 43 and 32% reduction on CF and WF, respectively, when comparing to the simulation considering steel production process for the shipping containers.

Other materials are also important for the good environmental performance, namely the use of different types of wood, on the internal coverings of walls and floor, as well as the use of cork in the external walls, covering of the shipping containers.

This approach allowed the identification of the following opportunities to improve the environmental performance: 1) Replacement of polyurethane with Expanded Insulation Corkboard, conducting to 8% reduction on total CF associated to modular solution. 2) Replacement of current ceramics for a more sustainable solution, for example, ceramics with elevated percentage of recycled material or "Porcelain Ceramic Slab". 3) Choose local suppliers that could allow a reduction of 15% on total CF.

When comparing this construction typology with others, it was possible to conclude that this project enables environmental performances up to 2 times higher than others, reflecting on much lower impacts. Therefore it was possible to compare, evaluate and establish this modular solution based on the characterization of its environmental footprint. For further notice it is possible to apply the approach used on this case study to other construction typologies.

The implementation of more sustainable solutions on construction sector, as modular solutions, drives through a compromise where environment, economy and human well-being are addressed and not compromised.

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