Greenhouse gas emission from construction process of multi-story wooden buildings

Atsushi Takano
Doctoral Candidate, Architect
Aalto University, Department of Forest Products Technology
Finland
atsushi.takano@aalto.fi

Francesco Pittau
Doctoral Candidate
Politecnico di Milano, Architecture, Built environment and Construction engineering
Italy
francesco.pittau@mail.polimi.it

Dr. Annette Hafner, Technical University of Munich, Germany, a.hafner@tum.de
Stephan Ott, Technical University of Munich, Germany, ott@tum.de

Short Summary

The purpose of this study is to investigate environmental impact for construction process of wood-based building. Detailed data collection from construction work is conducted on three multi-story wooden buildings. Greenhouse gas (GHG) emission value is calculated for production stage (material production and construction) and operation stage of the buildings, and a ratio of the emission from construction process is observed. The results present that construction phase holds about 20-30% of GHG emission in the production stage. In addition, it is shown that material production phase, construction phase and operation phase of the buildings account for approximately 16-35%, 6-10% and 55-78% of the total GHG emission, respectively. Based on the results, feature of the impact for wood-based construction and an issue regarding the data collection are discussed. This study demonstrates a relevance of construction process in a life cycle assessment of buildings. Since the result of environmental assessment is beneficial for the industry in order to optimize their work environmentally, simple and reliable assessment method is required based on further research.

Keywords: Life cycle assessment, Building construction, Wood-based building, Greenhouse gas GHG emission

1. Introduction

In life cycle assessment (LCA) of a building, major attention has been paid on a use phase of a building due to its high share of environmental impact in the life cycle. The reduction of environmental impact during operation of a building has been main target so far. As a result of the effort, the impact from the use phase has been mitigated and importance of the other life cycle stages has increased [1]. In general, construction material production phase has been regarded as the next target of mitigation and the other phase, such as construction phase, have not had priority because of its small proportion of the life cycle environmental impact [2, 3]. It has been reported that the construction phase contributes 2-26%, in many cases less than 10%, of overall life cycle impact of a building [4-10].

However, recent researches mentioned that the construction phase has relevant impact, and the trend of GHG emissions from construction equipment has increased significantly in the last decades [11-14]. They indicated that the process should not be underestimated and attempted to establish the framework for environmental management during the construction phase. The environmental impact of the process should be known to enable to optimize it in practical level.

The objective of this study is to review environmental impact of construction process. Detailed data collection and the assessment in terms of GHG emission for construction process are conducted with wood-based reference buildings. To make a comparative study with reliable data, GHG emission from material production and construction phase of wooden building elements of the buildings are assessed and compared. Manufacturing and installation of all building service equipment and basement are excluded from the assessment. In addition, the emission from operational energy use of the buildings is assessed and a ratio of the emission from construction process is observed.

2. Environmental impact of construction process

In the last two decades many LCA study on buildings and construction have been conducted. In general, building use phase has been dominant in the life cycle environmental impact of a building in terms of energy consumption resulting in GHG emissions. However, in some cases the construction process seems to have relevant impact with a great potential of reducing the environmental burden of buildings. For example, it has been reported that the use phase accounts for 70-98% of life cycle energy use of a building [15], while the construction phase holds 2-26% of the energy use, depending on case studies [4-10].

Some of the most recent researches mentioned that GHG emissions from construction process should not be underestimated. Ahn et al. [14] found that the decentralization of construction processes, which involves often several subcontractors, leads to critical issues in measuring the significance of GHG emissions from construction processes. Furthermore, the uniqueness of each project and the high fragmentation of the building industrial sector make every improvement difficult to pursue. Mora et al. [13] concluded that GHG emission from construction activities is significant and the trend of GHG emissions from construction equipment increased significantly in the last decade.

Gangolells et al. [16] stated that transportation and construction equipment, waste production, and water consumption have significant environmental consequences, implying that any improvements in these areas could be priority targets for reducing the overall life cycle impact of the building. Bilec et al. [17] found for a concrete parking structure that transportation of concrete to the site, particularly for the precast pieces, is the most significant construction process. Guggemos and Horvath [18] reported that work on the structural frame has the largest impacts in the construction phase, mostly due to heavy use of diesel equipment. This finding was also corroborated by Junnila and Horvath [19].

There is an open discussion of the implications of off-site construction as opposed to typical on-site construction. A relevant study was carried out in northern Japan by Nishioka et al. [20], who considered the environmental trade-offs in vertically integrated factory-built housing, which required more materials than a typical home but also performed better. The authors found that the energy and carbon debts incurred by the additional materials are paid off through efficiency gains in less than six years, well below the average lifetime of homes in that area. Kim [21] compared life cycle impacts of a modular and a conventionally constructed home in Michigan, analyzing energy use, material consumption, GHG emissions, and waste generation. This work suggested that solid waste generation, transportation energy, and GHG emissions are significantly lower when modular construction is used.

Quale et al. [22] carried out a comparative analysis of the two different construction methods considering different scenarios and transportation distances. From the results the GHG emission from the use of prefabricated modular systems is lower than traditional systems due to a limited duration of on-site activities, which leads less waste and worker transportation.

3. Methodology

3.1 Reference buildings

Three multi-story wood-based residential buildings are assessed in this study. Basic information of the reference buildings is summarized in Table 1. Functional unit is one m^2 of living area. Although context of the buildings differ each other, the assessment is conducted with the same methodology and accuracy according to the purpose of this study.

Table 1: Basic information of the reference buildings

Name	Location	Structure frame	Gross area (m^2)	Living area (m^2)	Floors	*Operative energy use (kwh/m2/a)
Building A	Germany	Sawn timber panel	726	488	5	63
Building B	Finland	Cross laminated timber	730	548	3	59
Building C	Italy	Cross laminated timber	1840	1398	5	43

*Operative energy use is the secondary energy including electricity and heating/cooling energy

3.2 Impact assessment and system boundary

GHG emission value for material production, construction, and use phase of the reference buildings is calculated. According to normative standard EN15978 [23], included life cycle phases are defined as shown in Table 2.

Table 2: Included life cycle phases and its abbreviation according to EN15978

Product stage (Module A1-3)			Construction process stage (Module A4-5)		Use stage (Module B)
A1	A2	A3	A4	A5	B6
Raw material supply	Transport	Manufacturing	Transport	Construction	Operational energy use

Since specification of basement differs significantly between the buildings and there are several uncertainties in non-wooden building element (e.g. prefabrication of steel staircase), the results of the assessment for the module A are limited to wood-based building element of the buildings in order to make the results comparable.

3.2.1 Module A1-3: Material production

The inventory is carried out from working drawings of the architects and structural engineers. Calculated mass of each component is cross-checked with material order list provided by the constructor. Building service equipment and furniture are excluded from the inventory, even if those are integrated to the building element, due to lack of information. The included inventories are summarized in Table 3.

Table 3: Mass of used materials in wood-based building elements (kg/m^2 of living area)

Material	Building A	Building B	Building C
Sawn timber	133	40	19
Cross laminated timber	20	151	241
Laminated veneer lumber	16	5	2
Glulam	82	40	
Plywood		7	
OSB		7	

Wood fibre board		16	
Gypsum board	82	60	78
Rock wool	12	33	10
Cork			4
Cellulose fibre		5	
Particle board	8		28
Ancillary material	23	2	11
Vapour barrier sheet		0,4	
Water proof sheet	1	3	6
Cement fibre board			14
Window and door	39	57	43

3.2.2 Module A4: Transportation

All information regarding the construction stage is collected by monitoring of construction work and machines and interview with the constructor. Transportation of building components and elements is taken into account according to the real case. The impact from transportation process is calculated by multiplying distance (km) and mass of deliverable (ton) as taking vehicle type into account. Worker transport to the factory or construction site is not included.

3.2.3 Module A5: Construction

Energy consumption during prefabrication of the wood-based element in the factory and on-site assembling of the prefabricated element is monitored. Possible data collection method is case specific due to working system of the constructors. Different methods, which seem to be the most relevant in each case, are applied. In case of building A, real monitoring data of the prefabrication factory and the interviewed information from the constructor were main source. In case of building B, a researcher has been stationed on the construction site and monitored the process everyday with the constructors. Monthly energy consumption data of the prefabrication factory and spent working time for the project in the factory were monitored by the prefabrication company. In case of building C, a special agreement was signed between the client and constructors regarding construction schedule. Therefore, each constructor planned detailed working activity in advance, which helped to collect relevant data.

3.2.4 Module A5: Waste management

Waste from prefabrication and on-site construction work is also considered based on the real case and literatures [24-27]. Waste management methods and transportation to waste treatment facilities are taken into account based on the interviewed information.

3.2.5 Module B6: Operational energy use

The calculation of operational energy use is based on the estimated electricity and heating/cooling energy demand of the buildings. Aggregated annual operational energy demand is summarized in Table 1. National energy mix is applied to the case of building A and C, and actual energy mix of the location is applied to the building B.

3.3 LCA Data

All calculations are conducted with Ecoinvent database V2.2. [28]. Ecoinvent is one of the most well-known LCA database which consists of process based life cycle inventory (LCI) data. Temporal representativeness is year 2000-2007 as annual average. Basically stored data is based on an average of current used technology. European average data is applied to the assessment of the module A1-3, and country average data is applied to the module A4-5. In principle, exact material data is applied for building materials from the database. However when there is not exact data in the database, most relevant material data is applied (e.g. plywood data instead of LVL).

3.4 Uncertainty

Several assumptions regarding the energy use during construction are applied in each case study when certain data is not available. This uncertainty would affect the result to some extent, although it was not estimated. However, every assumption is based on monthly data of the factory, data from similar production line, literature or interviewed information. Therefore, it is supposed that the associated error is not significant in this case.

4. Results and Discussion

4.1 Dominance analysis of the module A

Figure 1 shows GHG emission, from both fossil and biogenic fuel separately, for each phase in the module A of the three reference buildings. Although absolute value of the buildings differ each other significantly, similar trend can be seen. The module A1-3 accounts for 70-80% and the module A4-5 holds 20-30% of the total impact. In addition, the module A4 has relatively high share in the module A4-5, approximately 30% in the case of building A and more than 50% in the case of building B and C. It is remarkable that transportation of building components has higher impact than the actual construction work in the factory and on construction site in the two cases. This result originates in long transportation distance of some building components. For instance in the case of building B, Cross laminated timber (CLT), which is main building component, is delivered from Austria to Finland by ferry and truck. This would be exceptionally long transportation in an ordinary construction process. In the case of building C, there are also several components delivered from abroad. In the case of building A, most of components are delivered from Germany within 400km by truck.

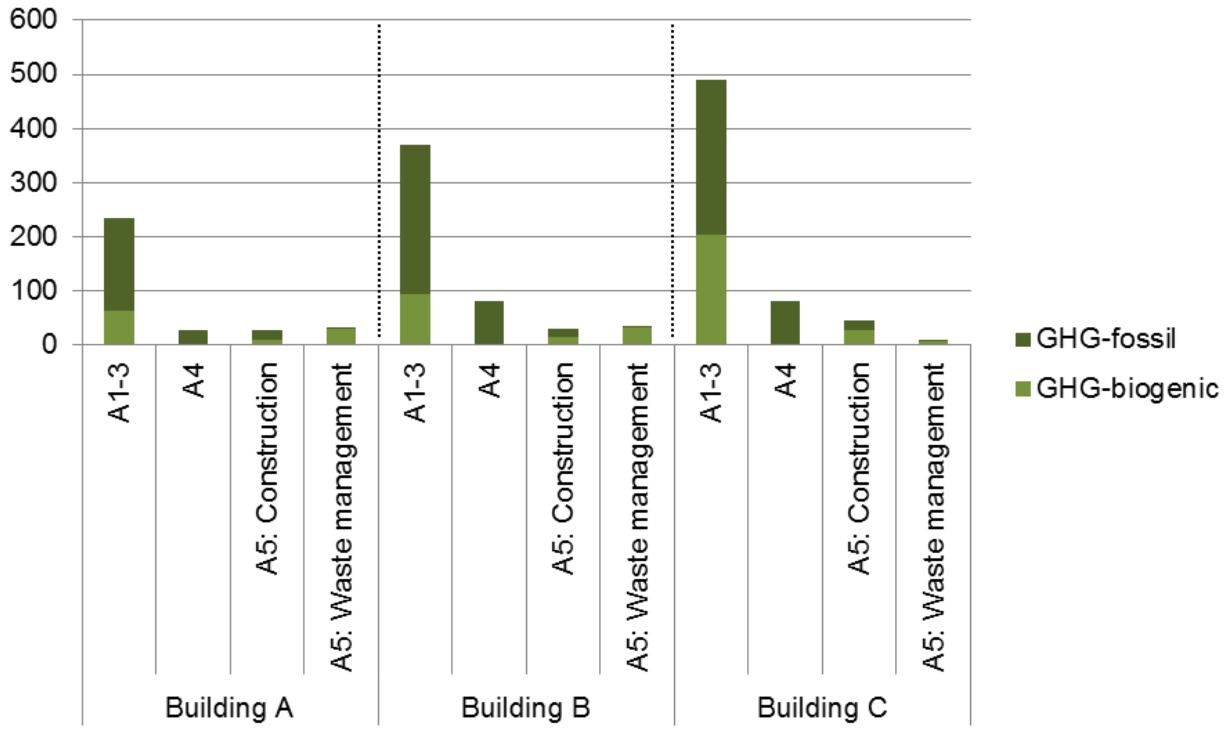

Fig. 1: GHG emission for the module A (kgCO_2-eq./m^2)

The module A5: prefabrication process and waste management also have relevant impact. However as shown in the figure, GHG emission from those phases consist of mainly biogenic GHG, which originates in a combustion of wood process residues. Therefore, the emission from the phases decreases significantly if biogenic CO_2 emission is regarded as zero based on the idea of carbon neutrality. This would be a main environmental feature of wood-based construction process. This result would also indicate the importance of the module A4.

4.2 Share of the construction stage

Figure 2 shows GHG emission for the module A and B6 of the three reference buildings. The module A1-3, A4-5 and B6 account for 16-35%, 6-10% and 55-78% of the total GHG emission, respectively.

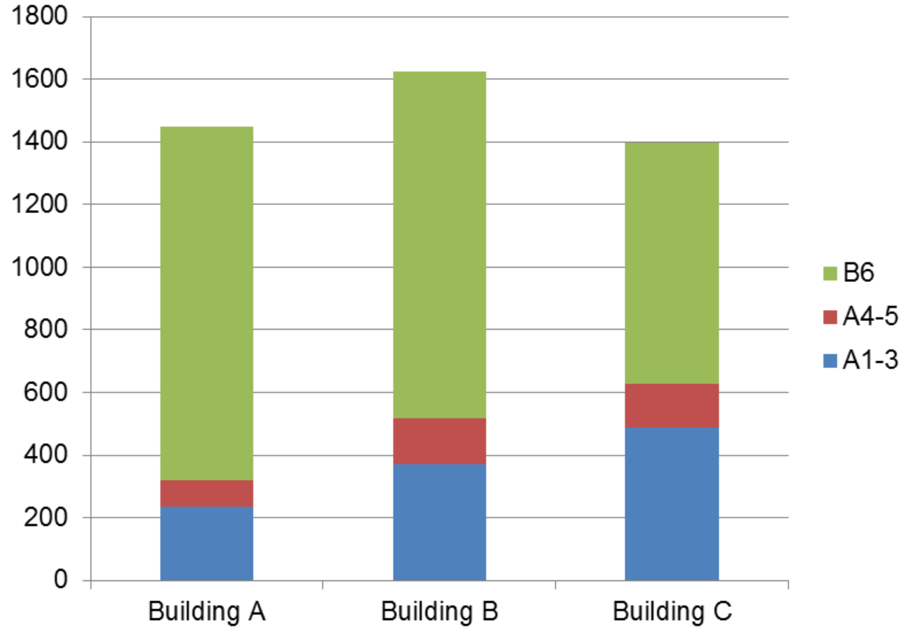

Fig. 2: GHG emission for the module A1-3, A4-5 and B6 (kgCO_2-eq./m^2)

The construction stage (A4-5) holds up to 10% of the total sorely. Naturally the share is increasing for the building with lower operational energy demand. This result will change when the other life cycle phases are included in the assessment to some extent. However, the ratio of the module A will also increase when the excluded construction materials and works (e.g. foundation and building services) are incorporated. Since the reference buildings are not high energy standard building, this result deserved to consider further.

Although the sample size is small, the module A4, transportation of building components and elements, seems to have higher priority to mitigate rather than actual construction work, the module A5, in the construction stage of wood-based building elements. Normally, loadage is optimized from economical reason. However, transportation distance is not always in proportion to a price of a product. Thus sometime it would happen to buy a product from far country due to cheaper price, although the same product could be available in a neighbouring city. From environmental aspect, it would be the worst case to order high impact products due to, for instance, inefficient manufacturing technology from far, because of a low price. Some products may be only available from specific location. But except such situation, it is good starting point to consider a balance of cost, environmental impact of product manufacturing and transportation distance and method when deciding construction material in order to mitigate the impact from the construction stage.

4.3 Data collection

It is experienced that data collection from transportation process and waste management is rather simple, while prefabrication process and on-site construction work is difficult to monitor. This difficulty seems to mainly originate in a situation of the industry, for instance rack of resources and time. In addition, data collection from on-site construction work may require special knowledge regarding construction work. In this context, proper planning of construction process is fundamental requirement in order to collect necessary information efficiently.

Since several projects or works happen at the same time in a factory and construction site, allocation of energy use is one critical issue. Monitoring of each process or production line with, for instance, electrical measuring instrument is relatively easy and accurate way. Recording of working hour for the process or project is also relevant in order to allocate aggregated information, such as monthly electricity and heating energy consumption in the factory.

5. Conclusion

GHG emission for the product, construction and use stage of the three reference wood-based buildings are assessed. Detailed data collection is conducted with the help of the constructors. Since every construction is unique, different data collection method are attempted in each case study according to the situation. The results show that the construction stage has relevant impact and especially transportation process is significant to mitigate GHG emission from the process.

Although an optimization of the construction phase may not have a significant effect on overall life cycle impact of a building, it would have a major impact at an industrial (aggregated) level. The environmental impact of the process should be known to enable to optimize it for constructors and designers. Further study is required in order to collect sufficient samples and pile up the experience in order to set a practicable and reliable assessment method for the construction stage.

6. Acknowledgement

This study was conducted in the European joint research project: €CO2- Wood in carbon efficient construction. Funding support from the CEI-Bois and Finnish Wood Research is gratefully acknowledged. The authors gratefully acknowledge the assistance of Huber&Sohn GmbHCo.KG, StoraEnso Oyj, Consorzio Stabile Arcale and Legnopiù.

7. References

[1] VERBEECK G, HENS H. *"Life cycle Optimization of extremely low energy buildings"*. Proceedings of Clima 2007 WellBeing Indoors. pp.8. 2007. Helsinki

[2] SCHEURER C, KEOLEIAN G.A., REPPE P. *"Life cycle energy and environmental performance of a new university building: modeling challenges and design implications".* Energy and Buildings 35 (2003), pp.1049–1064. Elsevier

[3] ADALBERTH K. *"Energy use in four multi-family buildings during their life cycle".* International Journal of Low Energy and Sustainable Buildings 2000 (2000), pp.1–22. Elsevier

[4] ADALBERTH K. *"Energy use during the life cycle of single-unit dwellings: Examples".* Building and Environment, 32(4), pp. 321–329. 1997. Elisevier

[5] COLE R.J. *"Energy and greenhouse gas emissions associated with the construction of alternative structural systems".* Building and Environment 34(3), pp. 335–348. 1996. Elisevier

[6] Cole R. J. (1998). Energy and greenhouse gas emissions associated with the construction of alternative structural systems, Building and Environment, 34(3), pp. 335–348.

[7] COLE R.J. and KERNAN P.C. *"Life-cycle energy use in office buildings"*, Building and Environment, 31(4), pp. 307–317. 1996. Elisevier

[8] KEOLEIAN G.A., BLANCHARD S, REPPE P. "Life-cycle energy, costs, and strategies for improving a single-family house". Journal of Industrial Ecology, 4(2), pp. 135–156. 2000. Yale University

[9] JUNNILA S, HORVATH A. *"Life-cycle environmental effects of an office building". Journal of Infrastructure System* 9-4, pp.157–166. 2003. American Society of Civil Engineering (ASCE)

[10] JUNNILA A, HORVATH A. GUGGEMOS A. *"Life-cycle assessment of office buildings in Europe and the United States".* Journal of Infrastructure System 12-1, pp.10–17. 2006. ASCE

[11] GUGGEMOS A, HORVATH A. *"Comparison of environmental effects of steel- and concrete-framed buildings". Journal of Infrastructure System* 11-2, pp.93–101. 2005. ASCE

[12] GUGGEMOS A, HORVATH A. *"Decision-Support Tool for Assessing the Environmental Effects of Constructing Commercial Buildings".* Journal of Architectural Engineering 12, pp.187-195. 2006. ASCE

[13] MORA F.P, AHN C, GOLPARVAR F.M., HAJIBABAI F. SHIFTEHFAR S, AN S. AZIZ Z. SONG A. *"A framework for managing emissions during construction"*. International Workshop on Green Buildings and Sustainable Construction. pp.13. 2009. National Science Foundation (NSF). Cairo

[14] AHN C. REKAPALLI P. MARTINEZ J. MORA F.P. *"Sustainability analysis of earthmoving operations".* Proceedings of the Winter Simulation Conference, pp.2605-2611. 2009. IEEE. Texas

[15] ORTIZ S, CASTELLS F, SONNEMANN G. *"Sustainability in the construction industry: A review of recent developments based on LCA"*. Construction Building Materials 23(1), pp. 28–39. 2009. Elisevier

[16] GANGOLELLS M, CASALS M, GASSO T, FORCADA N. *"A methodology for predicting the severity of environmental impacts related to the construction process of residential buildings"*. Building and Environment. 44(3), pp. 558–571. 2009. Elisevier

[17] BILEC M, RIES R, MATTHEWS H.S., Sharrard A.L. *"Example of a hybrid life-cycle assessment of construction processes"*. Journal of Infrastructure Systems. 12(4), pp. 207–215. 2006. ASCE

[18] GUGGEMOS A.A. and HORVATH A. *"Comparison of environmental effects of steel- and concrete-framed buildings"*. Journal of Infrastructure Systems. 11(2), p. 93. 2005. ASCE

[19] JUNNILA S and HORVATH A. *"Life-cycle environmental effects of an office building"*. Journal of Infrastructure Systems. 9(4), pp. 157-166. 2003. ASCE

[20] NISHIOKA Y, YANAGISAWA Y, SPENGLER J.D. *"Saving energy versus saving materials: Life-cycle inventory analysis of housing in a cold-climate region of Japan"*. Journal of industrial ecology. 4(1), pp. 119-135. 2000. Yale University

[21] KIM D. *"Preliminary life cycle analysis of modular and conventional housing in Benton Harbor, Michigan"*. Master's thesis, School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI, USA. 2008

[22] QUALE J, ECKELMAN M.J., WILLIAMS K.W., SLOADITSKIE G, ZIMMERMAN J.B. "*Comparing environmental impacts of building modular and conventional homes in the united states".* Journal of industrial ecology. 16(2), pp.243-253. 2012. Yale University

[23] EN15978: 2011, Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method

[24] PEURIFOY R, OBERLENDER G. *"Estimating Construction Costs 5th edition"*. McGraw-Hill Higher Education. 2002. Boston

[25] HOLM L, SCHAUFELBERGER J.E., GRIFFIN D, COLE T. *"Construction Cost Estimating: Process and Practice". Pearson Education Inc. 2005. New Jersey*

[26] POPESCU C.M., PHAOBUNJONG K, OVARARIN N. *"Estimating Building Costs".* Marcel Dekker Inc. 2005. New York

[27] BJÖRKLUND T and TILLMAN A.M. *"LCA of building Frame Structures: Environmental Impact over the life cycle of wooden and concrete frames"*. Technical Environmental Planning Report 1997:2. Chakmers University of Technology. 1997. Sweden

[28] ecoinvent Center. Swiss Center for Life Cycle Inventories http://www.ecoinvent.org/database/