
This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Pöyry, Amalia; Säynäjoki, Antti; Heinonen, Jukka; Junnonen, Juha-Matti; Junnila, Seppo
Embodied and Construction Phase Greenhouse Gas Emissions of a Low-energy Residential building

Published in:
Procedia Economics and Finance

DOI:
[10.1016/S2212-5671\(15\)00187-2](https://doi.org/10.1016/S2212-5671(15)00187-2)

Published: 01/01/2015

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Pöyry, A., Säynäjoki, A., Heinonen, J., Junnonen, J.-M., & Junnila, S. (2015). Embodied and Construction Phase Greenhouse Gas Emissions of a Low-energy Residential building. *Procedia Economics and Finance*, 21, 355-365. [https://doi.org/10.1016/S2212-5671\(15\)00187-2](https://doi.org/10.1016/S2212-5671(15)00187-2)

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.



8th Nordic Conference on Construction Economics and Organization

Embodied and construction phase greenhouse gas emissions of a low-energy residential building

Amalia Pöyry^a, Antti Säynäjoki^a, Jukka Heinonen^{c*}, Juha-Matti Junnonen^b and Seppo Junnila^a

^aAalto University, , 00076 Aalto, Finland

^bAalto University, , 00076 Aalto, Finland

^cUniversity of Iceland, 107 Reykjavík, Iceland

Abstract

Climate change is one of the biggest sustainability challenges of our time. In the context of the built environment, the emphasis is on increasing the energy efficiency of buildings, whereas other building life cycle phases are generally considered less important. However, in recent research it has been suggested that more attention should be given to construction phases, including emissions embodied in materials. They occur in early life cycle stages whereas a large share of use-phase related emissions occur outside the existing climate change mitigation target years, and, due to development in energy sector, might significantly deviate from what is projected today. In this study, by using the life cycle assessment (LCA), we assess the greenhouse gas emissions related to the materials and construction of a low-energy multi-storey residential building in Finland. We depict how the emissions are allocated to the different building systems and look for opportunities to reduce the emissions from this perspective. The novelty of the study arises from two factors: (1) we utilize the wide assessment scope that enables depicting the importance of the boundary decision and (2) not many construction-phase LCA studies of modern low-energy residential buildings exist.

© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Selection and/ peer-review under responsibility of Tampere University of Technology, Department of Civil Engineering

Keywords: Construction; embodied emission; greenhouse gas; life cycle assessment; life cycle inventory

1. Introduction

The effects of climate change for mankind and natural ecosystems are already apparent (IPCC, 2014). The total greenhouse gas (GHG) emissions caused by humans (anthropogenic) have increased from 1970 to 2010 with larger

* Corresponding author. Tel.: +354-823-0064. E-mail address: heinonen@hi.is

absolute increases between 2000 and 2010, despite the increasing number of climate change mitigation policies (IPCC, 2014). Climate change is also evaluated as one of the three planetary boundaries that we have overstepped and which can have disastrous consequences for humanity (Rockström et al., 2009).

Buildings are major contributors to climate change with a share of more than one third of global GHG emissions (UNEP, 2009). The emissions caused by buildings are spread over a long life span from material manufacture, the construction process, the use phase and maintenance to end of life. Recent literature suggests that the construction phase, including material manufacturing, transportation and construction site, even accounts a majority of the total GHG emissions of a building life cycle (Passer et al., 2012; Säynäjoki et al., 2012; Blengini & DiCarlo, 2010). In addition, this “carbon spike”, i.e. substantial construction phase GHG emissions, is caused within a very short time frame in the beginning of a building life cycle, which makes them more harmful considering the short and midterm climate change mitigation targets in comparison to the use phase emissions, which occur during the decades-long operational phase of a building (Säynäjoki et al., 2012). Additionally, the projected GHG emissions of the use phase contain significant uncertainties related to factors like future energy generation technology, and the actual emissions might deviate greatly from those projected now. This further highlights the relevance of the construction phase emissions, as they contain far less uncertainties compared to the operation phase emissions.

Life cycle assessment (LCA) is an established method for assessing the environmental performance of buildings (e.g. Treloar et al., 2000; Thormark, 2000; Junnila & Horvath, 2003). The two main LCA approaches are process LCA and input-output (IO) LCA. Process LCA is considered the most accurate LCA application due to the possibility of detailed analyses of specific processes (e.g. Bilec et al., 2006; Hendrickson et al., 2006). However, process LCA is highly work-intensive and since buildings include thousands of components, the assessments are unlikely to reach 100% coverage. Hybrid models combining process LCA and monetary based IO LCA can be utilized to expand the system boundary and reach higher assessment coverage.

GHG emissions of residential building construction have been relatively extensively studied in the past (e.g. Sartori & Hestnes, 2007). However, the extensiveness of the life cycle inventories (LCIs), i.e. the inventory of the components included in the assessment, varies significantly between the studies. Some studies include only the construction material manufacturing and transportation into the LCI, excluding phases like the construction site (Börjesson & Gustavsson, 2000; Zabalza Bribián et al., 2009). LCIs differ also in the sense of inclusion or exclusion of certain building components. Pasanen et al. (2011) excluded fixed furniture and household equipment from their LCI of a wood framed multi-story house. Zabalza Bribián et al. (2009) excluded fixed furniture and HVAC systems from their assessments of a single-family house in Spain. Although the extensiveness of an LCI has a definite impact on the results of a study, the absolute value is difficult to measure as the impacts of other differences in the LCA designs are almost impossible to separate from each other.

In this paper, we report on the conduct and results of a case study of the greenhouse gas (GHG) emissions of the pre-use stage of a low energy residential building in Finland, including the material manufacturing, the transportation and the construction processes. The main method utilised is the process LCA, complemented with the IO LCA to reach as high coverage as possible on the building components. The assessment is of attributional type as it describes the environmentally relevant flows to the studied system during the chosen temporal window and does not include any dynamics (Curran et al., 2002). Additionally, the assessment falls into the category of streamlined LCAs as it focuses solely on GHG emissions (Crawford, 2011). The LCI of the assessment includes basically the full inventory of the building components as well as the construction site.

The study extends the current LCA literature with a detailed building component assessment which depicts how several components, which are often left outside the assessment boundary, add significant amounts of emissions to the overall pre-use GHGs of a residential building. Additionally, a relevant issue for discussion is whether the current process LCA tools are capable of recognizing low impact materials and truly allow specific case analyses.

2. Method

2.1. Life cycle assessment

Life cycle assessment (LCA) is a methodology that evaluates all environmental loads of processes and products during their life cycle from raw material extraction to processing, manufacturing, use and maintenance and disposal or recycling (Klöpffer, 1997; Crawford, 2011). The usage of LCA as an environmental management tool had its beginning in the 1960s and 1970s (Hunt & Franklin, 1996, p.4). In the building sector, LCA has been utilized mostly since the 1990s (Fava, 2006), and the interest in LCA has been growing fast during the 2000s (Buyle et al., 2013). Today the main standard guiding LCA practice is the International Organization for Standards series ISO 14040:2006.

Process analysis and input-output (IO) are the primary LCA approaches (Sharma et al., 2011; Hendrickson, 2006). Hybrid LCA aims to combine these two in a way which reduces the weaknesses related to them (e.g. Suh et al., 2004). In this study the primary method applied was the process LCA, which is supplemented with the IO assessment for certain building parts to create a simple hybrid model. Below, all the three LCA options are described briefly.

2.1.1. Process LCA

The most common method used for LCAs is process LCA (Suh et al., 2004). It has also been stated that due to the complexity of the construction industry the best understanding of environmental implications would be achieved by process LCA (Sharrard et al., 2008). The objective of a process LCA is to evaluate the environmental impacts of each process related to a product's life cycle using a process flow diagram and including all relevant processes into the modeling (Bilec et al., 2010). In a process-based analysis a combination of process, product and location-specific data is used to calculate the environmental impacts of a product (Crawford, 2011). Thus, process-based LCA approach results in detailed process-specific analyses, detailed product comparisons and high-precision model outcomes (Chang et al., 2011; Lenzen & Treloar, 2006).

Process LCA carries certain inherent problems as well. The collection of process data is time consuming and the research process is highly data intensive. Moreover, process LCAs suffer from a systematic truncation error, since certain upstream activities related to the studied system are always left outside of the system boundaries (e.g. Suh et al., 2004). According to Lenzen and Treloar (2002), this truncation error can reduce the system completeness to 50%. Even relatively wide process LCAs do not reach reasonable system completeness, thus leading to underestimations. Process LCAs are also subject to data uncertainty problems related to both input and output data.

2.1.2. Input-Output LCA

IO LCA uses environmentally extended economic transaction matrixes (i.e. IO tables) to assess environmental impacts (Leontief, 1970). The IO transaction tables describe the purchase flows between economic sectors and the value added by each sector, thus enabling allocation of the environmental output of each sector to the studied system according to monetary values. If the IO tables with environmental data are available, IO analysis is relatively quick to conduct and reaches system completeness that is impossible to achieve with process LCA (e.g. Suh et al., 2004). Furthermore, the monetary data often exists.

However, IO LCAs suffer from several problems as well. In all IO models the number of sectors is significantly smaller than actually exists, meaning that each sector in a model actually represents a weighted average of several sectors (e.g. Suh et al., 2004). The result is aggregation error, meaning that the emissions intensity of a certain sector in an IO model can either underestimate or overestimate the actual emissions depending on how well the sector combination complies with the actual sector in the assessment. Homogeneity error arises from an inherent assumption in IO LCAs that the national average environmental intensities would be valid for all products manufactured by a certain sector (Crawford, 2011). Furthermore, the so-called linearity assumption of IO LCAs means that environmental impacts are assumed as linearly positively correlated with costs (Crawford, 2011), which can on occasion be far from the truth.

2.1.3. Hybrid analysis

Hybrid LCA is a method aiming to combine the best qualities of the two approaches (Suh et al., 2004; Bilec et al., 2006). Crawford (2011) regards it as the best method in the case of a complex system. Regarding the construction industry, hybrid LCAs are suggested to result in more complete and accurate assessments (Bilec et al., 2006; Guggemos & Horvath, 2005). Hybrid LCAs can also be used if process data or resources are unavailable (Suh et al., 2004).

3. Case: Pyry in the Härmälänranta residential area

The building chosen for the study is a new low-energy building in Finland, called Pyry, and located in a former industrial neighborhood of Härmälänranta in Tampere, Finland (Skanska, 2011). Härmälänranta aims to be a sustainable residential area close to the Tampere city centre. The buildings in the Härmälänranta area utilise energy efficient solutions. In addition, the shapes and orientations are designed to improve the low energy usage. The residential development will be completed in two phases. The first phase, including Pyry, was started in 2007 and the second phase will be completed in 2014-2026 (Skanska, 2012).

3.1. General qualities of the case building Pyry

The case building Pyry consists of 28 apartments, a gross floor area of 3,085 sqm, a heated net area of 2,081 sqm and a volume of 9,645 m³. The estimated energy requirements for Pyry are 80 kWh/sqm/a for heating and hot water and 14 kWh/sqm/a for communal building electricity, thus representing the best current energy class A (excluding household electricity) (Skanska, 2011; Ristimäki et al., 2013). The construction of Pyry was completed in December 2012. The characteristics of Pyry are depicted in Table 1, and it is illustrated in Fig. 1.

Table 1. Characteristics of the case building.

	Value	Unit
Gross floor area	3,085	m ²
Volume	9,645	m ³
Construction year	2012	year
Apartments	28	number
Heated living space	2,081	m ²
Frame	concrete	-



Fig. 1. Pyry located in Tampere.

M1 emission class (Building Information Group, 2014) materials were used for Pyry. In addition, all the waste produced during the construction phase was recycled and utilized either as material or energy (Skanska, 2011). Below, the main building components are presented in eight key categories.

Foundation: The category encompasses reinforced concrete site structures as well as polyvinyl chloride (PVC) underdrains, rainwater wells and pipes.

Buildings Structure: The foundation walls and the bearing ground floor are reinforced concrete “sandwich walls”. The insulation material used is polystyrene (EPS). Footings of the building are concrete and the bomb shelter structure is reinforced concrete with polystyrene insulation. The exterior structure includes a gravel and filter fabric tank for rainwater runoff.

Building Frame and Roofing: Building frame and roofing consists of reinforced concrete exterior wall, bearing partitioning walls, hollow core slabs, attic floor, roof and exterior structure, i.e. structure of entrance, terrace and balconies. The exterior walls are predominantly reinforced concrete with polyurethane and mineral wool insulation.

Wooden exterior walls contain gypsum plasterboard, plywood, sawn timber and polystyrene. The bearing partitioning walls are reinforced concrete and with mineral wool insulation. Intermediate floors and attic floor are of hollow-core slabs. The six stairwells are mosaic concrete. In addition, all the 28 apartments have separate glazed balconies with concrete structures.

Complementary Structures: Complementary structures encompass windows, doors, partitioning walls, flues and stair handrails. Lightweight partitioning walls are brick, except for sauna and wet rooms that are steel, as well as for storage space in the basement. The storage spaces are of wooden frames with wire netting. Wall coverings include ceramic tiles, for example in kitchens and bathrooms. All the windows are triple glazed with wood-aluminium frames and insulation gas. Three outer doors are double glazed doors with aluminium frames and one is wood aluminium. Indoors there are 18 steel doors with rock wool insulation and heatproof enamel. Wooden indoor doors include 28 front doors, 42 bathroom doors, 28 glazed doors for saunas, 71 communicating doors and 4 sliding doors.

Surface Structure: The surface structure includes internal walls, roof, ceilings, floor coverings, sauna structures and overall paintwork. The roofing consists of bitumen-felt covering, steel wells, polyvinyl chloride under pressure ventilators, steel drainpipes and gutters. Ceiling coverings are gypsum, metal, plywood and mineral wool. The materials for floor coverings include cement mortar, ceramic tiles, moisture insulation and parquet flooring. The parquet floor has cement mortar screed and expanded plastic mat underneath. Floor coverings also include acoustic insulating plastic carpets on the entrance and corridors. Sauna coverings consist of wooden walls with polyurethane insulation and ceilings with polyurethane and mineral wool insulation.

Furnishing: Immovable furniture, equipment in balconies, bathrooms, entrance and bomb shelter, and home appliances comprise the furnishing category. Furniture includes chipboard shelves and cupboards, sinks, water taps, mirrors, toilet seats and benches in saunas. Home appliances consist of stoves, ovens, freezers, refrigerators, dishwashers, sauna stoves and dry blowers. Drying racks, hooks, glazed shower walls and rails are also included in furnishings. In addition, the name boards, polyvinyl chloride carpet in the vestibules and mirrors appear here.

Construction Site: Construction site includes diesel for transportation and construction equipment and on-site water, energy and liquefied petroleum gas usage. Transportation includes building material cargo from the final supplier to the construction site.

HVAC and Electrical Systems: The category includes HVAC, electrical, plumbing and lightning systems.

4. Research process

A streamlined LCA was conducted to study the pre-use GHG impacts caused by Pyry. The indicator used is GWP₁₀₀ measured in kilograms of carbon dioxide equivalents per gross square meter (kg CO₂-eq/m²). SimaPro software and the ecoinvent v.2.0 database that covers over 4,000 processes (PRé Consultants 2010) was utilized in the assessment. The developing company provided budgeted cost and volume data of the materials, drawings and estimations of required work. The received data specified costs and either volume, area, number or running meters of nearly 600 different items, of which approximately 500 were included in the assessment. The emissions caused by transportation and activities at the construction site are also considered. Site clearing, excavation and construction of the outdoor area including roads, grass fields as well as outdoor building equipment (e.g. a sandbox and a flagpole) were not taken into account. The use and demolition of different construction molds were left out as well. All else was included in the process assessment, but the HVAC and electrical systems and household appliances were assessed with IO LCA. For the IO part, the U.S. industry based EIO-LCA (CMU) was utilized due to its integration with SimaPro.

To take into account the currency rate fluctuations and inflation between the present Finnish economy and the US industry 2002 model, a purchasing power parity (PPP) multiplier was used. Similar correction has been applied by Weber et al. (2008) and Säynäjoki et al. (2012). According to the OECD (2014) the PPP factor for 2012 is 0.93.

The material requirements for several items within the case building were established using volume estimates of the components (e.g. walls, ceilings, doors) in combination with estimates for the material composition of these components (e.g. of concrete or reinforced concrete) and for the material densities. The assumed densities are listed in Table 2. In addition, the masses of window frames and doors were calculated based on the assumption given by

ecoinvent. Throughout the inventory phase, architectural and technical drawings as well as components graphs and other data provided on the case building were utilized to amend the volume assessments. The amounts of some materials (e.g. paints) were estimated due to data shortcomings.

Table 2. Utilised material density factors.

Material	Density (kg/m ³)
Aluminium	2,700
Brass	7,800
Cement	3,150
Chipboard	630
Chromium steel	7,850
Concrete	2,380
Crushed stone	1,400
Gravel	270
Lightweight concrete	1,400
Mineral wool	40
Paint	1,000
Parquet	620
Plywood	620
Polystyrene	30
Polyurethane	40
Polyvinylchloride	1,410
Propylene	902
Sand	2,000
Sawn timber	450
Synthetic rubber	1,500
Window glass	2,500

5. Results

According to the assessment, the total construction phase GHG emissions of the case building are approximately 1,450 t CO₂-eq, or 470 kg CO₂-eq/m². Building frame and roofing constitute the largest category with a share of slightly over 40%, 590 tons. Interestingly, the second largest contributors were HVAC & the electrical systems which are often left outside of the assessment boundary. They were assessed at adding 270 t CO₂-eq to the overall GHGs, a share of nearly 20%. Without these emissions the per square meter emissions would drop to 390 kg CO₂-eq. The three categories with shares of approximately 10% are Building structure with 120 t CO₂-eq, Complementary structures with 130 t CO₂-eq and Construction site with 140 t CO₂e. The importance of the Construction site category is elevated due to the transportation of the construction materials being included in the category. These transportations were assessed to cause approximately 25 tons of the overall emissions. Another category often left outside of the assessment boundary are furnishings, which in the study seem to have relatively high importance since they add nearly 120 t CO₂-eq to the overall emissions, thus just below the share of Building structure. The total emissions categorized by the building component categories are depicted in Fig. 2.

The most significant individual components are hollow core slabs and beams and exterior walls with respective shares of 14% and 12%. Exterior structure accounts for 8% and windows and doors for 6%, but all other individual components for less than 4% of the overall load. The distribution of the GHGs from different sub-categories is presented in Table 3.

Table 3 GHG distribution of Pyry (kg CO₂e)

TOTAL	1,676,410
1. FOUNDATION	34,400
Base structure	31,600
Underdrains and pipeages	2,800
2. BUILDING STRUCTURE	124,300
Footings	23,000
Foundation walls and columns	1,500
Bearing ground floor	45,800
Bomb shelter structure	44,100
Special structure	3,300
Exterior structure	6,700
3. BUILDING FRAME AND ROOFING	591,300
Partitioning walls and pillars	74,200
Hollowcore slabs and beams	209,300
Stairs	2,000
Exterior walls	175,900
Exterior structure	119,200
Attic floor and roof	10,600
4. COMPLEMENTARY STRUCTURES	125,900
Windows and doors	88,600
Lightweight partition walls	16,700
Railings and ladders	5,400
Flues	15,300
5. SURFACE STRUCTURE	42,600
Roofing	3,700
Interior walls	9,300
Ceilings	6,600
Floor coverings	11,000
Saunas	8,300
Paintwork	3,800
6. FURNISHING	117,600
Kitchens	11,800
Hallways and walk-in closets	24,600
Bathrooms	8,100
Equipment	4,800
Household appliances	68,300
7. CONSTRUCTION SITE	136,900
On-site fuel use	6,100
On-site electricity use	76,000
On-site liquefied petroleum gas	4,300
District heating	24,600
Transportation	25,900
8. HVAC & ELECTRICITY SYSTEM	275,100
Heating	44,100
Plumbing	37,600
Automazation	27,400
Ventilation	102,800
Electricity	63,300

In Pyry, polyurethane is utilized as the main insulation material due to its high thermal resistance, air tightness strength and adhesion. In standard apartment buildings mineral wool is the most common insulation material. Interestingly the impact of this material selection is almost negligible according to the study. Whereas polyurethane causes higher emissions than mineral wool, it allows thinner walls and thus reduces other material requirements which compensate for the emissions. In the assessment polyurethane utilization was assumed to reduce the wall thickness by 100 millimeters and the density of mineral wool was assumed to be 40 kg/m³.

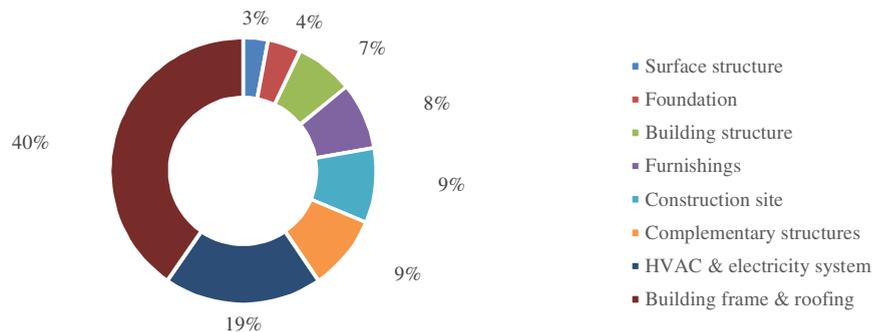


Fig 2 Embodied and construction phase GHG emissions of Pyry.

6. Discussion

The purpose of the study was to estimate the GHG emissions caused by the construction of a low-energy building in Finland. The total GHG emissions of the construction project were assessed at approximately 1,450 t CO₂-eq, which equals 470 kg/m². In terms of building systems, the most significant contributor to the emissions was found to be the building frame and the roofing with a share of 40%, while the HVAC and electrical system have a share of almost 20%, and complementary structures and construction site also noteworthy shares close to 10%. Furthermore, furnishings, which are often left outside assessments, were also found to add a share of close to 10%. Although the construction materials were categorized according to the building components rather than the main materials, the concrete dominates the building frame and the roofing as well as the foundations and the exterior structure and thus is the most significant single material causing GHG emissions.

In addition to the inherent process LCA uncertainties and weaknesses, such as the truncation error, the study contains two main sources of uncertainty. First, many of the material quantity assessments are based on assumed densities and volumes assessed from pictures. There is thus error potential. Secondly, the employed ecoinvent database is not really specific to the actually utilized materials but presents studies from elsewhere with potentially different production chains and thus the resulting emissions. This source of uncertainty is important, but it is impossible to assess how much and to which direction it pushes the results without further research.

Regarding the previous process LCA literature, the GHG intensity found in this study places it above the average, but still well below the highest end. The extensive inclusion of building components in the LCI largely explains the difference to many previous studies, but still significantly higher results have been reported. Of these, Passer et al. (2012) presented case studies reaching a level of 0.5-0.8 t CO₂-eq/m², and Blengini & DiCarlo (2010), who studied two different building designs with process LCA, reported intensities of 0.6-0.8 t CO₂-eq/m². On the other hand, several studies have resulted in intensities from 0.2 to 0.3 t CO₂-eq/m² (e.g. Saari 2001, Zabalza Bribián et al. 2009). The exact reasons are challenging to define, as the LCAs are unique in numerous aspects, but the extensiveness of the LCI seems to be one of the key issues. The study of Passer et al. (2012) of five residential buildings included 1700 construction items into the before-use stage LCI, which is clearly one of the main reasons explaining the high

results. The studies having ended up with significantly lower intensities have also predominantly narrower scopes, omitting materials and systems that sum up to important amounts of GHGs, as the study depicts.

Of the assessments with IO LCA basis, Ristimäki et al. (2013) have presented an IO based hybrid LCA assessment of the construction phase GHGs of the same Härmälänranta area. The area consists of seven similar buildings along with the area infrastructure so the results of a single building can be compared to Pyry. Ristimäki et al. (2013) utilize the Finnish IO-LCA application ENVIMAT and the local energy production intensities for the area. According to their assessment the construction phase emissions would be 1100 kg CO₂e/m². This indicates a rather significant truncation error existing in our study since the scope of the LCI is close to that of Ristimäki et al. (2013), although the latter suffers from the inherent problems of IO LCAs and there are uncertainties in this study as well; thus the conclusion is only indicative.

Process and IO LCA comparisons have been discussed in the literature (e.g. Junnila, 2006; Lenzen, 2000; Lenzen & Treloar, 2002). The truncation error of process LCA is a widely recognized reason for the assessments to underestimate, but the absolute magnitude of the error in a specific assessment is challenging to determine. In his study, Lenzen (2000) estimated the truncation error between the process and IO models to be of a factor of two. However, this is always case-specific due to the individual characteristics of each LCA model. Further comparison of a hybrid LCA model of Ristimäki et al. (2013) and the process LCA model of this study in order to investigate the sources and magnitude of the truncation error of the LCA model is suggested for future research.

Besides low energy design, which reduces the need for operating energy, the developing company also concentrated on reducing the environmental effects in the construction phase. Sustainable choices were preferred in selection of building materials in the sense of emission classes and produced waste. However, sustainable material choices were not recognized in the modeling, as they are not yet present in the ecoinvent database. This should be taken into consideration when developing the LCA databases and software in the future.

Finally, the single case setting of the study does not allow wide generalisations. Pyry is a good reference for today's multi-storey residential construction in Finland and the eco-invent data makes the study more general than a case study might be, but still the results are based on just one piece of evidence and deeper analyses require more data. A single case study approach was selected for the study due to the work-intensive nature of the process LCAs.

7. Conclusion

The study suggests that low-energy design does not significantly increase the pre-use GHGs. However, the GHGs caused in the pre-use phase are still relatively high compared to the annual use-phase emissions, meaning that the overall cumulative emissions remain higher than those from the existing less efficient building stock for a long period, complying with the "carbon spike" theory suggested by Säynäjoki et al. (2012). Concrete is the material causing the largest share of the emissions, the cement production being the actual main source. Thus, several developed or studied green cement variations seem highly potential alternatives. According to Imbabi et al. (2012), green cement options reducing the GHGs by up to 95% exist and "negative impact" (absorbing more than production emits) qualities are being currently developed. The cutting of the emissions from concrete would reduce the overall embodied emissions by tens of percentages in our case. Timber construction is another potential option, which is suggested to lead to similar reductions in magnitude (Robertson et al., 2012). Notwithstanding, our study also suggests that the systems often left outside pre-use phase LCAs contribute rather significantly to the overall GHGs. Thus, the concentration on the main materials is not enough to get a comprehensive view of the overall emissions. Although other systems and construction items provide the highest mitigation potential, such systems and items should also be considered when true low-impact buildings are designed in the future.

Acknowledgements

The authors thank the Academy of Finland (Grant No. 268099) and the Innovative City® Partnership Programme.

References

- AFNOR Normalisation, 2012. CEN/TC 350 Sustainability of Construction Works. Available at [Http://Portailgroupe.Afnor.Fr/Public_Espacenormalisation/CENTC350/Index.Html](http://Portailgroupe.Afnor.Fr/Public_Espacenormalisation/CENTC350/Index.Html) (Accessed On 4 January 2015).
- Bilec, M. M., Ries, R., Matthews, H. S., Sharrard, A. L., 2006. Example of a Hybrid Life-Cycle Assessment of Construction Processes. *Journal of Infrastructure Systems* 12, 207–15.
- Bilec, M. M.; Ries, R.J. & Matthews, H. S., 2010. Life-Cycle Assessment Modelling of Construction Processes. *Journal of Infrastructure Systems* 16(3), 199–205
- Blengini, G. A., Di Carlo, T., (2010): Energy-Saving Policies and Low-Energy Residential Buildings: An LCA Case Study to Support Decision Makers in Piedmont (Italy). *International Journal of Life Cycle Assessment* 15, 652–665.
- Byule, M., Braet, J., Audenaert, A., (2013). Life Cycle Assessment in The Construction Sector: A Review. *Renewable and Sustainable Energy Reviews* 26, 379–388. Available at [Http://Dx.Doi.Org/10.1016/J.Rser.2013.05.001](http://Dx.Doi.Org/10.1016/J.Rser.2013.05.001) (Accessed on 4 January 2015).
- Börjesson, P., Gustavsson, L., 2000. Greenhouse Gas Balances in Building Construction: Wood versus Concrete from Life-Cycle and Forest Land-Use Perspectives. *Energy Policy* 28, 575–588.
- Carnegie Mellon University Green Design Institute, 2008. Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 Industry Benchmark Model. Available at www.eiolca.net (Accessed on 4 January 2015).
- Chang, Y., Ries, R. J., Wang, Y., 2011. The Quantification of the Embodied Impacts of Construction Projects on Energy, Environment, and Society Based On I-O LCA. *Energy Policy* 39(10), 6321–6330
- Crawford, R. H., 2011. *Life Cycle Assessment in The Built Environment*. Spon Press, London.
- Curran, M.A., Mann, M., Norris, G., 2001. Report on the International Workshop on Electricity Data for Life Cycle Inventories, US Environmental Protection Agency, Cincinnati.
- Fava, J.A., 2006. Special Issue Honouring Helias A. Udo De Haes. Columns: 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, 6–8.
- Guggemos, A. A., Horvath, A., 2005. Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings. *Journal of Infrastructure Systems* 11(2), 93–101.
- Hendrickson, C. T., Lave, L. B., Matthews, H. S., 2006. *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach*, Resources for The Future Press.
- Hunt, R. G., Franklin, W. E., 1996. LCA History LCA - How It Came About - Personal Reflections on the Origin and the Development of LCA in The USA. *International Journal Of Life Cycle Assessment* 1(1), 4–7.
- Imbabi, M., Carrigan, C., Mckenna, S., 2012. Trends and Developments in Green Cement and Concrete Technology. *International Journal of Sustainable Built Environment* 1, 194–216.
- IPCC, 2014. *Climate Change 2014. Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY.
- ISO International Standards Organization, 2006. *ISO 14040 Environmental Management Life Cycle Assessment Principles and Framework*. ISO, Brussels, Belgium.
- Junnila, S., Horvath, A., 2003. Life-Cycle Environmental Effects of an Office Building, *Journal of Infrastructure Systems* 9 (4), 157–166.
- Junnila, S., Horvath, A., Guggemos, A. A., 2006. Life-Cycle Assessment of Office Buildings in Europe and the United States. *Journal of Infrastructure Systems* 12 (1), 10–17.
- Klöppfer, W., 1997. Life Cycle Assessment: From the Beginning to the Current State. *Environmental Science and Pollution Res.* 4(4), 223–228.
- Lenzen, M., 2000. Errors in Conventional and Input-Output–Based Life-Cycle Inventories. *Journal of Industrial Ecology* 4(4), 127–148.
- Lenzen, M., Treloar, G., 2002. Embodied Energy in Buildings: Wood versus Concrete. *Energy Policy* 30, 249–255.
- Leontief, W., 1970. Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics* 52(3), 262–271.
- Pasanen, P., Korteniemi, J., Sipari, A., 2011. Carbon Footprint Study for a Passive House Type Wooden-Framed Apartment Building (Passiivitalon Asuinkerrostalon Elinkaaren Hiilijalanjälki). *Sitran Selvityksiä*. Sitra, Helsinki. pp. 1–37.
- Passer, A., Kreiner, H., Maydl, P., 2012. Assessment of the Environmental Performance of Buildings: A Critical Evaluation of the Influence of Technical Building Equipment on Residential Buildings. *International Journal of Life Cycle Assessment* 17, 1116–1130.
- Pré Consultants, 2010. Introduction Into LCA With Simapro 7, Available at [Http://www.pre-sustainability.com/download/manuals/simapro7/introductiontolca.pdf](http://www.pre-sustainability.com/download/manuals/simapro7/introductiontolca.pdf) (Accessed on 4 January 2015).
- Ristimäki, M., Säynäjoki, A., Heinonen, J., Junnila, S., 2013. Combining Life Cycle Costing and Life Cycle Assessment for an Analysis of a New Residential District Energy System Design. *Energy* 63, 168–179.
- Robertson, A., Lam, F., Cole, R., 2012. A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete. *Buildings* 2, 245–270.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, S., Lambin, E., et al., 2009. A Safe Operating Space for Humanity. *Nature* 461(24), 472–475.
- Saari, A., 2001. *Environmental Information of Buildings and Building Components*. Buildings Information Foundation RTS, Helsinki.
- Sartori, I., Hestnes, A., 2007. Energy Use in the Life Cycle of Conventional and Lowenergy Buildings: A Review Article. *Energy and Buildings* 39, 249–257.

- Sharma, A., et al., 2011. Life Cycle Assessment of Buildings: A Review. *Renewable and Sustainable Energy Reviews* 15(1), 871–875.
- Sharrard, A. L., Matthews, S. H., Ries, R. J., 2008. Estimating Construction Project Environmental Effects Using an Input-Output-Based Hybrid Life-Cycle Assessment Model. *Journal of Infrastructure Systems* 14(4), 327-336.
- Skanska, 2011. Hyvän Olon Järvenrantakoti Härmälänrannan Pyry , Viima ja Tuisku Tampere. Available at http://skanska.smartpage.fi/fi/esitteet/pyry-viima-tuisku/files/skanska_pyry_viima_tuisku.pdf (Accessed on 4 January 2015).
- Skanska, 2012. Härmälänranta, Finland. Available at <http://skanska-sustainability-case-studies.com/case-studies/harmalanranta-finland/project-introduction> (Accessed on 4 January 2015).
- Suh, S., et al., 2004. System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Environmental Science & Technology* 38(3), 657–664.
- Säynäjoki, A., Heinonen J., Junnila, S., 2012. A Scenario Analysis of the Life Cycle Greenhouse Gas Emissions of a New Residential Area. *Environmental Research Letters* 7(3).
- 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), 429–435.
- Treloar, G. J., Love, P. E. D., Faniran, O. O., Iyer-Raniga, U., 2000. A Hybrid Life Cycle Assessment Method for Construction, *Construction Management and Economics* 18, 5–9.
- UNEP, 2009. Buildings and Climate Change – Summary for Decision Makers. United Nations Environment Programme. Available at www.unep.org/sbci/pdfs/sbci-bccsummary.pdf (Accessed on 4 January 2015).
- Zabalza Bribián I., Aranda Usón, A., 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, 2510–2520.