BIM-based environmental assessment in the building design process

Farshid Shadram, Marcus Sandberg, Jutta Schade, Thomas Olofsson
Luleå University of Technology, Sweden

ABSTRACT: *Today, climate change is an issue of great concern. In addition, the building sector is considered to be one of the major energy users causing considerable amount of greenhouse gas emissions. Although, energy-efficient buildings are built today that use low amount of energy during operation, the embedded energy from construction and production of building material can still be relatively high. This paper focuses on the application of Building Information Modeling (BIM) using Environmental Product Declaration (EPD) to assess the environmental impacts from building materials and production to enable the designers to make environmentally friendlier decisions. Toward this approach, we propose a model which is examined in a case study of a roof structure on a commercial building which was constructed by off-site prefabricated roof-elements. As a result, the feasibility of the proposed model is appreciated in the assessment of the carbon footprint and embodied energy of the building materials and components. The proposed model needs to be further developed regarding the specification of the materials and components to make the information exchange between the BIM model and EPD in the environmental assessment of the building design more practicable.*

KEYWORDS: *Building information modeling, Environmental product declaration, Life cycle energy, LCE, Embodied energy, Environmental impact, Carbon footprint*

1. Introduction

Global warming is an issue of great concern. In addition, the building sector is considered to be one of the major users of energy causing considerable amount of greenhouse gas (GHG) emissions. According to a report by the European commission (2009), buildings account for approximately 40% of the European Union's total energy use and GHG emissions. In Sweden, the building sector is estimated to contribute to 28% of the total energy use and consequently 20% of GHG emissions (Toller et al. 2009).

Efforts in mitigation of the environmental impact of buildings are focused on reduction of the operational energy use, including heating, cooling and domestic hot water supply. Although new solutions have been proposed in the optimization of the buildings' operational energy use in the recent decades, researchers have found that energy usage in construction and production of material is still relatively high. Yung et al. (2013) argue that the production of materials can contribute to a substantial percentage of the total energy use in a building's life. Traditionally, buildings were constructed from local materials with low energy use and low environmental impacts but in new buildings, materials supplied on a global level such as cement, aluminum, concrete and PVC are used that increase the energy use and environmental impact (Zabalza Bribián et al. 2009). Dimoudi and Tompa (2008) express that the GHG emissions associated with the construction and consequently, material production, are gaining greater importance when buildings are becoming more energy-efficient. Hence, the reduction of the environmental footprint of the building requires a general view of the whole building's life rather than restricting it to operational use only.

This research disregards the building's operation and concentrates on the environmental footprint caused by production of material and components. The main purpose of this research is to investigate the employment of Building Information Modeling (BIM) in the sustainable material selection, i.e. materials with low energy content and low environmental impacts, to facilitate decision-making for architects and designers in the building design process.

2. Theory

2.1 Life Cycle Assessment (LCA)

The prominent technique used in sustainability assessment of buildings since 1990 is Life Cycle Assessment (LCA), also known as cradle to grave analysis (Fava 2006). LCA is applied in the building's global and regional impact assessment. The impact categories are extensive e.g. global warming potential, proportion of ozone layer depletion, eutrophication, and acidification which are evaluated based on energy consumption, waste generation, etc. (Ramesh et al. 2010). The procedures of LCA are illustrated extensively in the ISO 14040 (2006) and ISO 14044 (2006) standards. Four different stages are studied in the LCA of a building; production, construction, operation and demolition (Erlandsson & Borg 2003; Zabalza Bribián et al. 2009). Figure 1 illustrates these stages more in detail.

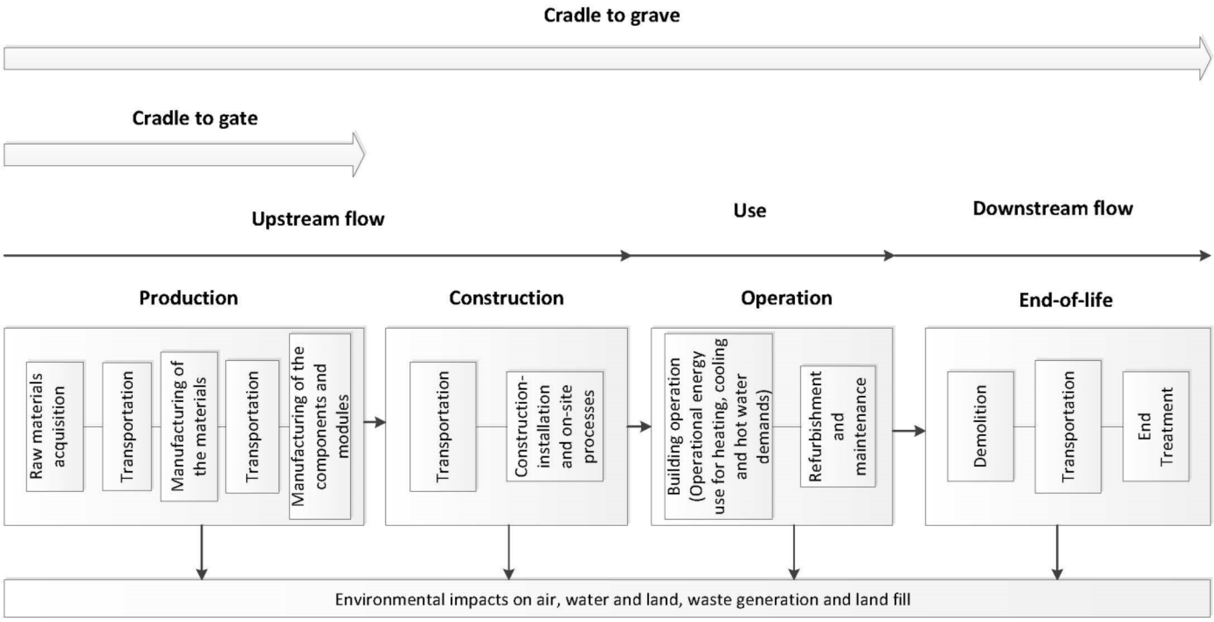

Figure 1: The life cycle stages of a building, adapted after (Khasreen et al. 2009)

The production phase refers to the required services in production of materials and components from raw material acquisition to production of the final commodities. The construction phase consists of transportation of the materials and components to the construction site and the installation services and on-site processes. Although, with current knowledge advancement in the building industry and with the increasing of the industrialized housing and prefabricated modules, the on-site construction activities are being increasingly restricted to the assembly of modules and parts. Consequently the number of gates in the production chain proliferates which results in an increase in the environmental impact in production in comparison with the construction phase. In the operation phase the environmental impacts are attributed to the operational energy demand concerning heating, cooling, domestic hot water and the refurbishment and maintenance services. Finally, the last phase is devoted to the demolition consisting of deconstruction services, transportation and the end treatment (i.e. either reuse, recycling or disposal of materials to the landfill). These life cycle phases are mainly distributed in 3 process flows, upstream (production and construction), use (operation) and downstream flow (deconstruction and disposal) (Ramesh et al. 2010).

2.2 Life Cycle Energy Analysis (LCEA)

The other form of LCA that is particularly related to the building's energy efficiency efforts is Life-Cycle Energy Analysis (LCEA) which has been evolved in the last few decades (Fay et al. 2000). The main representative factor in this method is the energy content and the environmental impacts are evaluated based on the amount of energy usage. Although, the LCEA has significantly been promoted as the environmental impact estimator in the building industry, the system boundary of this method is still unclear. Ramesh et al. (2010) define the system boundary of the building LCEA within three phases; production, operation and demolition. According to this definition, all the activities and services corresponding to the production and construction phases as well as refurbishment services of the operational phase in the building's LCA phases are incorporated in the production phase of LCEA. However, the other two phases, i.e. demolition and the operation phase except from the refurbishment activities, are the same as in LCA.

Hence, in accordance with these three LCEA phases, the building's Life Cycle Energy (LCE) and environmental impacts associated with the energy use are also being divided in three phases, embodied energy, operating energy and demolition energy. Meanwhile, other researchers as claimed by Ding (2004, cited in Dixit et al. 2010) provide a more comprehensive definition which distributes building's LCE in solely two phases, embodied energy and operating energy. In accordance with this definition the embodied energy also comprises the energy content of the demolition phase. Nevertheless, Ding (2004, cited in Dixit et al. 2010) states that the production of building materials and components off-site contributes to 75% of the total embodied energy. Whether the embodied energy includes the demolition energy or not, it contributes significantly to a buildings LCE when so-called "near zero-energy" buildings are constructed which use nearly zero or even less than zero operational energy. A case study by Hernandez & Kenny (2010) demonstrates a continual increase of the embodied energy when the building becomes increasingly energy-efficient. Thormark (2002) indicates that the embodied energy encompasses considerable part of the total energy use in the low energy buildings and its content in the low energy buildings is higher than conventional ones. In addition, Ramesh et al. (2010) state that low energy buildings perform better than self-sufficient (zero operating energy) buildings concerning the life cycle energy context since the embodied energy of the self-sufficient buildings is higher than low energy buildings. They also argue that a border in the reduction of operational energy exists where the sum of operational and embodied energy reach a minimum. Hence, with the advancement in the reduction of operating energy and achievement to the energy efficient buildings, the embodied energy of the material and components becomes a point of concern which requires more investigation to approach the concept of life cycle zero-energy buildings.

2.3 Building Information Modeling and sustainable building design

The National Building Information Model Standard Project Committee (NBIM-US 2014) defines BIM as:

Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.

The ability of BIM in information delivery has been appreciated by the building sustainability efforts, particularly regarding the decision making in the early stages of design and planning which can significantly benefit design optimizations in terms of reduction in energy use and consequently mitigation of environmental impacts caused by the energy usage (Wong & Fan 2013; Schade et al. 2011). Kulahcioglu et al. (2012) state that assessment of the environmental performance of buildings in the design stage is crucial, since replacement of the high impact materials, which have a significant impact on the environment, is possible. Numerous approaches have been focused on the application of BIM along with BIM-based LCA and/or LCEA tools to make the building designers and architects capable to perform energy estimations and environmental impact assessment of the buildings in the early phases of the design process (Motawa & Carter 2013; Schlueter & Thesseling 2009; Azhar et al. 2011)

These BIM-based LCA/LCEA tools have been developed to assess the environmental impacts and energy use of new, existing and under refurbishment buildings, as well as building products and components. These tools cover the stages of the buildings' life cycle differently; some assess only the operational phase, some other cover one or two phases of the buildings' life cycle and further have the ability to appraise the energy consumption and environmental performance of all phases. In a study by Haapio and Viitaniemi (2008), 16 existing building environmental assessment tools are analyzed and categorized. According to this study, the associated LCA/LCEA tools for assessment of embodied energy and environmental impact related to the production of materials and components are connected to different Life Cycle Inventory (LCI) databases. These databases contain the embodied energy and impact of the building materials and therefore make this assessment possible. Some examples of these LCI databases are Oekoinventare (ETHZ), DEAM or ATHENA. Trusty and Meil (2002, cited in Haapio & Viitaniemi 2008) argue that, the comparison of the environmental impact assessment carried out by these tools is impossible due to the employment of different databases and lack of a central database. Another drawback of these energy estimation and impact assessment tools is the lack of a homogenous and unique rating system.

On the other hand, challenge in environmental performance of the building sector has led to a competition between material manufacturers to launch more eco-efficient products. Hence, manufacturers are gradually being imposed to provide relevant, verified and comparable information about the environmental impact of their commodities and services in forms of Environmental Product Declaration (EPD), a declaration reviewed by an external party and demonstrates the total embodied energy and quantity of pollutants emitted in the production of a particular product, to be able to compete with others. Nevertheless, a limited number of the LCI databases have the ability to update after the new emerged EPDs, these databases only contain an average of embodied energy and impact value of each material. Considering that each specific material is being manufactured in unique processes and different mechanisms in different factories, the outcome of the embodied energy and environmental impacts estimated by these LCA/LCEA tools is ambiguous due to the imprecise value regarding the impacts of the individual material that is being used in the specific building project.

3. Aim and method:

Given the increasing number of the EPDs (International EPD System 2014; EPD Norway 2014) and considering that each building is unique with exclusive material and components, the aim of this research is to develop a method to assess the embodied energy and environmental impact of the building material production, by the application of BIM along with EPDs in the early stages of planning and design to enable the designers and architects to make environmentally friendlier decisions. The feasibility and obstacles of the proposed method was examined in a case study of a roof structure of a commercial built building which was constructed by off-site prefabricated roof-elements. In this study the main evaluated variables were the embodied energy and the global warming potential (GWP), i.e. embodied carbon footprint, which is one of the impact indicators considered in the environmental impact assessment of EPD. The data were gathered in collaboration with two companies, the company which manufactures prefabricated roof-elements and the company that manufactures the core constitutive material of the roof-elements i.e. the framing beams. In addition, information about delivery of the elements to the construction site was obtained through further contacts with the roof company to be able to estimate the environmental footprint associated with the transportation services.

4. Proposed method:

The purpose of the proposed method is to facilitate the integration of the information stored in the BIM models with the estimation and assessment of embodied energy and environmental impact from the production of material and components. The proposed method is primarily utilizing quantity take-off of the BIM materials and building parts and mapping these quantities with the constituents EPDs to assess the specific environmental impact of the design.

In this case a BIM model in native Autodesk Revit 2013 format and a Microsoft Excel 2010 sheet representing the EPDs was used. Since the environmental impact and embodied energy are set and expressed per Functional Unit (FU) in the EPDs it is crucial that the quantity take-offs of the BIM model have the same unit. When a 3D model of building is designed in Autodesk Revit, the common denominator shall be defined to make the information identifiable between the two data sets, the BIM model and the EPDs. The type mark in the 3D Revit model was used as the material and component tag in the case study.

Due to the practical and technical factors, the level of detail (LOD) of 3D objects in housing projects is generally set to element level, but given the specific purpose of this research and the tested specimen, which is a module/subassembly in the building and moreover due to the exclusive nature of the corresponding EPDs of the materials and components, the LOD is set to the material level. Hence, both the type marks in the 3D model and the Excel file containing EPDs shall be categorized and sorted out on the material level according to the corresponding EPD codes to make the information exchange feasible and detailed. The quantity take-off can be performed either by applying a BIM authoring tool e.g. Tocoman iLink or by using the schedules/quantities in the 3D Revit model. The constituents materials and components of the modules are identified on the EPD codes (i.e. type marks in the model) which later can be exported to an Excel sheet. Since the quantities in the new Excel sheet and the Excel sheet which consists of the environmental impacts and embodied energy, have same codes, the quantities can simply link to the environmental impacts and embodied energy of the materials and components and consequently the environmental footprint of the material production corresponding to the considered module can be computed. Figure 2 indicates the procedure of this proposed method.

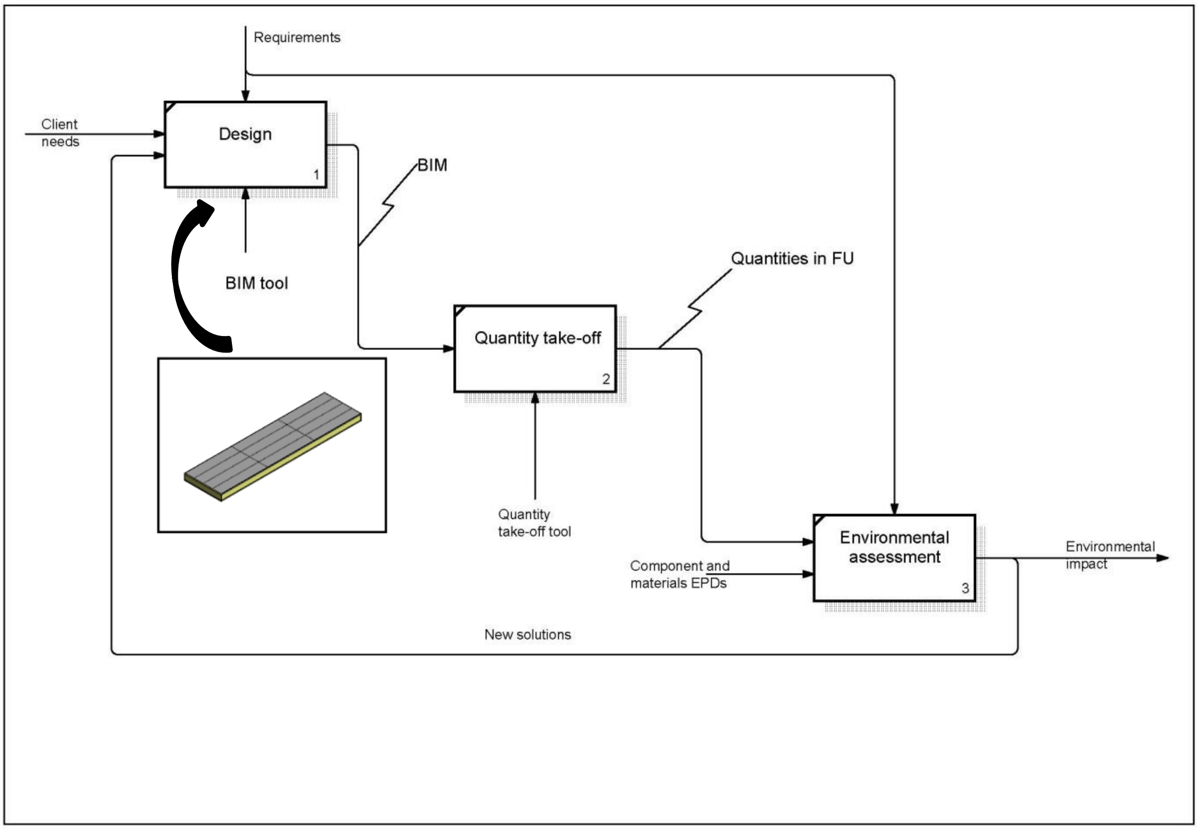

Figure 2: The proposed method to assess embodied energy and environmental impacts using BIM and EPDs.

5. Case study

5.1 The analysis of a roof structure

A case study was conducted to investigate the feasibility of the proposed method of environmental impact assessment and embodied energy estimation. In this study a roof structure of a commercial built building was examined. The building is a type of educational building and is located in Södertälje, south of Stockholm. The roof of the building stock was constructed from off-site prefabricated roof elements, these elements were transferred to the construction site where they were mounted together. The total surface of the roof was 1225 m^2, built by 42 off-site constructed roof elements.

The data was gathered in collaboration with two companies; the first company manufactures I-joist beams comprising flanges made from solid wood and a web made from Oriented Strand Board (OSB). The other company utilizes the I-joists as bearing structure in the construction of the roof elements and was also in charge for the implementation of the commercial building's roof, see figure 3.

Figure 3: I-joists manufactured by the first company and roof elements manufactured by the second company

Since the first company had an EPD for the I-joist beam, efforts were put into data collection on the EPDs of the constituent components in the considered roof structure. Moreover, information about delivery of the elements to the construction site was obtained through further contacts with the roof company to be able to estimate the environmental footprint associated with the transportation services. In total, six loaded truck was employed to transfer 42 roof elements to the construction site, i.e. 7 roof elements in each loaded truck. Table 1 presents materials and components being used in the manufacture of the considered roof element.

Table 1: List of constitutive materials and components in a roof element

Number	Material	Thickness	EPD	Functional Unit (presented in the EPDs)
1	Diffusion barrier paper	0.5 mm	Unavailable	Unavailable
2	Plywood board	15-17 mm	Unavailable	Unavailable
3	Glass wool insulation	400 mm	Available	Per cubic meter (m3)
4	Stone wool insulation (employed only at the edges of each element)	50 mm	Available	Per cubic meter (m3)
5	I-Joist beams (H40)	400 mm	Available	Per meter (m)
6	Coated Aluminium-Zinc sheet	0.5 mm	Unavailable	Unavailable

5.2 Quantity take-off and assessment of the embodied energy and carbon footprint

The proposed method in section four was used for the assessment of the embodied energy and carbon footprint in the case study. The embodied energy and carbon footprint of 1 m² of the considered roof element was estimated. Hence, a 3D model of 1 m² of the element was designed in Autodesk Revit using the constituent materials and components with the considered parameters in the Autodesk Revit family and subsequently loading the family components to the Revit project to design the roof element and specify the required data and attributes of the components. Whereas only three available EPDs were found (see table 1), the computed environmental declaration of the roof element by the associated company was utilized to make the assessment feasible. The energy content and carbon dioxide emissions of materials production that was presented in the company’s declaration was not as accurate as the EPDs, since the EPDs are being reviewed by an external party whereas the energy content and carbon footprint of the materials in the company’s declaration were carried out solely by the corresponding material manufacturer. In the case where no available data was found in the company’s declaration, regarding the carbon footprint and energy content of the constituent materials, a different approach was applied. For instance, regarding the coated Aluminium-Zinc sheet, the only accessible data was a declaration of the associated manufacturer about the energy use for production of this kind of sheet. Therefore the total energy use was converted to the amount of carbon dioxide equivalents by applying the Swedish conversion factor (Svensk energi 2014). Moreover, concerning the diffusion barrier paper an EPD of a similar material from another manufacturer was employed.

As the contribution of the renewable and non-renewable energy to the total energy use is clearly stated in an EPD, no obstacles were faced to determine the embodied energy of the materials that had an available EPD. But in order to be able to compute the embodied energy of the rest of the materials, additional approaches were adopted. In the company’s environmental declaration and the other product declarations which were carried out by the associated manufacturer, the total energy use was distributed to the electrical energy and fossil energy. However, the fossil energy enumerates as embodied energy, but not all content of the electrical energy, hence, more data was gathered about the electrical energy production of the associated country where the materials are being manufactured to distinguish the proportion of non-renewable energy in the production of the electrical energy and consequently be able to estimate the total embodied energy of each individual component (Sveriges energikarta 2010).

Regarding the common denominator (i.e. type marks), in the case where no EPD existed, it was defined by the component's name. Since the computed carbon dioxide and embodied energy pertained to 1 m^2 of the roof element, the estimated values were amplified based on the total roof area to appraise the total embodied energy and carbon footprint of the implemented roof. Finally, the carbon dioxide emission associated with the transport of elements from the roof company to construction site was calculated by computing the delivery distance which was approximately 566 km and the total number and type of the truck that was utilized in the delivery (Krantz 2013).

5.3 Calculated embodied energy and carbon footprint

Figure 4 and 5 indicate the embodied energy and carbon dioxide emissions associated with the production of each constituent material in the implemented building's roof along with the transportation emissions.

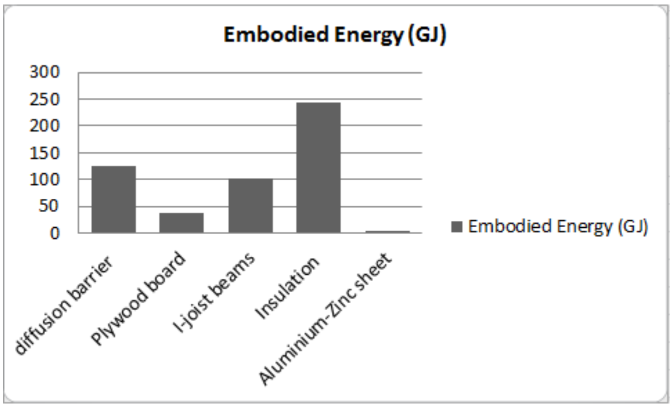

Figure 4: The embodied energy associated with the production of the constituent materials of the building's roof in the case study

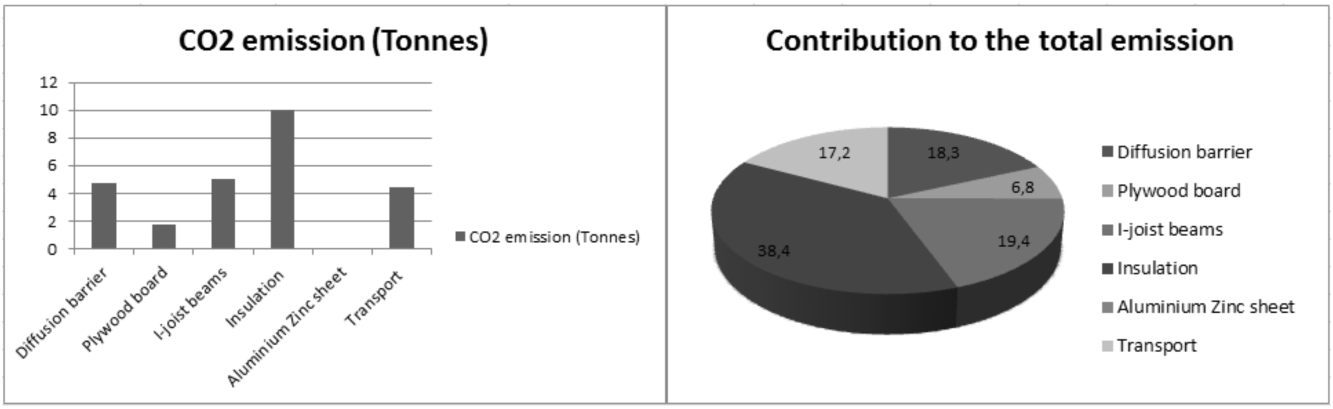

Figure 5: The corresponding carbon dioxide equivalents associated with the production of constituent materials and transportation services of the building's roof in the case study.

As shown in figure 4 and 5, the production of insulation has the highest embodied energy and consequently the largest amount of carbon dioxide emission. However, the insulation in the building's structure also reduces the energy use in the operational stage of the buildings life cycle. The next significant emitters of carbon dioxide are allocated to the production of I-joist beams and diffusion barrier, respectively. Unexpectedly, the contribution to the total carbon dioxide emissions from the transportation is not insignificant and constitutes of approximately 17 % of the total emissions. Regarding the coated Aluminium-Zinc sheet it is inferred that the presented information in the environmental declaration of the company was not considering the raw material acquisition of the ingredient materials and only included the energy use for production of this component in the factory.

Aluminium has high embodied energy due to the excavation and mining processes.

6. Discussion and conclusion

Assessment of the embodied energy and carbon footprint of the implemented commercial building's roof was demonstrated using the proposed method. Application of EPD numbers and component's name (where no EPD was available), as the common denominator facilitated the information exchange between the quantity take-off and assessment of the embodied energy and carbon footprint in the case study. Nevertheless, application of the component's name as the common denominator may not be the best choice, especially regarding assessment of the environmental impacts and embodied energy of the whole building when the number of constituent components and materials is vast. Hence, application of a system that has the ability to distinguish material and components with specific codes would be a solution regarding the lowest common denominator in this method. Currently in the Swedish construction industry a classification system called BSAB 96 (Byggtjänst 1998) is being applied in the building industry to facilitate information exchange between disciplines and actors in a project. In accordance with this system, all the building parts, elements, resources and activities are coded. Nevertheless, no attention has been set on the building materials in this system. Hence, additional approaches are required in this context. The other obstacle that was identified was the different FU in the EPDs, for instance in the I-joist beam the FU was expressed as 1 m of the component while the insulations FU was stated as 1 m^3 of the component. This variation can provide difficulties for the architects and building designers to estimate a whole building environmental impact. Hence, more research is required to investigate how the Quantity take-off should be performed to match the constituent materials and components FU of the EPDs.

7. Acknowledgement

This work was founded by the Swedish research council Formas. The authors would like to thank Masonite Beams AB and Lättelement AB for their contribution in this research and their assistance in data collection.

8. REFERENCES

AZHAR, S., CARLTON, W.A., OLSEN, D. and AHMAD, I., 2011. Building information modeling for sustainable design and LEED® rating analysis. *Automation in Construction,* **20**(2), pp. 217-224.

BYGGTJÄNST, S., 1998. BSAB 96 System och tillämpningar. *Stockholm: Svensk Byggtjänst*.

DIMOUDI, A. and TOMPA, C., 2008. Energy and environmental indicators related to construction of office buildings. *Resources, Conservation and Recycling,* **53**(1–2), pp. 86-95.

DIXIT, M.K., FERNÁNDEZ-SOLÍS, J.L., LAVY, S. and CULP, C.H., 2010. Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings,* **42**(8), pp. 1238-1247.

EPD NORWAY, 2014, EPD Norge, Available from: http://www.epd-norge.no/. [15 June 2014].

ERLANDSSON, M. and BORG, M., 2003. Generic LCA-methodology applicable for buildings, constructions and operation services—today practice and development needs. *Building and Environment,* **38**(7), pp. 919-938.

EUROPEAN COMMISSION, 2009. *E.U. energy and transport in figures: statistical pocketbook.* Luxembourg: Office for Official Publications of the European Communities, c2001-c2010.

FAVA, J.A., 2006. Will the next 10 years be as productive in advancing life cycle approaches as the last 15 years? *The International Journal of Life Cycle Assessment,* **11**, pp. 6-8.

FAY, R., TRELOAR, G. and IYER-RANIGA, U., 2000. Life-cycle energy analysis of buildings: a case study. *Building Research & Information,* **28**(1), pp. 31-41.

HAAPIO, A. and VIITANIEMI, P., 2008. A critical review of building environmental assessment tools. *Environmental Impact Assessment Review,* **28**(7), pp. 469-482.

HERNANDEZ, P. and KENNY, P., 2010. From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings,* **42**(6), pp. 815-821.

INTERNATIONAL EPD SYSTEM, 2014, Environmental Product Declarations - Product Category Rules. Available from: http://www.environdec.com/ [15 June 2014].

ISO 2006. 14040: 2006. *Environmental management-Life cycle assessment-Principles and framework. European Committee for Standardization*.

ISO 2006. 14044: 2006. *Environmental management-Life cycle assessment-Requirements and guidelines. European Committee for Standardization*.

KHASREEN, M.M., BANFILL, P.F. and MENZIES, G.F., 2009. Life-cycle assessment and the environmental impact of buildings: a review. *Sustainability,* **1**(3), pp. 674-701.

KRANTZ, J., 2013. *An Earthworks Energy Model for Practical use in Road Construction*, Master Thesis, Luleå Technology University.

KULAHCIOGLU, T., DANG, J. and TOKLU, C., 2012. A 3D analyzer for BIM-enabled Life Cycle Assessment of the whole process of construction. *HVAC&R Research,* **18**(1-2), pp. 283-293.

MOTAWA, I. and CARTER, K., 2013. Sustainable BIM-based Evaluation of Buildings. *Procedia - Social and Behavioral Sciences,* **74**(0), pp. 419-428.

NBIM-US, 2014, The National BIM Standard - United States. Available from: http://www.nationalbimstandard.org/ [15 June 2014].

RAMESH, T., PRAKASH, R. and SHUKLA, K.K., 2010. Life cycle energy analysis of buildings: An overview. *Energy and Buildings,* **42**(10), pp. 1592-1600.

SCHADE, J., OLOFSSON, T. and SCHREYER, M., 2011. Decision-making in a model-based design process. *Construction Management and Economics,* **29**(4), pp. 371-382.

SCHLUETER, A. and THESSELING, F., 2009. Building information model based energy/exergy performance assessment in early design stages. *Automation in Construction,* **18**(2), pp. 153-163.

SVENSK ENERGI, 2014, Hur mycket koldioxid medför din elanvändning? [How much carbon dioxide causes your electricity usage ?]. Available from: http://www.svenskenergi.se/Elfakta/Miljo-och-klimat/Klimatpaverkan/Hur-mycket-koldioxid-medfor-din-elanvandning/ [01 June 2014].

SVERIGES ENERGIKARTA, 2010. *Scenario om hur energiläget i Sverige kan se ut år 2050 [Scenario of how the energy situation in Sweden may look like in 2050].* Stockholm, Sweden: The royal Swedish academy of sciences.

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**(4), pp. 429-435.

TOLLER, S., WADESKOG, A., FINNVEDEN, G., MALMQVIST, T. and CARLSSON, A., 2009. Bygg-och fastighetssektorns miljöpåverkan.

WONG, K. and FAN, Q., 2013. Building information modelling (BIM) for sustainable building design. *Facilities,* **31**(3/4), pp. 138-157.

YUNG, P., LAM, K.C. and YU, C., 2013. An audit of life cycle energy analyses of buildings. *Habitat International,* **39**(0), pp. 43-54.

ZABALZA BRIBIÁN, I., ARANDA USÓN, A. and 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**(12), pp. 2510-2520.