Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 113 (2017) 90 – 97

Energy Procedia

International Scientific Conference "Environmental and Climate Technologies", CONECT 2016, 12–14 October 2016, Riga, Latvia

Environmental performances of a timber-concrete prefabricated composite wall system

Stefano Fortuna, Tiziano Dalla Mora*, Fabio Peron, Piercarlo Romagnoni

Department of Design and Planning in Complex Environments, University IUAV of Venice, Santa Croce, 191, Tolentini Venice 30135, Italy

Abstract

The improvement of environmental performance in building construction could be achieved by prefabrication. This study quantifies and compares the environmental impacts of a Concrete Glulam Framed Panel (CGFP): the basic configuration of this precast component consists in a Cross-Laminated Timber (CLT) frame structure supporting a thin reinforced concrete slab with an interior insulation panel and covered by finishing layers. The research investigates also alternative design of configuration with the substitution of different insulation materials in order to minimize the Embodied Energy and Carbon Footprint values.
The boundary of the quantitative analysis is "cradle to gate" including the structural support system; an IMPACT 2002+ characterization methodology is employed to translate inventory flows into impacts indicators.
Results present very low values for carbon footprint (60.63 kg CO_2eq m^{-2}) and the embodied energy values (919.44 MJ m^{-2}) indicate this hybrid precast structure as a valid alternative building constructions and processes.
A detailed discussion of the outputs is presented, including the comparison of the environmental performances depending on different insulation materials.
© 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the scientific committee of the International Scientific Conference "Environmental and Climate Technologies".

Keywords: precast panels; prefabrication; environmental impact; embodied energy; carbon footprint; cradle-to-gate; glulam; cross-laminated timber; reinforced concrete

* Corresponding author.
E-mail address: tdallamora@iuav.it

1876-6102 © 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the scientific committee of the International Scientific Conference "Environmental and Climate Technologies".
doi:10.1016/j.egypro.2017.04.024

1. Introduction

Nowadays climate change is one of the most serious threats to human society and the reduction of CO_2 emissions is the main topic towards the global warning [1]. Buildings are widely responsible for environmental impact through consumption of resources, production of waste and emission of greenhouse gas. Construction sector includes a large amount of activities, from construction to management, from production to dismission: buildings in fact consume the 60 % of the raw materials extracted from the lithosphere [2], up to 40 % of global energy and led to 36 % of anthropogenetic greenhouse gas (GHG) emissions in industrialized countries [3, 4].

The general life-time carbon emission for a traditional house [5] is given by the primary materials, manufacture, transportation and construction [6]. In this sense the prefabrication of building components could be a validate strategy for optimize building process: it's shown the possibility to reduce the construction waste up to 52 % [7], due to the optimization of cut-off [8], affecting positively on energy, cost and time efficiency and also to reduce environmental impacts; for example, embodied energy indicator measures the energy consumed during extraction, processing, manufacturing, and transportation at all stages [9] and carbon foot print indicator measures the environmental impact of human activities on global climate [10].

In general there is an absence of detailed scientific research or case studies dealing with the overall environmental benefits of prefabrication [7] particularly the embodied energy savings resulting from waste reduction and the improved efficiency of material usage. Moreover the Concrete Glulam Framed Panel (CGFP) presents a particular hybrid configuration based on a CLT frame structure and a reinforced concrete cover. Different studies focus on materials, especially concrete and steel: Guggemos and Horvath [11] have identified and quantified the energy required for two construction of office buildings, the first with a structural steel frame and the second with a cast in place concrete frame, and findings revealed that the total life cycle energy use of both steel and concrete framed buildings were comparable. In general research undertook a comparative life cycle assessment (LCA) of the performance of the conventional construction method in relation to the use of a selected prefabrication method: about 44 % saving in embodied energy could be incurred from the use of precast concrete technology in relation to conventional construction of the same building. In a literature review Perez-Garcia et al. [12] show the environmental benefits provided by the Multilayer Structural Panels technology when applied to construct low rise residential buildings, evaluating the economic cost, the embodied energy and the amount of CO_2 emissions during the construction phase.

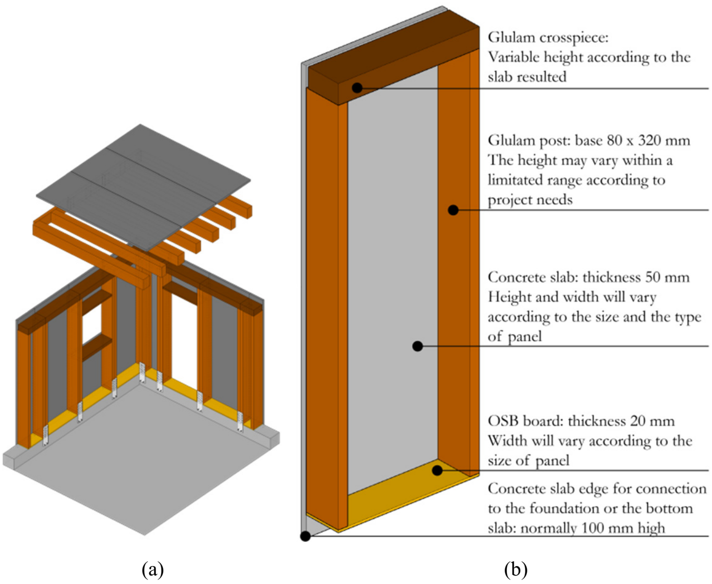

Fig. 1. CGFP model. (a) Model of a construction made by CGFP system; (b) characteristics and materials of a typical external wall component.

This study investigates the environmental impact of the CGFP (Fig. 1) and its components and materials from "cradle to gate". In fact the prefabrication strategy affords improved environmental performance for building construction and a life-cycle assessment approach gives the possibility to evaluate the main impact categories of products or processes, associated to the pre-production, production. The aim is to quantify the carbon dioxide emissions and the embodied energy of the modular prefabricated panel for residential buildings in order to determine the amount of the environmental effects of building life cycles and furthermore to assess the potential benefits on using different kinds of insulation materials.

Table 1. CGFP model and characterization of materials.

Material	Density, kg m^{-3}	Weight, kg
Double plasterboard sheet	800	60.2
OSB panel for fastening systems	550	20.57
Monolith of polystyrene foam with graphite	17	20.18
Smoothing and colored cement, finishing 2 mm	2400	504
Pillar of laminated wood section 80 x 320 mm	418	66.46
Glulam crosspiece	520	29.95
OSB board: thickness 20 mm width will vary according to the size of panel	550	4.235
Aluminum profiles	2700	1.08
Polyethylene joint (n.22)	1100	0.0721
Profiled iron	7800	

2. Life cycle assessment

2.1. CGFP configuration analysis

The CGFP panel object of this study is characterized by the assembling of different materials and products: a wooden frame supporting a reinforced concrete slab and including an inner polystyrene foam with graphite.

The scope of this research is the evaluation of a partial LCA, using an approach "from cradle to gate" (Fig. 2); in a 50-year building lifetime horizon, the system boundary considers a definite scenario: the facilities and equipment used for the extraction and production of raw materials; the transport and the conversion of the materials into production process; the assembling in factory of each products in order to build the panel; the assessment stops at the factory gate, before the finished product has been transported in site construction.

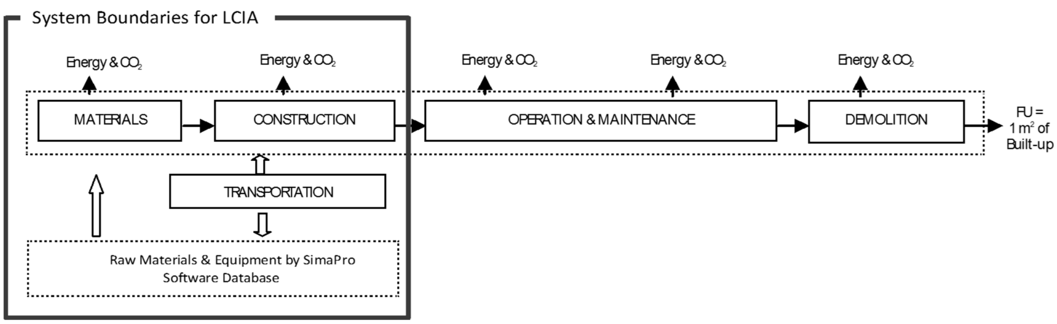

Fig. 2. System Boundary for LCIA of CGFP typical configuration.

The definition of functional unit is fundamental in life cycle assessment. The functional unit is defined in ISO 14040:2006 [12] as the quantified performance of a product system for use as a reference unit: so all inputs, outputs, and analysis are relative to the functional unit in order to ensure a comparisons between alternative products, processes, or services made on an equivalent basis. The chosen functional unit for this study is 1 m^2 of opaque wall component as a reference for both inventory flows and environmental impacts. The CGFP panel covers a front area of 4.2 m^2 and the paper compares some alternative solutions of the inner insulation materials with the same thermal resistance (R-value 7.43 m^2 K W^{-1}). The assumed life span of the panels was 50 years with no maintenance necessary in that period. It was assumed that the panels will be used for construction/retrofitting of buildings located in the province of Treviso (Italy).

Evaluation of impacts along the life cycle for all materials was developed using *SimaPro* [14], Ecoinvent database [15], Impact 2002+ v2.05 [16] and IPCC 2013 [17] method. As a consequence the impacts are expressed in points: a composite measure of the overall environmental impact of any material, product or service. A point represents the average impact in a specific category caused by a person during one year in Europe [16]. This study presents values expressed in points per square meters of components surface.

According to LCA framework, a first phase called Life Cycle Inventory (LCI) was aimed to collect all data about the processes and the quantity of each material used in term of volume and density, in order to calculate the total weight of each material (Table 1). The inventory analysis was conducted using secondary data obtained from the Ecoinvent database included in the calculation software. Processes analysis underlined that glued laminated timber shows the higher impact, while the other materials have lower ones due to their little amount. The last calculation concerns the damage impact for each material and a comparison is presented (Table 2) for evaluating the output. In Human health category, OSB panel produces minimal impact while glued laminated timber is responsible for the greatest weight on the environment because of the amount of the material and the processes. The most important damages of glued laminated timber are due to the impact categories Respiratory inorganics (35.1 %), Land occupation (18.8 %), Non-renewable energy (15.9 %), Global warming (13.5 %) and Terrestrial ecotoxicity (11.5 %). In Ecosystem quality, glued laminated timber produces the greater impact due to the raw materials and processes utilized. In Climate change the assessment show lower values for OSB and Reinforcing steel, but the higher values are presented in the concrete panel because of clinker production. In Resources comparison of insulation foam and concrete is interesting. Total sum of impacts are quite similar and shows higher outcomes because of the higher volumes in the CGFP panel. Otherwise eco-points for Resources are very different due to the high consumption of non-renewable energy in the production of polystyrene foam slab.

Table 2. Assessment for damage category impact of materials with IMPACT 2002+ method, expressed in eco-points per square meters, pt m^{-2}.

Damage category	Human health, pt m^{-2}	Ecosystem quality, pt m^{-2}	Climate change, pt m^{-2}	Resources, pt m^{-2}	Total, pt m^{-2}
Gypsum plaster board, at plant	0.00086263	0.00016832	0.00056327	0.00046753	0.00206175
Aluminum, secondary, from old scrap, at plant	0.00001089	0.00000240	0.00001234	0.00000686	0.00003249
Oriented strand board, at plant	0.00061737	0.00053710	0.00036376	0.00046039	0.00197861
Polystyrene foam slab with graphite, 6 % recycled	0.00081505	0.00009442	0.00109508	0.00210795	0.00411250
Concrete, normal, at plant	0.00135403	0.00019873	0.00198625	0.00078793	0.00432694
Reinforcing steel, at plant	0.00111175	0.00011530	0.00063626	0.00041956	0.00228289
Welding, arc, steel	0.00001063	0.00000294	0.00000355	0.00000300	0.00002014
Polyethylene, HDPE, granulate, at plant	0.00000387	0.00000010	0.00000316	0.00000878	0.00001591
Blow moulding	0.00000354	0.00000044	0.00000235	0.00000257	0.00000891
Glued laminated timber, indoor use, at plant	0.00347911	0.00270095	0.00118043	0.00139273	0.00875323
Aluminium, secondary, from old scrap, at plant	0.00001089	0.00000240	0.00001234	0.00000686	0.00003249
Reinforcing steel, at plant	0.00020929	0.00002171	0.00011978	0.00007898	0.00042975
Zinc coating, pieces	0.00006893	0.00006154	0.00002436	0.00002275	0.00017758
Total	0.00855799	0.00390638	0.00600292	0.00576589	0.02423318

Finally the environmental impact of CGFP configuration is summarized in the total value of 0.02423 (pt m^{-2}) eco-points for square meters and the involved LCA processes affect particularly the Human health damage category with 0.0085 eco-points per square meters (pt m^{-2}).

2.2. Different insulation materials analysis

In the previous analysis CGFP configuration shows how the insulation material affects almost the 18 % of total impact, (corresponding to a 0.0044 pt m^{-2}) that is similar to concrete slab impact: while concrete is a component with optimized characteristics in structural and formal terms, insulation materials could be analyzed in order to promote alternative design (e.g. a minor thickness allows more space for system) and with the aim to reduce the general environmental impacts. EPS installed in the panel was replaced with a selection of various organic and non-organic materials [18] to obtain the values of the damage and to identify those with less impact at equivalent thermal transmittance.

Table 3. Selection and characterization of insulation materials.

Material	Unit	Fiberglass	XPS	EPS	Fiberboard	Mineral wool	Aerogel	VIP
Thermal conductivity (λ)	W $m^{-1}K^{-1}$	0.048	0.036	0.035	0.038	0.037	0.013	0.006
Resistance (R)	m^2K W^{-1}	7.43	7.43	7.43	7.43	7.43	7.43	7.43
Thickness (s)	m	0.36	0.27	0.26	0.28	0.27	0.09	0.04
Density	kg m^{-3}	150	20	34	150	110	120	175
LCA	**pt m^{-2}**	**0.02604**	**0.00707**	**0.00879**	**0.02167**	**0.01432**	**0.00396**	**0.01019**

A mandatory constrain is material size because the available thickness is 0.28 m and the insulating material should have the same or minor thickness (Table 3). The characteristics of each insulation panel provide a very wide difference of impact values.

Table 4. Assessment of damage category impact of CGFP, developed with different combinations based on insulation materials with IMPACT 2002+ method, expressed in eco-points per square meters [pt m^{-2}].

Damage category	Unit	Fiberglass	XPS	EPS	Fiberboard	Mineral wool	Aerogel	VIP
Human health	pt m^{-2}	0.01075	0.00163	0.00199	0.00649	0.00591	0.00111	0.00261
Ecosystem quality	pt m^{-2}	0.00085	0.00010	0.00014	0.00443	0.00047	0.00004	0.00034
Climate change	pt m^{-2}	0.00712	0.00254	0.00244	0.00160	0.00392	0.00132	0.00278
Resources	pt m^{-2}	0.00732	0.00279	0.00422	0.00915	0.00403	0.00149	0.00446
Total	pt m^{-2}	0.02604	0.00707	0.00879	0.02167	0.01432	0.00396	0.01019
Difference with EPS	%	+ 196 %	– 20 %	/	+ 147 %	+ 63 %	– 55 %	+ 16 %

This setting also affects the total environmental impact assessment of each combination of insulation and structure in respect to other materials (Table 4): the analysis demonstrates that the least impact is presented by aerogel insulation (0.004 pt m^{-2}) with about half values in respect to EPS (0.009 pt m^{-2}); overall output show that the employment of EPS is already performant and it represents a low environmental impact in respect to other materials.

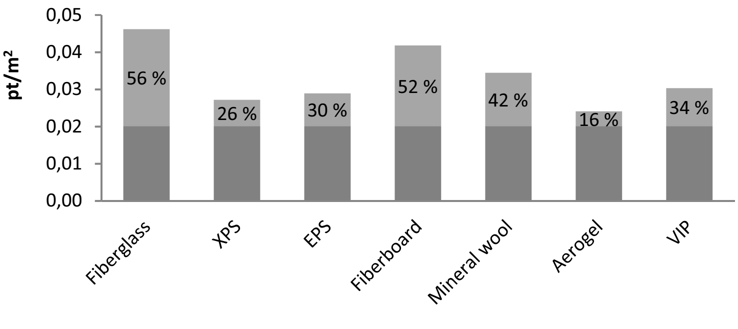

Fig. 3. Assessment for impact of each insulation foam (in light grey) in respect with the other materials (in dark grey), expressed in eco-points per square meters [pt m^{-2}]. A percent value represents the weight of impact for each insulation foam in the whole component.

All insulation materials present low values of impact in terms of Ecosystem quality, except Fiberboard because of the dispersion of metallic substances in soil during the production, in particular Aluminum (49.6 %) and Zinc (32.6 %). Fiberglass presents high values in Climate change because of the Carbon dioxide, representing the 95 % in the whole damage category. The most damage of Human health is due to Particulates in air (39 %) and Nitrogen oxides in air (23 %) and Sulfur dioxide (22 %). Resources category affects by Gas, (43 %) and Coal (28 %), Oil (13 %).

After this calculation it's relevant to underline the general weight of each insulation material in relation to structure (Fig. 3): the incidence of each insulation into the general impact of the CGFP reveals very different values (from very low relevance to almost 40 %), but the most important information obtained concerns the great relevance on selection about the insulation component and the reduction of environmental impacts that it follows.

3. Embodied Energy and Carbon Footprint

The analyses conducted permits also to evaluate the environmental impacts of basic configuration of CGFP from the point of view of Embodied Energy (919.44 MJ m^{-2} or 2766 MJ m^{-3}) and Carbon Footprint (60.63 kg CO_2eq m^{-2} or 254.65 kg CO_2eq).

Embodied Energy is the total amount of energy used throughout the product's life-cycle: raw material extraction, transportation, manufacture. In the evaluation of the damage category impact Resource category shows values about non-renewable energy and mineral extraction, that is precisely the Embodied Energy: graphics below (Table 5) shows how each compartment of energy consumption has different amount and weight for each considered process.

Table 5. Embodied Energy for insulation materials.

	Unit	Fiberglass	XPS	EPS	Fiberboard	Mineral wool	Aerogel	VIP
Embodied Energy	MJ m^{-2}	1104.47	424.36	640.87	1388.49	607.46	226.46	676.48
Difference with EPS	%	+ 72 %	– 34 %	/	+ 117 %	– 5 %	– 65 %	+ 6 %

Fiberboard has higher impact than other insulation material due to the relevance of some processes and its amount of energy for producing it. Aerogel instead presents lowest values because it is a silica-based synthetic porous material with a process characterized by a minor consumption of energy or creating it (Fig. 4).

A Carbon Footprint is an environmental index and is historically defined as "the total sets of greenhouse gas emissions caused by an organization, event, product or individual". So it measures the impact that these emissions have on climate change to anthropogenic. The carbon footprint is expressed in equivalent carbon dioxide, which value indicates the level of the GWP (Global Warming Potential) of greenhouse gases, or rather their global warming potential for each selected material. A comparison between the production process of packages was developed according to the method 2013 IPCC (Intergovernmental Panel on Climate Change), that lists the climate change factors of IPCC with a timeframe of 20, 100 and 500 years: an unit value is attributed on-base percentage to the material with higher equivalent carbon dioxide and the remaining values were get consequently.

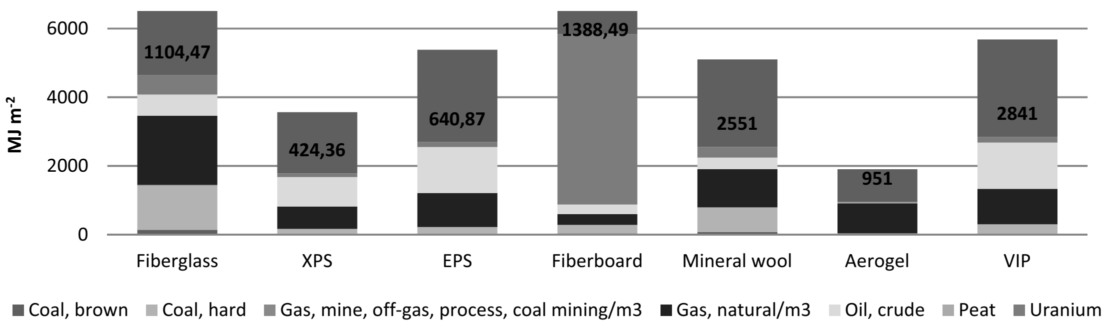

Fig. 4. Amount of Embodied Energy for insulation materials evidencing all compartments for non-renewable energy expressed in megajoule [MJ]. Total value of all compartments is presented for each insulation foam, on the top of the column.

The analysis has been made with IPCC 2013 GWP 100a v.1.00 method: materials such as aerogels and fiberboard have low impacts since in the first case the material used is little amount, while the second has low values due to its nature and process (Fig. 5).

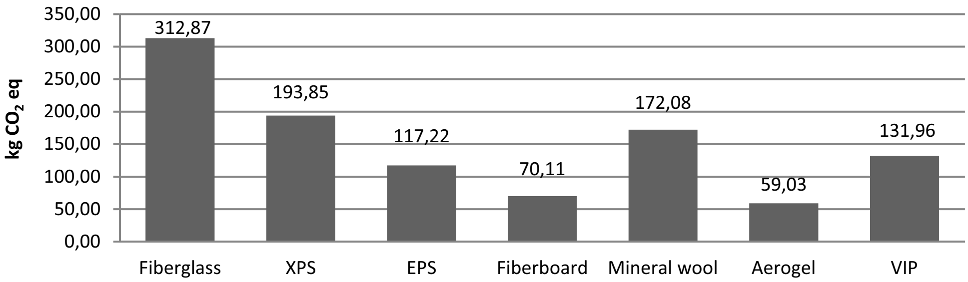

Fig. 5. Processes matching with IPCC 2013 GWP 100a method, expressed in kilograms of equivalent carbon dioxide [kg CO_2eq].

3.1. Results and discussion

The most important outcome of this analysis lays in the fact that EPS foam in the basic CGFP is already a validate configuration in terms of transmittance values and environmental impacts. The evaluation of parameters like Embodied Energy and Carbon Footprint allows a comparison with the environmental assessment of other precast panels.

The analysis of the environmental impact in CGFP panel confirms the results of the case study in Monahan J. et al. [19]: analyzing three scenario with precast elements, the constructions in timber and concrete reveal a lower embodied energy values due to the less energy intensive processes involved in respect to a steel construction. Moreover, focusing on the external wall component, CGFP configuration shows a quite similar structure in timber frame that includes insulation materials and finish layers, but embodied energy values are lower and comparable in respect to the external wall (1971.8 MJ m^{-2}) in this study, so the general trend of breakdown energy is confirmed and very low.

One more comparison is given by the Australian National Timber Development Council document [20] that listed embodied energy values for common building elements; for external wall in timber frame, brick veneer covered, including internal insulation, values are very similar (1060 MJ m^{-2}) and the main difference lays in the fact that CGFP panel is precast and includes other processes.

In Culakova et al. [21], a multi-criteria analysis of material selection shows how to reduce the environmental impacts by the use of alternative solutions from renewable materials: the scenario with massive cross laminated timber (CLT) panel and wood-fiber insulation is very interesting because at equal thermal properties (0.11 W $m^{-2}K^{-1}$) the outcomes give very similar to CGFP panel in terms of embodied energy (1089.940 MJ m^{-2}) and carbon footprint (–81.094 kg CO_2eq m^{-2}).

Evaluation on alternative insulation materials reveals that the replacement of EPS gives some benefits: Aerogel or VIP allows a low thickness (0.10 m and 0.04 m respectively), allowing to increase the thermal resistance of the precast component or to use the cavity for installing system pipelines or cable; in terms of Embodied Energy and Carbon Footprint only Aerogel could decrease the environmental impacts in both the analyzed methods (2692 MJ, 117.22 kg CO_2eq), while materials such as XPS and Fiberboard are valid alternatives (respectively 1782 MJ and 70.11 kg CO_2eq).

Next step of research could consider the life cycle in terms of the economic assessment in order to evaluate the cost effectiveness of this hybrid component. One more step could consider a whole construction made by this technological system in order to evaluate the energy, environmental, economic assessment of all components, determining a comparison in comparison to traditional building.

Acknowledgements

The authors acknowledge the kind collaboration of Montini Case (http://montinicase.it) producer of the CGFP building system.

References

[1] Taborianski VM, Prado RTA. Methodology of CO_2 emission evaluation in the life cycle of office building facades. Environmental Impact Assessment Review 2012;33(1):41–47.

[2] Harris DJ. A quantitative approach to the assessment of the environmental impact of building materials, Building and Environment. 1999;34:751–758.

[3] United Nations Environment Programme (UNEP). Buildings and Climate Change: Summary for Decision-Makers; UNEP Sustainable Building and Climate Initiative, Paris, France; 2009. Available: http://www.unep.org/sbci/pdfs/SBCI-BCCSummary.pdf

[4] IPCC. Climate Change 2007-The Fourth Assessment Report of the Intergovernmental Panel on Climate Change; Geneva, Switzerland; 2007.

[5] Barisa A, Rosa M, Laicane I, Sarmins R. Application of Low-Carbon Technologies for Cutting Household GHG Emissions. Energy Procedia 2015;72:230–237.

[6] Sartori I, Hestnes AG. Energy use in the life cycle of conventional and low-energy buildings: a review article. Energy and Buildings 2007;39(3):249–257.

[7] Jaillon L, Poon CS, Chiang YH. Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong, Waste Management 2009;29(1):309–320.

[8] Osmani M, Glass J, Price A. Architect and contractor attitudes to waste minimisation. Waste and Resource Management 2006;2(1):65–72.

[9] Boustead I, Hancock GF. Handbook of Industrial Energy Analysis. Ellis Horwood Limited. Chichester; 1979.

[10] Wright L, Kemp S, Williams I. Carbon footprinting: towards a universally accepted definition. Carbon Management 2011;2(1):61–72.

[11] Guggemos AA, Horvath A. Comparison of environmental effects of steel and concrete-framed buildings. Journal of Infrastructure Systems 2005;11(2): 93–101.

[12] Perez-Garcia A, Víllora AG, Pérez GG. Building's eco-efficiency improvements based on reinforced concrete multilayer structural panels. Energy and Buildings 2014;85:1–11.

[13] ISO14040. Environmental management – life cycle assessment – principles and framework (ISO 14040:2000). CEN European Bureau for Standardisation; 2000.

[14] Simulation software SimaPro 8.0.5.13, Prè (Product Ecology Consultants, NL).

[15] Ecoinvent Data v3.2, Ecoinvent Centre.

[16] Jolliet O, Margni M, Charles R et al. IMPACT 2002+: A new life cycle impact assessment methodology. International Journal of Life Cycle Assessment 2003;8(6):324–330.

[17] Intergovernmental Panel on Climate Change. IPCC Fifth Assessment Report. The Physical Science Basis; 2013. Available: http://www.climatechange2013.org/

[18] Database ProCasaClima 2015 in Casaenergetica.it. Tutte le caratteristiche dei materiali isolanti per l'edilizia. Available: http://www.casaenergetica.it/info/tecnologia/materiali.html

[19] Aye L, Ngo T, Crawford RH, Gammampila R, Mendis P. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. Energy and Buildings 2012;47:159–168.

[20] Forest and Wood Products Research and Corporation, National Timber Development Council. Environmentally friendly housing using timber : principles (1st ed.). Brisbane: Forest and Wood Products Research and Development Corporation; 2001.

[21] Culakova M, Vilcekova V, Katunska J, Kridlova Burdova E. Multi-Criteria Analysis of Material Selection in order to Reduction of Environmental Impacts. Chemical Engineering Transactions 2013;35:379–384.