LIFE CYCLE ASSESSMENT STUDY OF A PREFABRICATED STEEL RESIDENTIAL BUILDING

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1. ABSTRACT

In the field of prefabricated residential buildings, structural steel represents an attractive material as its members and systems exhibit high mechanical performance and at the same time provide great benefits such as fast construction, reliability and durability. Concerning the design and construction of such applications, a new requirement for sustainability has emerged in the latest years. The assessment of impacts of the building activities as well as minimizing building costs, materials and waste are becoming nowadays some additional goals of the design process. The herein presented research activity focuses on the life cycle performance of steel members in a residential building using prefabricated construction technologies by applying an LCA study and carrying out an environmental impact assessment. In addition and since initially, environmental calculations were not incorporated in the design and construction of the project, the paper describes the input of each parameter of the project in terms of sustainability, thus contributing to the broadening of knowledge on the integrated design of metal structures.

2. INTRODUCTION

Towards the goal of sustainability, new aspects and parameters have been introduced regarding the design of buildings. Among others, the choice of structural materials, as well as the construction technology and the relative systems used, possess a significant role in the sustainable performance of buildings. In the last years, the use of applications based on prefabricated steel components in the residential sector is rapidly increasing due to developments of their construction technology and their efficient response to the demand for sustainability credentials. In the field of residential buildings particularly, prefabricated steel systems can contribute effectively to achieving a high level of sustainability, reducing the environmental impacts, as well as minimising materials use and waste. Steel's high strength-to-weight ratio make it a preferable choice for single or multi-storey dwellings, while its long-span capabilities allow for the design of flexible, column-free spaces that can adapt to changes during the life of the structure. One major advantage of the prefabrication technology is that it increases the speed of construction significantly, whereas according to recent studies panellized systems are 60 to 70% faster than traditional methods [1]. The benefits of this rapid construction comprise reduced waste, more efficient production process and improved environmental performance. Furthermore, the fact that all steel elements are manufactured off-site maximises the reliability of steel construction and minimizes defects. Sustainable design involves life cycle assessment studies which cover the entire life cycle of the buildings whereas inventory data is used in order to proceed with the calculation of the environmental effects [2]. The present paper focuses on the life cycle performance of steel members in a prefabricated residential application by applying an LCA study and carrying out an environmental impact assessment. The investigation of a steel housing project in terms of sustainability is analysed and the importance of an integrated approach in the design is highlighted.

3. LIFE CYCLE ASSESSMENT STUDY

3.1 The case of a prefabricated residential steel building

The examined project is a single-storey steel house with a basement. The area covered is 119m² with the concrete basement covering 60m² (Figure 1). The cross sections of the steel members are hollow sections RHS 100x50x3 and SHS 100x4. As far as the structural materials is concerned, S235 was used for the steel structure, whereas C16 and S500s for the reinforced concrete. The structural design was carried out according to the relevant codes. The basic advantages of the structural steel as the easy configuration and construction using prefabrication, adding a relatively small dead weight to the building, the flexibility it enables in architectural design and above all, the reversibility opportunity it gives for future interventions were regarded in the choice of the steel [3].

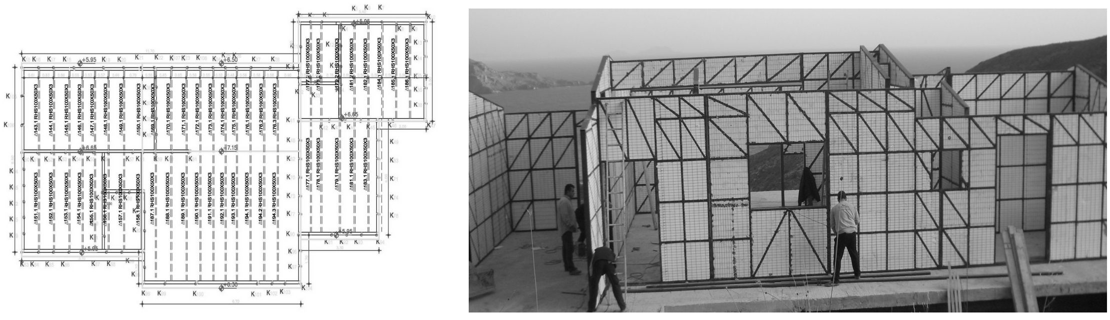

Fig. 1. Prefabricated steel residential building

3.2 LCA methodology

Life cycle assessment (LCA) is one of the most acknowledged and widely used methodologies for the quantification of environmental impacts [4]. It is based on a detailed documentation of the materials and processes required throughout the complete life cycle of the project, from raw material acquisition and initial construction to maintenance and end scenarios [5]. In regard to construction, LCA takes into account five phases, namely the design (development), the constructional material production (resource extraction), the construction (production), the use (consumption) and finally the demolishment-rehabilitation (end of life activities) [6]. The analysis is conducted through 4 steps; goal and scope definition, inventory analysis, impact assessment and interpretation. The herein presented LCA study of the prefabricated steel house is conducted with the Simapro software, while the Eco-indicator 99 (E) methodology (V2.07 / Europe EI 99 E/E) is used for the impact assessment [7].

3.3 Theoretical parameters

In order to conduct an LCA study it is initially necessary to define a number of theoretical parameters which will define the focus and extent of the study. These parameters include the goal of the study, its scope and its subject (or system). The goal of the current LCA study is to identify the key areas responsible for the primary environmental impacts associated with the construction of the examined building and also the environmental indicators mainly burdened. The system to be studied is the construction of the specific pre-fabricated steel-framed building and therefore the functional unit used is the sum of construction processes and materials used for the delivery of the project. In regard to the scope of the study, it should be noted that works related to infrastructure and landscaping were excluded, while no processes or materials concerning the maintenance of the steel building were taken into account.

3.4 Documentation of materials and processes

The second stage of the LCA study is to list all the necessary materials and processes for the completion or delivery of the functional unit – in this case, the construction of the pre-fabricated steel house. These materials and processes are then assigned to specific Life Cycle Inventory (LCI) datasets which contain environmental information regarding the inputs and outputs associated with the specific materials or processes. These datasets are used as found in existing LCI databases developed globally and contain all required resource quantities and relevant substance emissions to the environment (emissions to water, air and soil, such as CO_2, CH_4, SO_2 etc.). For the current study, Table 1 shows the main construction materials with the respective quantities and processes used for the pre-fabricated steel house construction.

In addition to these materials, the necessary transport processes were taken into account, for the transport of the materials to the site. A 10 km distance covered by road was assumed. For the association of the materials and processes with the respective environmental loads, data contained in existing LCI databases was used. Primarily, the Ecoinvent database was used, as it contains data mostly from the geographical region of Europe. While the LCI dataset referring to the steel structural members was used as found in the LCI database developed at the Institute of Metal Structures of the Aristotle

University of Thessaloniki [8]. In some cases, a complete match of the available datasets and the required processes was not possible. When it could not be avoided, logical assumptions were made in order to include all the environmental inputs and outputs as accurately as possible.

Components	**Products / processes**	**Quantity**
Steel members	RHS and SHS sectioned (Fe360) steel members	7,45 t
Covering boards	Interior and exterior board coverings	580 m²
	Mortar used for the covering boards	365,4 kg
Concrete foundation	C16/20 type concrete for the composite slabs and foundation of the building	40 m³
	Reinforcing steel bars	5 t
Concrete basement	C16/20 type concrete for the composite slabs and foundation of the building	32,4 t
	Reinforcing steel bars	4 t
Roof covering	Classic roman tiles were used	123,8 m²
Floor covering	Ceramic tiles were laid on all of the building floors	166 m²
	Mortar used for the ceramic tile covered area	166 m²
Insulation	Insulation material used for the pre-fabricated steel-framed panels	725 kg
Excavation	Excavation for basement and foundation	414 m³

Table 1. Inventory analysis of the pre-fabricated steel-framed building

3.5 End scenario

Each LCA analysis includes certain assumptions which are made in regard to the events that take place at the end of the life cycle of the subject or system under examination. These assumptions include procedures such as disposal in sanitary landfills, recycling, reuse etc. and collectively constitute an end scenario. For the current research, it is assumed that at the end of the building's service life and/or after the decision for demolition has been made, the largest percentage of steel panels are suitable for reuse in similar residential buildings which are to be constructed. Only 10% of the structural steel and 20% of the covering boards and insulation are assumed to be inappropriate for reuse, while the rest of the construction materials are sent for recycling. In specific, concrete, roof and floor tiles can be crushed and used as gravel. The particular characteristic of the selected scenario is that it enables the quantification of the sustainability potential of the pre-fabricated steel housing technology. In such cases, the ideal goal would be to reuse the already constructed steel-framed and insulated panels without the need of their disassembly.

3.6 Environmental impact assessment

The environmental impact assessment is the stage of an LCA study during which the environmental impact assessment results are calculated. For the current research, results were calculated according to the Eco-Indicator 99 impact assessment methodology (E) v2.07 (Europe EI 99 E/E), which contains a significant range of environmental indicators to quantify the environmental impacts caused. The results obtained from this methodology are calculated in Eco-Indicator points (Pt), with the value of 1 Pt being representative of one thousandth of the annual environmental load of one average European inhabitant [9].

In Figure 2, the environmental impact results referring to the life cycle of the pre-fabricated steel house are presented.

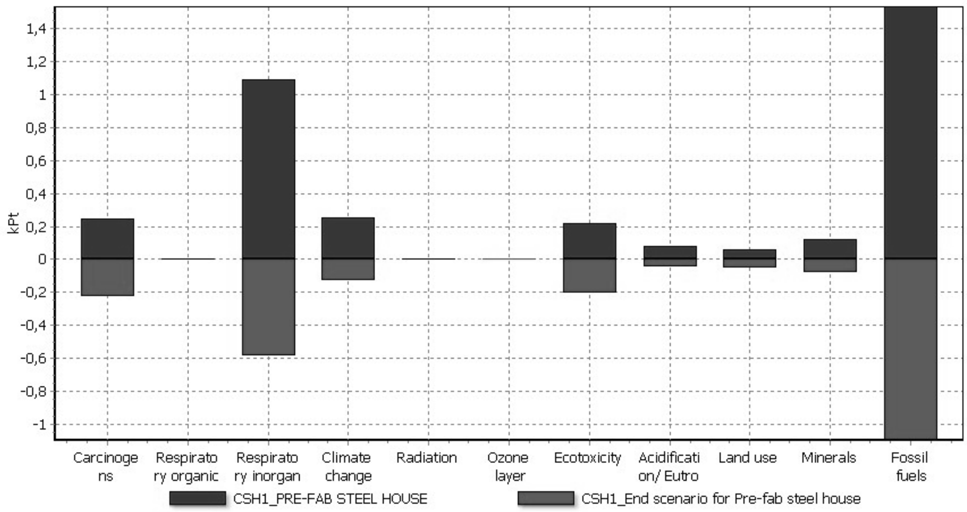

Fig. 2. Environmental impact results for the life cycle of the pre-fabricated steel house

Each environmental indicator used is presented in the horizontal axis, while the actual impact caused is marked on the vertical axis. Positive values refer to environmental burden, while negative ones refer to environmental benefits. As can be observed, the environmental benefits are not only noticeable, but also comparable to the impacts caused. This observation highlights the importance and environmental potential of the end-of-life scenarios in steel structures, as the benefits ensured are directly related to the reuse of the steel panels of the pre-fabricated house. It is also evident that certain environmental indicators are affected more than others, while some accept negligible or almost no burden. The ones that are primarily affected are ‘Fossil fuels’ referring to resources and ‘Respiratory inorganics’ referring to human health. ‘Carcinogens’, ‘Climate change’ and ‘Ecotoxicity’ are also affected, yet to quite a lower degree. In total, the environmental impact of the steel building’s life cycle is 1,18 kPt, with a 3,6 kPt impact caused by the construction of the house and a 2,42 kPt benefit caused by the end-of-life scenario selected. In order to identify the processes or materials necessary for the construction of the pre-fabricated steel house, it is also necessary to calculate the environmental impact caused only by the construction stage, as opposed to that caused by the building’s life cycle. In Figure 3, these results are presented according to the main environmental impact categories used in the Eco-Indicator 99 methodology.

In the ‘human health’ category, the concrete used for the foundation and basement (739,3 Pt in total) and also the steel structural members (437,4 Pt) cause the highest impacts. The ceramic tiles used for floor covering also cause significant impact (280,4 Pt). The ‘ecosystem quality’ category is affected to a lower degree, with the concrete and structural steel members causing the largest percentage of environmental impact (165,8 Pt in total and 141,7 Pt respectively). The ‘resources’ category is affected to a similarly increased degree as ‘human health’. The concrete and steel used cause the highest impacts (772,7 Pt in total and 498,8 Pt respectively), while the insulation used in the steel panels also causes a significant impact of 171,3 Pt.

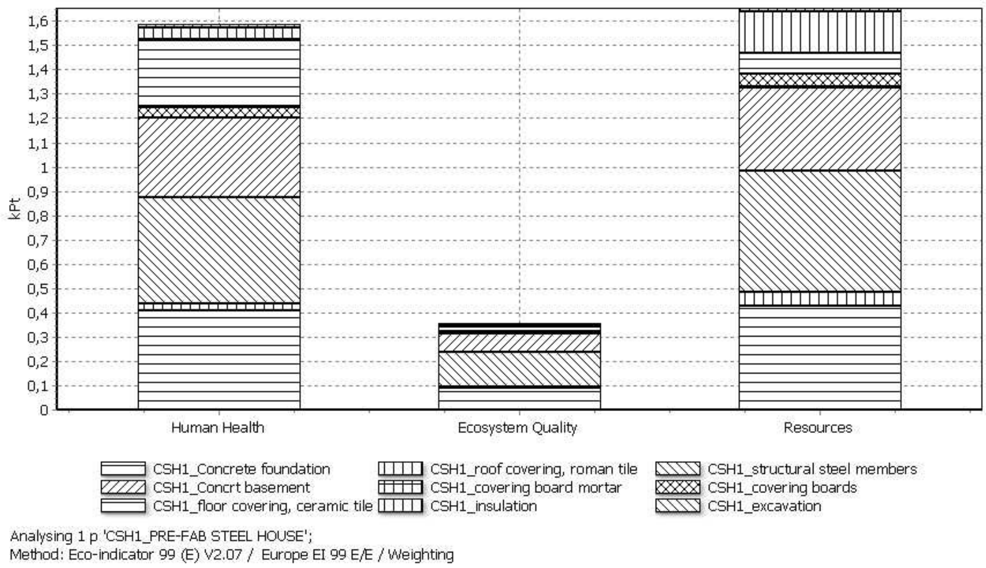

Fig. 3. Environmental impact of the construction of the pre-fabricated steel house per main environmental category

4. CONCLUSIONS

The assessment of the environmental sustainability of construction projects such as buildings can be achieved with the use of life cycle-based methodologies such as LCA. Its application entails a series of stages to be carried out in order to quantify the environmental impact associated with the delivery of a building project. The current research utilizes this methodology and focuses on its application on a pre-fabricated steel house. An inventory analysis was carried out to provide a list of processes and materials necessary for the construction of the steel building, while an end scenario mainly based on the reuse of the pre-fabricated steel panels in other projects was examined.

The environmental benefits associated with the reuse of the largest percentage of steel panels were found to significantly decrease the burden caused by the construction of the building, across all environmental impact indicators. Indicators such as 'fossil fuels' and 'respiratory inorganics' which were primarily burdened were also found to be positively influenced by the environmental benefits associated with the reuse of the steel panels. As a result, the total environmental impact of the pre-fabricated steel building's life cycle was decreased to less than half of the impact calculated for the construction of the building. This is a major advantage of the specific building technology as it incorporates significant environmental benefits which are not achievable otherwise. The main reason for these benefits is avoiding the need for additional manufacturing processes at the end of the building's life cycle, as the materials are reused as received after their removal. As a result a reuse end scenario is much more beneficial compared to landfill or recycling ones.

The key processes and materials identified as responsible for the highest environmental impacts were the concrete used for the construction of the building's foundation and basement and the steel structural members used. The ceramic tiles used as the floor covering material and the insulation material used in the steel panels were also found to cause noticeable environmental impact in the ‘human health’ and ‘resources’ environmental impact categories respectively. These issues can be used as focus points for future research in order to minimize the environmental impact of pre-fabricated steel building even further.

5. ACKNOWLEDGEMENTS

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ΜΕΛΕΤΗ ΑΝΑΛΥΣΗΣ ΚΥΚΛΟΥ ΖΩΗΣ ΣΕ ΠΡΟΚΑΤΑΣΚΕΥΑΜΕΝΗ ΜΕΤΑΛΛΙΚΗ ΚΑΤΟΙΚΙΑ

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ΠΕΡΙΛΗΨΗ

Στον κλάδο των προκατασκευασμένων κτιρίων κατοικιών, ο δομικός χάλυβας αποτελεί ένα ανταγωνιστικό υλικό, καθώς τα αντίστοιχα δομικά μέλη και συστήματα χαρακτηρίζονται από υψηλή μηχανική αντοχή ενώ συγχρόνως εξασφαλίζουν σημαντικά οφέλη όπως ταχεία κατασκευή, αξιοπιστία και αντοχή στο χρόνο. Όσον αφορά στο σχεδιασμό και την κατασκευή αυτού του είδους, ένα νέο κριτήριο έχει προκύψει τα τελευταία χρόνια. Η αποτίμηση των επιπτώσεων της κατασκευαστικής δραστηριότητας, καθώς και η ελαχιστοποίηση του κόστους κατασκευής, αποτελούν πλέον επιπλέον στόχους στο στάδιο της μελέτης. Η παρούσα έρευνα εστιάζει στην απόδοση του κύκλου ζωής των χαλύβδινων δομικών μελών σε ένα κτίριο κατοικίας που βασίζεται στην τεχνολογία της προκατασκευής, με την διενέργεια μελέτης αξιοποίησης κύκλου ζωής (LCA) και αποτίμησης περιβαλλοντικών επιπτώσεων. Επιπρόσθετα, καθώς οι περιβαλλοντικές παράμετροι δεν έχουν συμπεριληφθεί στη μελέτη και κατασκευή του κτιρίου, η εργασία περιγράφει την επίδραση κάθε παραμέτρου στο έργο σε σχέση με την αειφορία, συνεισφέροντας έτσι στη διεύρυνση της γνώσης σχετικά με την ολοκληρωμένη μελέτη αυτού του είδους των κατασκευών.