Department of Forest Products Technology

Wood in sustainable construction - a material perspective

Learning from vernacular architecture

Atsushi Takano

Aalto University

DOCTORAL
DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 97/2015

Wood in sustainable construction - a material perspective

Learning from vernacular architecture

Atsushi Takano

Doctoral dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the School of Chemical Technology for public examination and debate in Auditorium (Forest Products Building 2) at the Aalto University School of Chemical Technology (Espoo, Finland) on the 4th of September, 2015, at 14 o'clock.

Aalto University
School of Chemical Technology
Department of Forest Products Technology
Wood Material Technology / Wood Architecture

Supervising professor
Professor Mark Hughes, Aalto University, Finland

Thesis advisor
Professor Stefan Winter, Technical University of Munich, Germany

Preliminary examiners
Assistant Professor York Ostermeyer, Chalmers University of Technology, Sweden
Associate Professor Catarina Thormark, Malmö University, Sweden
Dr. Bastian Wittstock, thinkstep AG, Senior Consultant, Germany

Opponent
Professor Holger Wallbaum, Chalmers University of Technology, Sweden

Aalto University publication series
DOCTORAL DISSERTATIONS 97/2015

ISBN 978-952-60-6293-8 (printed)
ISBN 978-952-60-6294-5 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-6294-5

Unigrafia Oy
Helsinki 2015

Finland

Publication orders (printed book):
The dissertation can be read at: http://aaltodoc.aalto.fi/

441 697
Printed matter

Aalto University

Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Author
Atsushi Takano

Name of the doctoral dissertation
Wood in sustainable construction - a material perspective
Learning from vernacular architecture

Publisher School of Chemical Technology

Unit Department of Forest Products Technology

Series Aalto University publication series DOCTORAL DISSERTATIONS 97/2015

Field of research Wood Material Technology / Wood Architecture

Manuscript submitted 1 April 2015 **Date of the defence** 4 September 2015

Permission to publish granted (date) 23 June 2015 **Language** English

☐ **Monograph** ☒ **Article dissertation (summary + original articles)**

Abstract

Traditionally, vernacular buildings were constructed based upon a deep understanding of the surroundings and the features of locally sourced materials. This wisdom led to a rational building composition and appropriate material selection, which ensured adequate living conditions and proper building life cycle, without any advanced technologies. In the discussion about reducing the environmental impacts of a building, there should be useful ideas to be taken from traditional solutions for the further development of modern buildings.

A life cycle perspective is nowadays becoming more significant for comprehensive building analysis as the distribution of the environmental impacts over a building life cycle change. In such a context, building material selection is an important factor. Wood products have lately attracted attention as promising construction materials due to their unique environmental properties. This study investigated the optimal use and development of wood products in sustainable construction in comparison to other building materials, based on life cycle assessment method. With regard to learning from vernacular buildings, a holistic analysis of wood in construction was carried out.

In this dissertation, first the methodological issues relating to the fair assessment of wood products and wood construction based on the current normative standards and assessment data were discussed. Secondly, wood in sustainable construction was discussed according to ten principles in terms of appropriate building material selection over the building life cycle.

This study demonstrated that there are both strengths and weakness to the use of wood in sustainable construction. In this sense, the importance of diverse perspectives to building materials has been highlighted. It was also discussed that wood may contribute to the environment more positively when it is used more. A reduction in consumption (e.g. energy) and emissions (e.g. CO_2) has thus far been the principle behind mitigating environmental impacts. In this context, for instance, a CLT (Cross laminated timber) framed building would not be preferable since it requires a large amount of wood, resulting in high embodied energy. However, on the other hand, that gives significant environmental benefits (e.g. energy recovery) to the building. In this case, by optimising the weaknesses (high embodied energy) and maximising the strengths (environmental benefits), the greater use of wood may improve the environmental profile of a building. This would be a paradigm shift from the current approach to the environmental problems. In that sense, wood seems to have significant potential. It would be important to consider a specific approach and use for wood in construction based upon the proper understanding of their characteristics as practiced in traditional buildings.

Keywords Life cycle asessment,Wood, Sustainability, Vernacular architecture

ISBN (printed) 978-952-60-6293-8 **ISBN (pdf)** 978-952-60-6294-5

ISSN-L 1799-4934 **ISSN (printed)** 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2015

Pages 138 **urn** http://urn.fi/URN:ISBN:978-952-60-6294-5

Acknowledgements

The research works consisting of this thesis were mainly carried out in the Department of Forest Products Technology and the Department of Architecture at Aalto University during 2012-2015. Short-term field surveys were also accomplished in Finland, Germany in cooperation with the researchers at Technical University of Munich (TUM) and Japan in 2012-2013. The financial support of Aalto University (Aalto Energy Efficiency Research Program), the Kone Foundation, the Finnish Funding Agency for Innovation, Finnish Wood Research Oy, the Walter Ahlström Foundation, Scandinavia-Japan Sasakawa Foundation, Puumiesten ammattikasvatussäätiö and the Doctoral Program in the Built Environment (RYM-TO) is gratefully acknowledged. In addition, I gratefully acknowledge the assistance of Huber&Sohn GmbH Co. KG and StoraEnso Oyj for the research data.

I would like to express my profound gratitude to my supervisor, Prof. Mark Hughes, and to my instructor, Prof. Stefan Winter, for their guidance and encouragement in this research. Prof. Hughes and Prof. Winter have always provided indispensable support.

Besides the official instructors, I warmly would like to thank Prof. Pekka Heikkinen for his guidance in the supplemental field of this study. He has always reminded me a practical perspective toward wood architecture. I would also like to express my cordial thanks to Mr. Matti Kuittinen for his significant support and advice all the time.

I would like to thank all my co-authors (except mentioned above); Mr. Lauri Linkosalmi, Mr. Sudip Kumar Pal and Dr. Kari Alanne (Aalto), Prof. Annette Hafner (Ruhr University), Mr. Stephan Ott (TUM), Dr. Francesco Pittau and Prof. Enrico De Angelis (Politecnico di Milano), for their productive cooperation and fruitful contribution. I would also like to thank the doctoral program planning officer Lic. Sirje Liukko and special thanks are due to all current and former teachers and colleagues at the Department of Forest Products Technology and the Department of Architecture. I have been very fortunate to have their support and encouragement during this marvellous journey.

Finally, I would like to express my gratitude to my family for their great support. This work could not come true without their understanding of my preoccupation with the work.

Espoo, July 2015
Atsushi Takano

List of publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their Roman numerals:

I. Takano A, Winter S, Hughes M, Linkosalmi L. 2014. Comparison of life cycle assessment databases: A case study on building assessment. Building and Environment 79: 20-30. doi:10.1016/j.buildenv.2014.04.025

II. Takano A, Hafner A, Linkosalmi L, Ott S, Hughes M, Winter S. 2015. Life cycle assessment of wood construction according to the normative standards. European Journal of Wood and Wood Products 73: 299-312. doi: 10.1007/s00107-015-0890-4

III. Takano A, Hughes M, Winter S. 2014. A multidisciplinary approach to sustainable building material selection: A case study in a Finnish context. Building and Environment 82: 526-535. doi:10.1016/j.buildenv.2014.09.026

IV. Takano A, Sudip SK, Kuittinen M, Alanne K, Hughes M, Winter S. 2015. The effect of material selection on life cycle energy balance: A case study on a hypothetical building model in Finland. Building and Environment 89: 192-202. doi:10.1016/j.buildenv.2015.03.001

V. Takano A, Pittau F, Hafner A, Ott S, Hughes M, De Angelis E. 2014. Greenhouse gas emission from construction stage of wooden buildings. International Wood Products Journal 5 (4): 217-223. doi: 10.1179/2042645314Y.0000000077

Author’s contribution

Publication I, III
Defined the research plan with input from co-authors, was responsible for the calculation work, analysis of the results and wrote the manuscript with input from co-authors.

Publication II
Defined the research plan with input from co-authors, was responsible for the calculation work, excluding the end of life phase calculation, analysis of the results and wrote the manuscript with input from co-authors.

Publication IV
Defined the research plan with input from co-authors, was responsible for the calculation work, excluding the operational energy simulation, analysis of the results and wrote the manuscript with input from co-authors.

Publication V
Defined the research plan with input from co-authors, was responsible for the calculation work, excluding reference building B, analysis of the results and wrote the manuscript with input from co-authors.

List of abbreviations

Aircrete	Autoclaved aerated concrete
CEN/TC	Technical Committee of the European Committee for Standardization
C&DW	Construction and demolition waste
CLT	Cross laminated timber
CS	Carbon storage
DI	Difference index
EC	Energy content
EE-R/-NR	Renewable / Non renewable embodied energy
EoL	End of Life
EPD	Environmental Product Declaration
GDP	Gross Domestic Product
GHG	Greenhouse gas
GWP	Global Warming Potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LVL	Laminated veneer lumber
LWT	Light weight timber
OSB	Oriented strand board
PER/PENR	Renewable / Non renewable primary energy
PERE/PENRE	Use of Renewable / Non renewable primary energy for energetic purposes
PERM/PENRM	Use of Renewable / Non-renewable primary energy resources used as raw materials
PRD	Percentage of relative differences
RC	Reinforced concrete
RU-R/NR	Renewable / Non-renewable resource use
SPWPs	Secondary processed wood products

Contents

1. Introduction

1.1 Background

Developing the building sector can provide substantial benefits to society; however the sector also contributes significantly to Humankind's environmental footprint. Globally, for instance, buildings are responsible for more than 40% of total primary energy consumption and a third of total greenhouse gas (GHG) emissions (UNEP 2009, IEA 2013). The building sector normally accounts for 10-40% of Gross Domestic Product (GDP) and, at national level, usually accounts for 5-10% of employment (UNEP 2007 and 2009). Improving the environmental profile of buildings therefore has significant potential to stimulate both economic and social development, providing for the growth of new business, increasing employment and improving living conditions. In short, the environmental development of a building during its life cycle has an important role to play in terms of the sustainable development of our society, today and into the future (UNEP 2007 and 2009).

In this context, the life cycle energy use and environmental impacts of buildings have been intensively studied over the past few decades. Because of its dominance in the overall life cycle energy use, most attention has thus far been focussed on the energy used in a building's functioning (operational energy) and associated impacts. Practical solutions for low energy buildings (e.g. a high level thermal insulation and air tightness of building envelopes; heat recovery ventilation system) have been intensively developed and as a result, operational energy demand and associated impacts have been significantly mitigated, leading to the introduction and development of low energy buildings. Although the operation phase is still responsible for the major part of the life cycle energy use of buildings, as a result of the aforementioned measures to improve operational energy efficiency, the relative importance of the energy used in other life cycle phases (e.g. material production phase (embodied energy)) is nowadays increasing.

A building is composed of a combination of many different products, which are made from various raw materials. The manufacture of building products is actually responsible for about 30% of annual global raw material consumption (UNEP 2008). In the building sector, raw materials are extracted, processed, transported, assembled with other products and finally disposed of (or reused/recycled) at the end of a building's life. These processes all contribute to energy use and environmental impacts. Building material selection is, therefore, a significant factor in the development of sustainable construction. Against this background, wood and wood-based building products have lately attracted considerable attention as a promising construction material due to their unique environmental properties (e.g. renewability, reusability, carbon storage capacity, energy content, etc.). In fact, recently the development of sustainable wood construction has become a matter of public interest. In particular, the development of high-rise and large scale buildings from wood, replacing concrete and steel, has become a global trend, incorporating several aspects (e.g. environmental aspects, industrial potential). In addition, the life cycle assessment (LCA) of wood products and wood construction has nowadays also been frequently discussed.

Prior to industrialization, buildings were traditionally constructed using locally sourced materials and manual labour. As a result, building artisans acquired deep knowledge of the materials that they used, resulting in proper material selection and maintenance that lead to efficient resource use and sustainable building life cycles (Murakami 2008). This would be the wisdom of traditional vernacular buildings cultivated before industrialization of the construction system, which is clearly an advantage compared to modern buildings. Although little scientific attention has so far been paid to vernacular architectures from an environmental aspect, there should be useful ideas to be taken from their solution (Murakami 2008, Kimura et al. 1999). A combination of traditional and modern building solutions could offer an interesting and profitable approach to the further development of sustainable modern buildings. As to building material selection, the idea that "the right material in the right place" should be particularly notable. The nature of materials was intrinsically understood from various aspects and suitable materials were used according to the function required, the location of use and so forth (Murakami 2008, Thoma 2003).

1.2 Knowledge gaps

The effects of material selection on the environmental impacts of a building and the environmental profiles of wood products have been widely investigated. However, most previous studies have been limited to certain life cycle phases, assessment parameters or variation of materials studied. When this study was started in 2012, there had probably been no comprehensive and comparative material studies from environmental aspect, providing a holistic understanding of the advantages/disadvantages of wood products over the building life cycle.

It is already well known that wood is, in general, an environmental friendly material (CEI-Bois 2006 and 2014, USDA 2010), however little work has been conducted on how, specifically, wood in construction can be further developed from a life cycle perspective to enhance the sustainability of buildings. This thesis aims to address this gap knowledge.

1.3 Objectives

The main objective of this study was to investigate the optimal use and development of wood products in sustainable construction in comparison to other common building materials. With regard to learning from vernacular buildings, a holistic analysis of wood in construction was carried out with the aim of gaining a wider understanding of wood products so as to consider how they might be further used and developed. The effect of material selection, mainly on environmental indicators, over the building life cycle using the life cycle assessment (LCA) method was quantified and discussed. This dissertation also discusses the assessment data and methodologies for the fair assessment of wood in construction.

1.4 Organization of thesis

This thesis consists of three main sections and is based on five original papers. Firstly, the theoretical background to the environmental impacts of buildings and its assessment, the inherent environmental properties of wood products and sustainable solutions in vernacular buildings are introduced. Secondly, the methodologies used are briefly presented and the discussion is carried out based on the core results of Papers I-V and literature studies. Lastly, conclusions are drawn with suggestions for possible practical development and future research.

The papers appended at the end of this thesis provide detailed accounts of the findings and the basis for the discussion. Since LCA is a data intensive method, the availability of a reliable and adequate dataset is significant for the assessment. In addition, proper assessment methodologies are a prerequisite for comparative study. Therefore, in the first place, and as background to the study, existing LCA databases and the latest normative standards relating to the assessment of building and wood products were investigated (Papers I-II). Based on these studies, the effect of building material selection in a Finnish context was quantified, covering the whole building life cycle and several environmental and economic indicators (Papers III-IV). Furthermore, a detailed profile of GHG emissions associated with the construction process of wooden buildings was studied (Paper V). Figure 1-1 shows the relationship between the studies consisting of this dissertation.

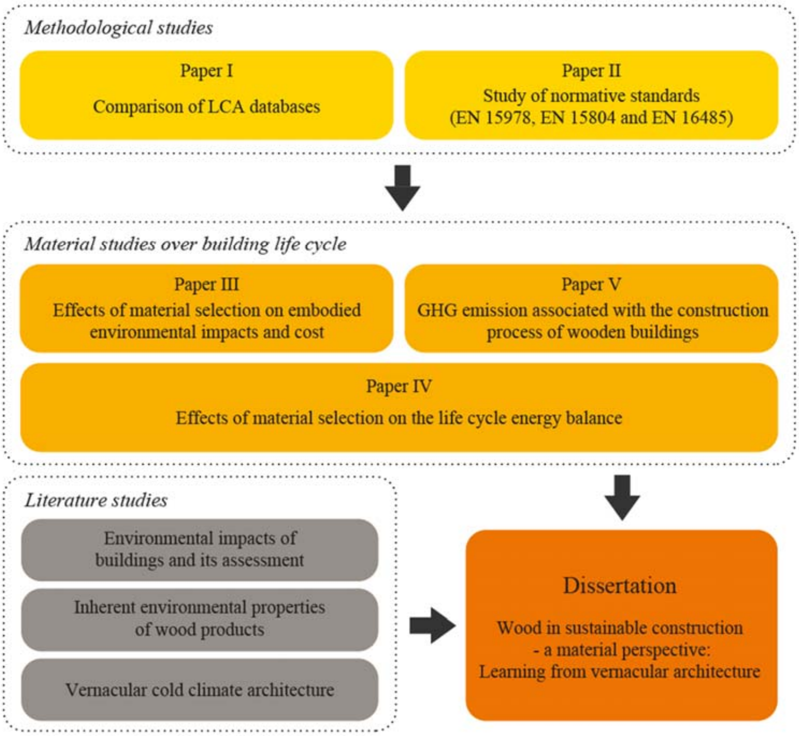


Figure 1- 1. *Composition of this thesis*

2. Theoretical background

2.1 The environmental impacts of buildings

In an effort to mitigate the life cycle energy consumption and impacts of buildings, the main focus has been on the operational energy and associated impacts because it accounts for the highest proportion of the life cycle energy consumption and impacts. For instance, about half of the global final energy consumption in the building sector can be attributed to the operational energy (IEA 2011). Practical solutions for low operational energy buildings have been studied extensively over the past few decades especially in Europe and North America. The energy performance of buildings (e.g. thermal insulation performance and air tightness) has been improved and advances in the efficiency of building service equipment (e.g. the ventilation system with heat exchange and heat pump system) have been made. These measures have been complemented by building energy standards, which thus far have been orientated towards reducing operational energy. As a result of these efforts, although operational energy still accounts for the major part of the life cycle energy use of buildings, the relative importance of the other life cycle stages has increased, especially in the case of low energy buildings (Karimpour et al. 2014, Mohammed et al. 2013, Verbeeck and Hens 2010, Ramesh et al. 2010, Sartori and Hestnes 2007, Thormark 2002). Based on the literature review, Sartori and Hestnes (2007) have, for instance, reported that embodied energy accounts for up to 46% of the life cycle energy use (service life of 50 years) in the case of low energy buildings and up to 38% in the case of conventional buildings, whilst Mohammed et al. (2013) noted that embodied carbon emission could account for up to 68% of emissions over a 60 year life cycle. As the distribution of the energy use and environmental impacts over building life cycle change, a life cycle perspective is becoming more significant for comprehensive building analysis.

Although the development of new low energy and low impact buildings is important in the long-term, their contribution to the overall impacts of the building sector may be minor in the short-term (Bell 2004, Itard et al. 2008). This is mainly because of the relatively small proportion of additional new (low energy and low impact) construction to the existing building stock. An improvement in the energy efficiency of existing buildings may play a significant role in mitigating energy use and environmental impacts in the short-term (Harvey 2009). It is, therefore, important to consider both new and existing buildings in environmental development.

2.2 The effects of building material selection

With this background, the correct selection of building materials has great importance for the development of sustainable construction. Material selection directly affects the environmental impact of a building since it is a complex system consisting of many different materials. Several researchers have investigated the relationship between the selection of building materials and the resulting impacts. Basbagill et al. (2013), for instance, investigated the influence of material choice and thickness on a building's embodied impact in four building elements (Substructure, Shell, Interiors and Services). They noted that a significant reduction in embodied impact could be achieved by changes to the cladding materials, piles as well as glazing and flooring materials, whereas changes to materials and thicknesses were not important in the case of the doors, stairs and building service equipment. Thormark (2006) investigated the effect of material choice on both the embodied energy and recycling potential in an energy efficient apartment block in Sweden, noting that embodied energy could be decreased by approximately 17% (or increased by about 6%) through implementing a simple material change.

Material selection can have an appreciable effect on the construction process as well. Cole (1999), for instance, studied the energy consumption and greenhouse gas emissions associated with the on-site construction of buildings in a Canadian context. He demonstrated that there were significant differences when alternative frame materials (wood, steel and concrete) were used. The steel structure was found to consume the lowest energy and emit the lowest GHG during construction and the concrete structure the highest (the concrete structure requiring up to 40 times more energy than the steel construction). The use of wood typically resulted in 2-3 times more construction energy consumption and GHG emission than steel. Cole and Kernan (1996) compared the life cycle energy use of office buildings built with wood, steel or concrete frames in Canada. Their results showed that the concrete structure consumed up to 1.39 times more energy, and the steel structure up to 1.82 times more energy, than the wood structure. Eriksson (2003) also noted that wood construction uses less energy than steel or concrete construction and estimated that increasing wood construction in Europe (about 35% greater annual sawn timber use) could reduce GHG emissions by up to 35 to 50 Mt CO_{2eq} per year, which corresponds to about 0.9 to 1.3% of total annual European emissions.

The effect of building material choice on operational energy has also been investigated. Dodoo et al. (2012) analysed the effect of thermal mass on the space heating energy demand and life cycle primary energy balances of a building. They calculated the energy saving benefits of thermal mass during the operation phase of a reference building located in Växjö in southern Sweden, having either a concrete or a wood frame. They found that the concrete frame building had a slightly lower space heating energy demand (0.5-2.4%) than the wooden framed alternative due to the higher thermal mass of the concrete-based materials. Jokisalo and Kurnitski (2005) and Ståhl (2009) conducted simulations using a similar approach and found that the space heating energy savings benefits of thermal mass to be about 0.7-2.0% for buildings in the Nordic climate. Zhu et al. (2009) compared identical wood and concrete constructions in Las Vegas and found that the wood construction required higher space heating energy, but lower space cooling energy than the concrete construction. The effect of thermal mass in buildings is swayed by several parameters such as climatic location, orientation, window area, thermal insulation, ventilation and the occupancy pattern of the buildings (ORNL 2001, Balaras 1996).

Although to date there has been little research carried out about the end of life (EoL) stage of buildings (Karimpour et al. 2014), the recycling aspect has been highlighted as being a potentially significant factor in reducing the life cycle energy use of buildings (Thormark 2006, Dodoo et al, 2012). For instance, Thormark (2006) found that recycling in low energy buildings in Sweden resulted in a 40% recovery of the embodied energy. In addition, Höglmeier et al. (2013) analysed the cascading potential of wood used in the building stock of south-east Germany finding that more than half of the recovered wood could be utilized for high-quality secondary applications. These studies indicate the importance of considering the EoL scenarios of the building materials right from the beginning of the construction project.

2.3 The inherent environmental properties of wood products

Wood is one of the most traditional and widely used building materials that is, thanks to its diverse characteristics, suitable for a variety of applications. Due to their unique environmental properties, in the context promoting sustainability in the building sector, wood and wood-based building products have lately attracted considerable attention as promising construction materials. Firstly, renewability is a notable character of wood, which sets it apart from other construction materials such as steel, concrete and fossil oil-based products. In addition, during growth, trees sequester carbon from the atmosphere through photosynthesis and part of this absorbed carbon is stored in wood products. Carbon in wood products remains stored for as long as the product is in use. In short, wood products provide a physical storage mechanism for carbon, which provides climate benefits depending on temporal aspects (Sathre and O'Connor 2010). When a wood product is burnt at end of life the stored carbon is released, however energy can also be recovered. This recovery of post-use wood and wood processing residues for use in place of fossil fuels significantly lowers the energy and carbon balances of a building (Gustavsson and Sathre 2006, CEI-Bois 2006, Hennigar et al. 2008).

The environmental advantages of using wood products vary depending on the interaction between forest growth, carbon storage in the forest and in wood-products, and the substitution of fossil fuel and other materials. Liu and Han (2009) studied carbon storage in living trees and wood products over a 400 year time span under three different forest management scenarios: no-harvesting, harvesting at the age of maximum mean annual increment (MAI) and harvesting at a time after maximum MAI but before the occurrence of natural disturbance. They found that, on a landscape level, carbon storage in living trees is the highest in scenario where no harvesting takes place. However, the total carbon storage (both in living tree and in wood products) is greater in the other harvest scenarios. In the no-harvest scenario, carbon storage in living trees is possibly lost due to natural disturbances, resulting in fluctuations in the total carbon storage. The authors concluded that a combination of improved forest management and efficient transfer of carbon into wood products would be a reasonable proposition to ensure long-term, stable, carbon storage. The same conclusion was reached by Perez-Garcia et al. (2005).

When it is assumed that post-use wood and wood process residues are used for energy purposes, the benefit of carbon storage become less significant over time. Werner et al. (2005) analysed how GHG impacts changed as the use of wood products increased in Switzerland. They noted that to begin with the carbon stock in the products increases as wood use increases but that later this will stabilize as the amount of wood entering the system balances the amount of wood leaving the system. In such situations, the effect of using wood products to substitute fossil fuel has a significant role to play in reducing net GHG emissions. In the case of the reuse or recycling of post-use wood, Sathre and Gustavsson (2006) investigated the energy and carbon balances for three recovered wood cascade chains; the direct effects due to physical or logistical differences between virgin and cascaded wood, substitution effects from wood cascading derived from a reduction in the use of non-wood materials, and land use effects due to a reduction in the volume of harvested wood because of an increase in wood cascading. Their results indicated that the most significant effect on both the energy and carbon balance was land use effects, followed by substitution effects, whilst the direct effects were relatively minor. In particular, it was noted that the carbon storage in unharvested wood due to the cascading of recovered wood could be significant. Börjesson and Gustavsson (2000) compared the effects of three different post-use wood handling scenarios: i) burning for energy, ii) 50% for reuse and 50% for energy or iii) landfill, on the life cycle energy and GHG balance of a reference building. They found that the most favourable outcome arose when half the post-use wood was reused and half burned. When post-use wood is cascaded, forest harvest and energy use for the material production can be reduced in subsequent building construction.

2.4 Assessment methods and data for wood and wood construction

In order to assess the environmental profile of buildings, several analytical methods have been developed and applied (König et al. 2010). Life cycle assessment (LCA), which is a method to quantify the environmental impact of a product during its life cycle, is one of the most commonly used assessment methods (ISO 14040 2006, ISO 14044 2006). LCA has been applied to buildings since 1990 (Fava 2006), and numerous studies relating to building life cycle impacts have been undertaken internationally. LCA is a data-intensive method and the results vary on a case-by-case basis with different methodologies being applied depending upon the purpose of the assessment (Peeredoom 1999, Erlandsson and Borg 2003). Thus, normative standards have been developed that are aimed at harmonizing the assessment methodologies. The normative standards EN15804 (2012+A1:2013) and EN15978 (2011), developed by Technical Committee TC 350 of the European Committee for Standardization (CEN/TC 350), provide a framework for the assessment of building products and buildings. The standards state the methodological provisions related to the life cycle modules (module A1–3: Product stage, A4–5: Construction process stage, B: Use stage and C: End-of-Life stage) and an additional information module (module D: Benefits and loads beyond the system boundary). In particular, module D, which shows the additional benefits and loads resulting from the reuse/recycling operations at the end of life of a building, is unique in defining a solution for the transparent description of the recycling aspects in building LCA (Leroy et al. 2012). The standards also bring transparency to issues of life cycle inventory (LCI), system boundaries, division into the subcategories to be included and so forth.

The European research project "EeBGuide" (Wittstock et al. 2012) summarized the provisions of CEN/TC 350 and the international reference life cycle data system (ILCD) handbook (EC-JRC-IES 2010) in order to produce expert guidance on conducting LCA studies for energy efficient buildings and building products. The EeBGuide document identified more than 150 topics to be considered when conducting product or building LCAs according to the LCA framework (e.g. goal and scope definition, inventory analysis) and the life cycle stages of EN 15804 and EN 15978 standards (modules A–D). The provisions and guidance are broken down according to the study types (screening, simplified and complete LCA) and make a distinction between stand-alone LCAs and comparative assertions. Moncaster and Symons (2013) introduced a simple tool for assessing the embodied carbon and energy in UK buildings (the ECEB tool). This tool was developed to help in making design decisions at the feasibility stage that, as far as possible, are in line with EN 15804 and EN 15978. They concluded that the standards provide accurate analysis for the early life cycle phases (module A1–5) but only an approximation for the latter phases (modules B3–5 and C). In addition, the authors mentioned that the lack of precise LCA data, especially for the product stage (module A1–3), the construction process (module A5) as well as the end-of-life stage (module C), makes the conduct of an accurate assessment difficult.

For the building assessment, EN 15978 refers to the use of data obtained from Environmental Product Declarations (EPDs) defined in EN 15804. In addition, EN 16485 (2014) developed by CEN/TC175, provides detailed assessment rules for wood and wood-based products used in construction, in line with EN 15804. The LCA of bio-based materials, principally wood products, has recently been discussed in view of their unique inherent (carbon storage) properties, discussed above. Pawelzik et al. (2013) stated that the LCA standards do not yet address details of the life cycle of bio-based materials, and reviewed key issues and methodologies regarding their LCA.

2.5 Wisdom in traditional vernacular cold climate architecture

Traditional vernacular buildings were constructed with local materials and techniques. However, such restrictions cultivated building solutions to secure adequate living conditions, adapted to the surrounding (Murakami 2008, Kimura et al. 1999). As a consequence, before industrialization unique building solutions could be found all over the world. From a LCA perspective, it could be assumed that the traditional buildings had lower life cycle environmental impacts due to, for instance, low production, construction and transportation energy. In addition, traditional buildings had been composed of very simple material combinations that allowed easy maintenance and disassembly, resulting in long building life spans and a high reuse/recycling ratio of the materials recovered from disassembly (Kimura et al. 1999, Uchida 2009). Murakami (2008) investigated the operational performance (e.g. thermal and moisture conditions of the indoor space in relation to the outdoor) of several vernacular buildings (e.g. an Eskimo hut in Canada, a cave house in Turkey and a waterborne house in Malaysia) based on in situ measurements and computer simulation. He also assessed the environmental performance of the buildings using CASBEE (Comprehensive Assessment System for Building Environmental Efficiency, Murakami 2004) and has concluded that the vernacular buildings had very low environmental impacts thanks to their passive design solutions (e.g. conditioning an indoor living environment in accordance with local climate (without mechanical system), locally sourced material use). Although the vernacular buildings would be inferior to a modern building, for instance, in terms of indoor living quality, there should be hints in traditional building solutions to develop environmental performance of modern buildings (Murakami 2008).

There have been several traditional building types built in cold climate areas such as; the Igloo (Eskimo hut) in North America, the Chise (Ainu's house) in North Japan and the log cabin,for instance, in Siberia, central Europe and Scandinavia. As even primitive example would be the pit dwelling, which was a hole dug into the ground that was covered by a layer of soil that acted as thermal insulation and provided thermal mass. These were commonly built in Scandinavia, North America and North-East Asia (Hasegawa 1987, Emori 2004). In Finland, most wooden buildings were of log construction up to the 1930s and the Finnish log cabin has a very long history reaching back to the Iron Age (Suikkari 2001). Simple wood construction using entire tree trunks is apparently vernacular architecture in Finland. As an example of vernacular cold climate architecture, an outline of the sustainable solutions embodied in a

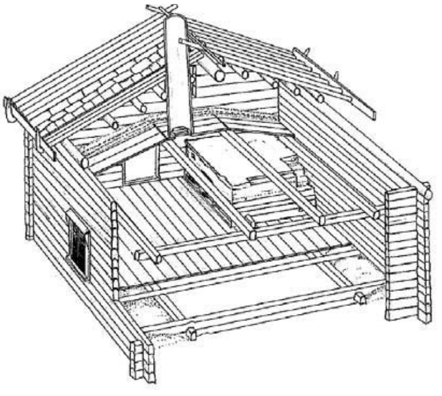


Figure 2-1. *Composition of a Finnish chimneyless log cabin (Lindberg 2011, p. 166)*

Finnish log cabin are briefly summarised as follows.

In principle, the Finnish log cabin was a very simple rectangular shaped building. Originally (before the 18th century), the cabin was a one-room building without a chimney which was heated by a relatively large stove (smoke stove) compared to the room size (figure 2-1). The cabin was normally built on a corner stone foundation and raised slightly from the ground. The floor was made of log halves set on the floor joists. In order to protect the cabin from ground frost in winter, the cabin had a double layer of logs under the floor and a mixture of porous dirt, turf and sand was inserted between the two layers of logs to act as thermal insulation. The exterior wall was made by stacking hewn logs, normally of pine or spruce, on top of each other. This log wall worked as the load-bearing frame, thermal insulation and interior/exterior cladding. This multifunctionality makes best use of the inherent structural and thermal properties of wood. The roof consisted of a log frame onto which sheets of birch bark were laid to act as a waterproof layer. Thin debarked logs were placed on top of the bark layer to hold the bark in place. There was an intermediate ceiling under the roof, which was typically composed of log beams, wooden boards, moss and fine sand. Moss and sand functioned as thermal insulation and provided an airtight layer (Hasegawa 1987, Huttunen 2012, Sailo 2011, Lindberg 2011, Savo-Seura et al. 2009).

The building materials were rationally selected according to their features, availability and location of use (table 2-1). In addition, several measures were employed in order to prolong the building life span. A critical enemy of wood is water (moisture). In principle, there is no problem so long as wood is dry. Thus, all parts of the cabin were designed to ensure that they would dry out quickly. For instance, the tip of the ridgepole was sharpened with an axe in order to prevent water penetration into the wood and to drain water away, whilst the surfaces of logs were hewn to prevent water penetration. In addition, old pine logs (approximately 160 years old or more) were preferred since they were very durable and did not decay easily thanks to the high content of resins and extractives. The bottom logs tended to become wet due to moisture from the ground, so that the best logs were used there. Thanks to proper material selection and well developed detailing, the cabin could have quite a long service life, for instance the life span of logs, ridgepole and the birch bark waterproof layer were normally more than 100 years, about 30 years and 50-100 years, respectively. Moreover, damaged parts of the building could be easily replaced because of the simple building composition and, due to their large dimensions, logs could also be reused in new building when an existing building was deconstructed (Huttunen 2012, Sailo 2011).

Table 2-1. *Materials used in the cabin (Huttunen 2012, Sailo 2011)*

Material	Feature	Location of use
Pine	Durability, Workability (Lightness and softness)	Log, Eave, Slat
Spruce	Relatively high water-resistance, Workability (Lightness and softness)	Ridge pole, Log, Shingles
Birch	High water-resistance	Water proof layer
Aspen	Light-resistance, Translucency, Workability (Lightness and softness)	Ridge pole, Opening (window pane), Log
Branch (Birch or Spruce)	Workability (Flexibility)	Fixing rope
Moss	Air tightness	Air tightening between logs
Turf, sand, Dirt	Adiabaticity	Insulation
Snow	Adiabaticity, Air-tightness	Additional insulation

The cabin would be heated by the smoke stove for a couple of hours per day. It seems to have been a very energy and resource efficient heating method because heating with a normal stove (with chimney) would take more time (approximately twice as long) to make the room warm enough. Releasing the smoke directly into the interior space would minimise heat loss, although the air quality of the space would of course become worse (figure 2-2). In addition, the heat could be stored in the stove, logs and ceiling (log halves and sand) that might provide omnidirectional radiant heat to the occupants (Huttunen 2012, Korhonen 2011).

Although the cabin as such was not assessed in this study, many things could be assumed. For instance, the embodied energy would certainly be lower and recyclability of building components would be higher than modern buildings thanks to its composition as described above. The multifunctional simple envelope constructed out of local materials (log wall) would be particularly notable. The multifunctionality of a building element would be a common building solution found in many vernacular buildings (Kimura et al. 1999), which would be an extension of the limited technology and resources. In addition, the operational energy would also be efficient based on the unique space heating system. Natural energy was maximised and the building composition was optimized in order to secure an adequate living condition with minimal energy. Nevertheless, of course, traditional buildings are not always better than modern buildings as noted by Murakami (2008). In addition, the building and construction system fundamentally differ depending on the period considered, in particular before and after the industrialization. Therefore, it would be adequate to incorporate the advantages of both traditional (e.g. appropriate materials use based on multiple understanding of their properties, simple and rational building composition) and modern (e.g. advanced building materials and technologies, comfortable building operation system) building solutions for the development of sustainable built environment. In this study, traditional building solutions are thus referred to in the discussion with the core results of the appended papers, which are based on results from modern building systems (e.g. material production and construction system, building configuration, materials).

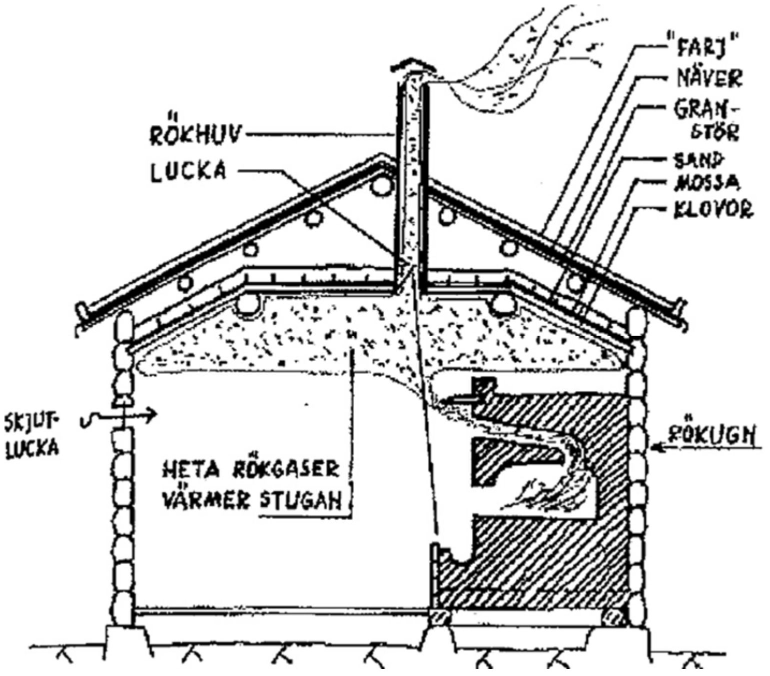


Figure 2- 2. Heating system of the chimneyless cabin (Korhonen 2011, p.31)

3. Approaches and methodologies

The papers comprising this dissertation each have distinct research questions and aspects. Thus, although the study objects (e.g. reference building, assessment indicators, system boundary, etc.) differ from each other, the basic approaches and methodologies used in the assessments are shared amongst the studies. All of the studies are associated with an aspect of wood in construction and give a contribution to this dissertation. As for learning from traditional vernacular architecture, a wider understanding of wooden materials over the building life cycle can be obtained in order to consider the correct way in which to use and develop them in sustainable construction.

First, the methodological issues for the fair assessment of wood products and wood construction are discussed based on the results of Papers I and II. Second, wood in the context of sustainable construction is discussed based on a quantification of the effects of material selection studied in Papers III-V in conjunction with the traditional building solutions. In this chapter, the methodologies and terminologies used in Papers I-V are briefly summarised. Further information can be found in the papers themselves.

This study is based on a limited number of case studies including certain types of building and building materials, sustainability indicators and scenarios. This limitation, naturally influences the discussion and the conclusions reached in this study to some extent. However, this limitation is not considered to be so critical in the context of this study, since the discussion was carried out from a broader perspective, rather than focusing on some specific numerial results, although the assessment on other sustainability indicators (e.g. acidification potential) may bring different discussion.

3.1 Analysis of life cycle assessment data

Buildings are complex structures consisting of many materials. Appropriate LCA data for building materials is thus a prerequisite for the assessment. However, several researchers have reported that, depending on the databases, there are fundamental gaps in the modelling of data, which can sometimes result in significant difference in the assessment results (Yokoo et al. 2013, Frischknecht 2006, Peeredoom et al. 1999). Therefore, the numerical and methodological differences between existing LCA databases used for the purpose of building LCAs were investigated in Paper I. The following five LCA databases were compared by calculating GHG emission values using the datasets in the material production phase (Cradle-to-Gate) of three reference buildings.

- GaBi (2013)
- ecoinvent (2013)
- IBO (2013)
- CFP (2013)
- Synergia (2010)

At the time the research was carried out, the latest versions of all the databases were used. More details about the databases are to be found in Paper I. In the paper, numerical differences in the building assessment results arising from the different databases used were observed and the reasons for the variations were investigated from the point of view of the database's methodological background. In addition, possible opportunities for the further development of LCA databases and the communication of assessment results were discussed. Based on the study, the issues in the databases for the assessment of wood construction are discussed in section 4.1.1 of this dissertation. In addition, all the calculations in Papers II-V were carried out with ecoinvent due to its transparency and comprehensive data compared to the others.

3.2 Analysis of the latest standards for the building assessment

In order to conduct a transparent and comparable assessment for wood construction, the latest normative standards EN15804 (2012+A1:2013), EN 15978 (2011) and EN 16485 (2014) were studied in Paper II. As noted in section 2.4 there are references other than the CEN/TC standards for conducting building LCA (e.g. the ILCD handbook); however the terminology and provisions in each are not currently harmonized (Wittstock et al. 2012). Therefore, different descriptions and results may appear in the assessment depending upon the reference used. Having understood this point, this study focused on the standards mentioned above since they deal consistently with the LCA of building products and buildings and include specific guidelines for the handling of wood and wood-based products used in construction.

First, global warming potential (as an indicator describing the environmental impacts) and primary energy balance (as an indicator describing resource use over the service life of a reference building) were assessed by following the standards. Then possible points for development in the standards, especially concerning wood products and wood construction, were discussed from a practical perspective. The building studied (reference building 1) was a 4-story apartment block (living floor area: 488 m^2) located in Mietraching (Architect: Schankula Architekten/ Diplomingenieure, Structural engineers: Bauart Konstruktions GmbH + Co.KG, Constructor: Huber&Sohn Co.KG), approx. 50 km south-east of Munich and completed in 2010. Further information regarding the study can be found in Paper II. In this dissertation, major discussion points in the paper are summarised in sections 4.1.2-4.1.4.

3.3 Analysis of building sustainability from a material perspective

Based on the results and discussions in Papers I and II, LCA were carried out on the reference buildings with a material perspective. Paper III analysed how building material selection affected the environmental and economic indicators in the material production phase of a building, whilst Paper IV demonstrated the influence of material selection on the life cycle energy balance of a reference building model, in a Finnish context. Paper V investigated the detailed profile of GHG emissions associated with the construction process of wooden reference buildings. The results of the papers are discussed from the perspective of wood in sustainable construction in section 4.2. The assessment methodologies used in Papers III-V are briefly summarised in the following section.

3.3.1 Reference buildings

In Papers III-V, several reference buildings were used according to the purposes of the study. The case studies were conducted on relatively small scale buildings (residential buildings). Here, each reference building is briefly introduced. The reference building used in Paper III (reference building 2) was a three story townhouse building planned for Helsinki (60°N, 25°E). The building consisted of five houses in a row. A hypothetical building model (reference building 3) was used as the study object in Paper IV. The dimensions of the model were scaled to those of a detached house. This building was assumed to be located in Helsinki as well. Three multi-story wooden residential buildings (reference buildings 4-A, 4-B and 4-C) were assessed in Paper V. Basic information about each of the reference buildings is summarized in table 3-1. The functional unit was 1 m^2 of the living floor area, which is an area enclosed by the inside of the walls, excluding technical and maintenance spaces (e.g. machine room and storage). Although the contexts of the buildings (e.g. location and size) differ from each other, this was not considered to be a critical problem for the purposes of this study.

Table 3-1. *Basic information about the reference buildings (Adapted from Papers III-V)*

Name	**Location**	**Structure frame**	**Gross area (m^2)**	**Living area (m^2)**	**Floors**
Reference building 2	Helsinki	Refer to section 3.3.2	1243	986	3
Reference building 3	Helsinki	Refer to section 3.3.2	120	96	2
Reference building 4-A	Germany	Sawn timber panels	726	488	5
Reference building 4-B	Finland	Cross laminated timber	730	548	3
Reference building 4-C	Italy	Cross laminated timber	1840	1398	5

3.3.2 Building materials compared

In Papers III and IV, a comparative study was carried out on three building component categories: the structural frame, surface and inner components. Building service equipment and furniture were excluded from the calculation because they were out of the scope of the study. In the structural frame category, six frame materials: light weight timber (LWT), cross laminated timber (CLT), reinforced concrete panel (RC), autoclaved aerated concrete (Aircrete), brick (Brick) and light gauge steel (Steel), were compared using the reference buildings. The typical compositions of each building element were selected from the literature (Palolahti et al. 2013). In order to observe the differences arising from the selection of the frame materials, other building components (e.g. thermal insulation) were, as far as possible, held constant. U-value was constant in all cases regardless of the frame material and was according to Finnish building code D3 (2012). In addition to the comparison of the structural frame materials, alternative frame material combinations were also studied (table 3-2, Paper IV). Here, the aim was to observe how the life cycle energy balance changes when heavy weight (RC) and light weight (LWT and CLT) structures are combined in a building. In addition to the structural frame comparison, the influence that the selection of the material for the surface and inner components had on the indicators was compared using the reference building having the LWT frame. The energy performance of the building (e.g. U-value) was the same in all cases. The aim was to provide a description of both the differences between the materials and the contribution of the component categories on the end results. Detailed information regarding the materials compared is found in Papers III and IV.

Table 3-2. *Alternative combinations of the frame materials (Adapted from Paper IV)*

		Combination 1	Combination 2	Combination 3
Foundation + Ground floor		Concrete		
Exterior wall	1F	RC	RC	CLT
	2F		LWT	
Intermediate floor		LWT	LWT	RC
Roof		LWT	LWT	RC

3.3.3 Indicators

Although several indicators were assessed in Papers III-V, three indicators are mainly considered in this dissertation; primary energy balance, GHG balance and cost balance, which represent the environmental and economic aspects of sustainability. Both renewable (-R) and non-renewable (-NR) primary energy consumption and benefits were assessed. Primary energy consumption in the production phase of the building (embodied energy) was expressed as EE-R/EE-NR, whilst the energy content of products used in the building was expressed as EC in Paper III. The life cycle primary energy balance was displayed as PER and PENR in Paper IV. The CML 2001 method: global warming potential 100 years (Frischknecht et al. 2007), was used to quantify GHG emissions from both fossil fuel use (fossil GHG) and biomass fuel use (biogenic GHG) with the LCI data in ecoinvent. The CO_2 emission from biomass combustion was considered to be zero based on the idea of biogenic carbon neutrality (EN 16485: 2014) in Paper III. The temporal carbon storage in the wood products used was accounted for according to EN 16449 (2014) as an environmental benefit of the buildings in Papers III (as CS) and V. Although this study followed the assessment rules defined by the standards, the handling of biogenic CO_2 and carbon storage in wood and wood construction will be discussed at length in chapter 4, since it is a complex issue and is not harmonized amongst the guidelines for the LCAs of products and buildings. For instance, the international standard regarding the carbon footprint calculation of products (ISO 14067 2013) contains provisions for the inclusion of GHG emissions and removals arising from both fossil and biogenic carbon sources and sinks in the assessment report. Initial material cost was accounted for based on data in the published literature (Palolahti et al. 2013, Taloon 2014) in Paper III. The consistency of these two information sources was confirmed by comparing the price of the same products. More details are given in the papers.

3.3.4 Assessment at each stage of the building life cycle

Building life cycle information																Additional information outside the system boundary
Product stage			Construction stage		Use stage							End of Life stage				Potential benefits and loads
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Constructiob - Installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse - Recovery - Recycling - potential

Figure 3-1. Life cycle modules for building LCAs according to EN 15978

According to EN 15978 (2011), the life cycle phases studied in Paper III-V were defined as shown in figure 3-1. In principle, the assessment in each module was carried out by following the standard. In the production stage (module A1-3), the inventory was carried out from the working drawings of the architects and structural engineers. Material losses during the construction process were taken into account. The calculation was carried out by multiplying the mass of each building component (kg) and the unit impact value (in MJ/kg, kg CO_2e/kg, or €/kg) obtained from the references mentioned in the previous section. All information regarding the construction stage (module A4-5) was collected by reviewing the construction documents, monitoring the construction works and interviewing the constructors. Data collection methods were determined on a case-by-case basis. Transportation of the building components and elements (module A4) was modelled according to the case. The impact from the module was calculated by multiplying the distance (km) and the mass of deliverable (ton), taking the vehicle type into account. Worker transport to the factory or construction site was not included. The impact from the prefabrication and on-site construction work (module A5) was assessed based on the amount and types of energy consumed during the process. The impacts associated with the prefabrication and on-site work were displayed separately in Paper V in order to observe them in detailed. The maintenance of the buildings (module B2-5) was modelled according to the expected service life and maintenance interval of the building components (YM 2008, Scheurer et al. 2003). The calculation of the operation stage (module B6) was based on the energy demand either estimated by the designer for the purpose of energy performance certification or simulated with IDA ICE (2014). At the end of life stage (module C), it was assumed that the buildings were demolished by selective dismantling and the building components were managed according to the scenarios created based on the literature (European Commission 2011, Kuosa 2012). The primary energy consumed during the stage - deconstruction, transportation, waste processing for reuse or recycling and disposal - were assessed up to where the end-of-waste state of the materials is reached (Paper IV). The net energy benefit of the recycled materials (module D) was calculated as the primary energy use avoided through the substitution of primary materials production with materials that were recycled (Paper IV). Although the assessment results in this module varied depending on the scenario, the aim here was to describe the possible energy benefit of each building material after its service life, based on current recycling methods.

3.3.5 Analysis techniques

In Paper III, the differences between the frame materials were quantified relative to an average of all the alternatives. In this study, this is termed the “difference index (DI)”. A DI of 3 means that the result is three times as large as the average, a DI of 2 twice as large and 1 is the same as the average. When the DI is a decimal, for instance 0.5, the result is half that of the average. A DI of 0 indicates that the frame material does not have any value in that indicator.

In Papers III and IV, for the comparative study of the inner and surface components, the percentage relative differences (PRD) were used. The original specification of the LWT version was set as the reference value and the PRD in the results of the alternative materials were determined using equation 1.

$$PRD = (Value.x - Value.ref)/\ Value.ref\ \times 100 \qquad (1)$$

Where PRD is Percentage of relative differences (%)

$Value_{.x}$ is the value calculated with material x (MJ, kg, kg CO_2e or €)

$Value_{.ref}$ is the value calculated with the original specification (MJ, kg, kg CO_2e or €)

This method can indicate a positive or negative difference compared to the reference case and facilitates comparison as an index. More details are to be found in Paper III.

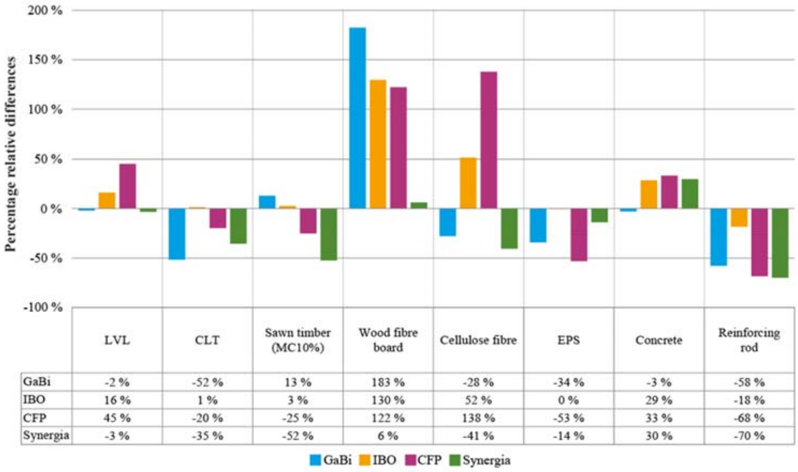
4. Results and discussion

4.1 Assessment data and methods for wood construction

In Papers I and II, it was commonly noted that the number of appropriate product data and a clear statement of the bases of their values are very important for comparative building assessment. Although the building assessment results showed similar trends even with the different databases, in many cases background information about the data (e.g. representativeness, system boundary or allocation) was not open. In addition, even if such information was open, it was not necessarily easy for users to modify the existing LCA data as required, for instance, by the standards (Wittstock et al. 2012). There is, therefore, still difficulty in conducting a comparable building assessment in line with the standards. This issue would be particularly problematic in the assessment of wood construction because of the following reasons, 1) the variety of wood products and 2) the inherent environmental properties of wood (e.g. energy content and temporal carbon storage).

4.1.1 Variety of wood products

Nowadays many different types of wood-based construction materials are available; not only sawn timber, but also engineered wood products (e.g. Glulam, laminated veneer lumber (LVL) and cross laminate timber (CLT)) and board products (e.g. plywood, LVL sheet, oriented strand board (OSB) and particleboard). The manufacturing system varies according to the product and also the location where the product is manufactured. Thus, the environmental information naturally differs between products, and sometimes even with the same product exhibits different environmental impacts. For instance, figure 4-1 shows the relative differences in the GHG emission value of the main wooden building components data stored in five different databases (Paper I). Here it can clearly be seen that there are large variations between the data, which have different representativeness (geographical, technical and temporal). In general, in the case of wood product manufacturing the thermal energy used for the drying and pressing processes account for the major (about 70-90%) part of total energy use (Tucker et



	LVL	CLT	Sawn timber (MC10%)	Wood fibre board	Cellulose fibre	EPS	Concrete	Reinforcing rod
GaBi	-2 %	-52 %	13 %	183 %	-28 %	-34 %	-3 %	-58 %
IBO	16 %	1 %	3 %	130 %	52 %	0 %	29 %	-18 %
CFP	45 %	-20 %	-25 %	122 %	138 %	-53 %	33 %	-68 %
Synergia	-3 %	-35 %	-52 %	6 %	-41 %	-14 %	30 %	-70 %

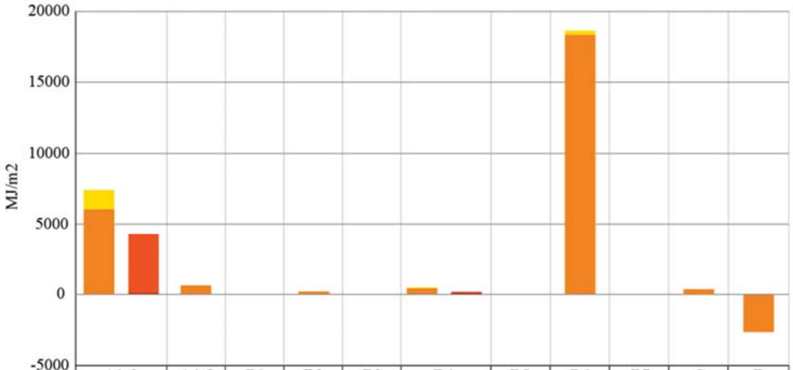
Figure 4-1. *Percentage relative differences in the GHG emission value of main building components shown by the different databases. The reference database is ecoinvent (Adapted from Paper I)*

al. 2009, FAO 2013a). Often biomass fuel is used alongside fossil fuels to generate this thermal energy and the ratio between the two varies according to country, region and even from mill to mill. Thus, the GHG emission value of wood products tends to be variable depending upon the database in question. In contrast, as shown in the fig. 4-1, the GHG emission value for concrete is similar in all databases. This result originates from the globally uniform nature of the concrete production system and its energy profile, coming mainly from fossil fuels (EPA 2007). According to the Environmental Product Declaration standard (EPD, EN15804 2012+A1:2013), it is a requirement to declare information in terms of the use of resources based on the life cycle inventory (LCI) with the life cycle impact assessment (LCIA) result. In addition to this, it would be more understandable to indicate the distribution of energy resources along with the production process, especially for wood products that tend to have a case specific manufacturing system. That information could, for instance, be visualized with the basic steps of the process shown as a flowchart. Describing such background information in a simple and transparent way should deepen the understanding of wood product data and might stimulate a comparative study between them, resulting in the real development of wood products from an environmental perspective.

There is a gap between databases with regard to the amount of wood product data. Table 4-1 shows the wood product data in the databases studied in Paper I. As mentioned in the article, there is a shortage of information about particular wood products in some databases and as a result some materials had to be substituted with data from similar products in the assessment. For instance, insulation board was used instead of cellulose fibre insulation in the case of CFP. The substitution of product data clearly lowers the accuracy of the building assessment. The provision of accurate data about specific wood products is therefore a fundamental requirement for accurate and comparative assessment. In particular, the development of national open databases based on an international data format, for instance the EPD system, would lead to the further popularization of the environmental assessment of buildings and would also widen the understanding of the environmental performance of wood products in relation to their specific context (e.g. locality, species). Although EN 15978 refers to the use of EPDs based on EN 15804 for building assessment, such data is clearly lacking at the moment. At the time the research was carried out only a few datasets (e.g. Rüter and Diederichs 2012, IBU 2013, Wood for Good 2013) existed that had been compiled in line with EN 15804. The preparation of a sufficient number of data of suitable format and quality is thus, as Moncaster and Symons (2013) have also mentioned, urgently required, especially for the assessment of data-intensive modules such as the product stage (module A1–3), construction process (module A5) and end-of life stage (module C). Since wood products are biomaterial and their production systems vary from each other, ideally it would be important to describe their environmental profiles on a case by case basis. The manufacturing and construction industries are expected to develop standardized data according to the EPD format described in EN 15804. Other issues, not within the scope of this thesis but nevertheless still important, regarding the LCA data of building products, are introduced in Papers I and II.

4.1.2 Energy content

As described in EN 16485 (2014), the energy content - the use of renewable/non-renewable primary energy resources used as raw materials (PERM/PENRM) in the definition of EN 15804 and EN 15978 (2011) - of products is regarded as an inherent material property. That can be counted as the energy recovery potential of a building if the building materials with an energy content are reused/recycled as secondary product or are used as fuel at the end of the life of a building (module C). Several studies have demonstrated the energy recovery benefits of the subsequent use of wood products as a fuel (Dodoo 2011, Thormark 2006, Scharai-Rad and Welling 2002). In the standards, it is stipulated that the use of primary energy for energetic purposes (PERE/PENRE) and PERM/PENRM should be shown separately as resource input in the material production phase of a building. However, the handling of PERM/PENRM exiting the system boundary by reusing/recycling building materials is not clearly defined in the standards. Figure 4-2 shows the life cycle primary energy balance of reference building 1 (table 3-1) in accordance with the provisions in the standards



	A1-3		A4-5	B1	B2	B3	B4		B5	B6	B7	C	D
🟨 PERE	1326		5	MNA	13	0	49		0	301	MNA	9	-5
🟥 PERM		4205	0	MNA	0	0		87	0	0	MNA	0	0
🟧 PENRE	6049		619	MNA	175	0	416		0	18306	MNA	357	-2654
🟫 PENRM		54	0	MNA	0	0		45	0	0	MNA	0	0

Figure 4-2. *Primary energy balance of the reference building 1 described in accordance with provisions in the standards (Adapted from Paper II)*

(Paper II). Here the energy content (PERM/PENRM) is counted as the energy consumption in module A1-3 of the system studied. With regards to this result, if the energy content is counted solely as the input, it might be distorted in favour of a construction with lower energy content in its components, like concrete and steel structures. Therefore, the fluxes of the energy content should be documented fairly within the system boundary by following, for instance, the scheme shown in figure 4-3 (Paper II), in which the energy content incoming/outgoing to/from the systems are described and they are balanced within the system boundary. In the building assessment, although the benefits of energy recovery from the materials used in the building could be reported in module D, it would also be relevant to express the energy content as input (positive value) in module A1-3 and as output (negative value) in module C based on the amount of materials reused/recycled in the next system. Additionally, in the product data differences between PERE/PENRE and PERM/PENRM should be clearly documented in order to avoid any misinterpretation of the values.

Figure 4-4 shows the same results as figure 4-2 but taking into account the foregoing discussions (Paper II). A proper description of the impacts and potentials of a building according to its system would lead to a comparable assessment and could be a starting point for the further development of buildings and building materials.

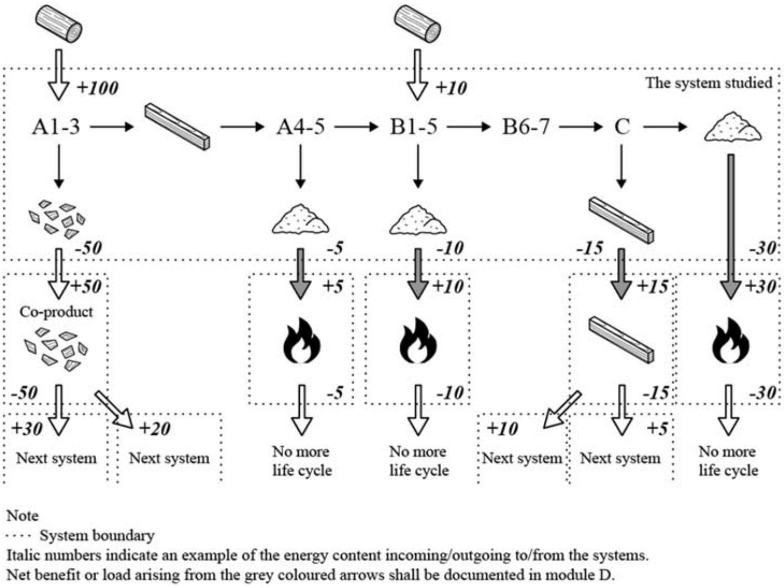
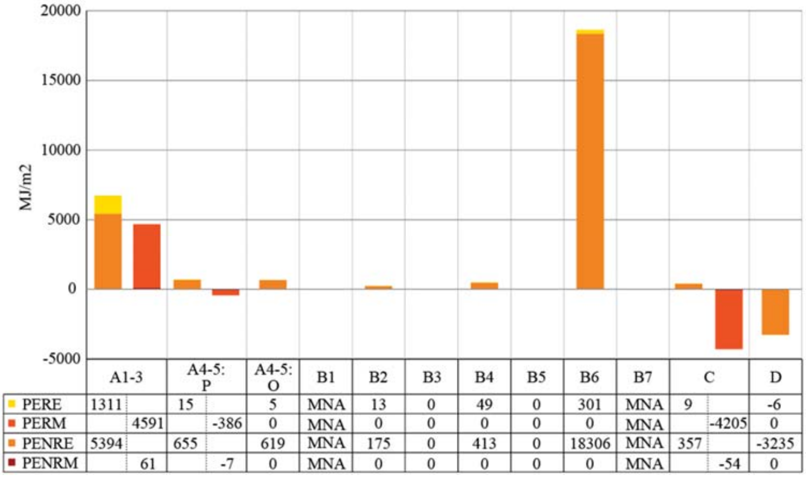


Figure 4-3. *Example of the energy content fluxes in the case of wood products (Adapted from Paper II)*



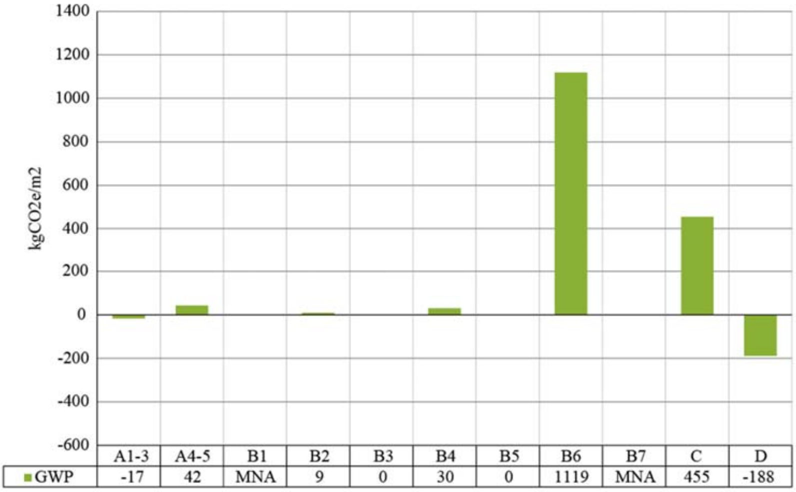
	A1-3		A4-5: P		A4-5: O	B1	B2	B3	B4	B5	B6	B7	C		D
🟨 PERE	1311		15		5	MNA	13	0	49	0	301	MNA	9		-6
🟥 PERM		4591		-386	0	MNA	0	0	0	0	0	MNA		-4205	0
🟧 PENRE	5394		655		619	MNA	175	0	413	0	18306	MNA	357		-3235
🟥 PENRM		61		-7	0	MNA	0	0	0	0	0	MNA		-54	0

Figure 4-4. *Primary energy balance of the reference building 1 described in accordance with the discussions (Adapted from Paper II)*

4.1.3 Biogenic carbon

As mentioned previously, biomass fuel is often used alongside fossil fuels in wood product manufacturing, so that the GHG emissions from the process include biogenic carbon emissions to some extent. In addition, wood products store biogenic carbon for the duration of their service lives as an inherent material property (EN 16485). First of all, biogenic carbon emissions and carbon storage naturally need to be distinguished in the product data. According to EN 16485, biogenic carbon emissions can be regarded as zero based on the idea of biogenic carbon neutrality, if the biomass used can be assumed to originate from sustainable forest sources. In this sense, carbon storage in wood products may be a virtual value and in fact it will be zero, balanced during natural decay or incineration of the products. However, it can be included in the assessment result as additional environmental information (EN16449 2014). Although the carbon stock in wood products may stabilize and become less significant over the building life cycle and forest rotation period, initially it is the dominant factor influencing GHG balance (Werner et al. 2005, Sathre 2007). It would, therefore, be important to describe biogenic carbon flow clearly and fairly in the assessment results as regulated, for instance, by ISO 14067 (2013), regardless of the idea of carbon neutrality.

However according to the current standards, life cycle GHG balance (GWP: global warming potential) shall be expressed as an aggregated value of fossil based GHG and biogenic carbon (both emission and storage) as shown in figure 4-5 (Paper II). Here the CO_2 emissions from biomass fuel combustion are taken to be zero over the life cycle. Biogenic carbon storage in wood products is counted in module A1, which results in a net negative impact for module A1-3. On the other hand, in module C the biogenic carbon storage that exits the system is counted as a positive value. Hence the biogenic carbon balance and the contribution of biogenic carbon to the GHG emission is zero over the life cycle of the building, as mentioned in EN 16485. However, without looking at their detailed contents, it might be difficult to understand why the result



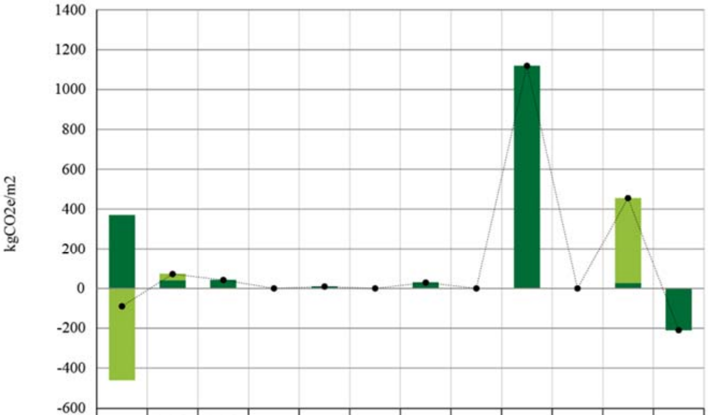
	A1-3	A4-5	B1	B2	B3	B4	B5	B6	B7	C	D
🟩 GWP	-17	42	MNA	9	0	30	0	1119	MNA	455	-188

Figure 4-5. *Global warming potential of the reference building 1 described in accordance with provisions in the standards (adapted from Paper II)*

for module A1-3 shows a negative value, whilst that of module C shows such a high positive value. In order to solve this issue, it would be relevant to separate fossil and biogenic carbon fluxes in the assessment results, for instance, as shown in figure 4-6 (Paper II). In the figure, the biogenic carbon fluxes and fossil GHG emission can be seen separately in addition to the GWP. Here the meaning of GWP can be understood clearly in relation to the biogenic and fossil carbon aspects. This way could fairly express the environmental features of wood construction and would also help to detect targets for mitigating the GWP of the building being studied.

4.1.4 System boundary for the assessment

In the definition given in EN 15978, the construction stage (module A4-5) includes processes from the delivery of the construction products from factory gate to the completion of the on-site construction work. This means that, in principle, the prefabrication process of the building elements and their transportation are counted in the product stage (module A1-3), as shown in the fig. 4-2 and 4-5. However, this arrangement would lead to at least two problems. Firstly, the allocation of environmental impacts linked to the prefabrication process to module A1–3 would make the comparison of product data difficult. Secondly, the results for module A1-3 may be distorted in favour of an on-site oriented construction system. In other words, proper interpretation of the assessment results would become rather difficult. In general, the degree of prefabrication seems to be increasing in construction work (Nord 2008). It would, therefore, be worth considering the prefabrication process as part of the construction stage



	A1-3	A4-5: P	A4-5: O	B1	B2	B3	B4	B5	B6	B7	C	D
■ Biogenic Carbon content	-461	33	0	MNA	0	0	0	0	0	MNA	428	0
■ Fossil GHG emission	371	40	42	MNA	9	0	30	0	1119	MNA	27	-210
● GWP	-90	73	42	MNA	9	0	30	0	1119	MNA	455	-210

Figure 4-6. *Global warming potential of reference building 1 described in accordance with the discussions (Adapted from Paper II)*

(module A4-5) and subdividing the stage into two information modules (e.g. module "A4–5: P" for prefabrication process, module "A4-5: O" for on-site construction process), as shown in figs. 4-4 and 4-6. This approach will give more transparency to the assessment results that would bring developments in the efficiency of the process. Moreover, in this system, the environmental benefits from the prefabrication process waste, which are regarded as co-products in the current standards, can be described in module D. This would be fair, especially for wood construction with a high degree of prefabrication, since the most of construction waste is generated during the prefabrication process.

4.2 Optimal use of wood in sustainable construction

Based on the results reported in Papers III-V, the more reasonable utilization of wood products and how they could be further developed in sustainable construction is discussed here in light of the three indicators described in section 3.3.3 (primary energy balance, GHG balance and cost balance). The discussion is in accordance with the principles of appropriate material selection over the building life cycle, summarised from the literatures (figure 4.7) (UNEP 2007, 2008 and 2009, Sathre and O'Connor 2010). As for learning from vernacular buildings, the discussion is covered from a wider perspective and insights are included in the discussion where relevant. Furthermore, the fact that the relative importance of life cycle phases other than the use phase of a building increase when the operational energy performance of a building improves, is taken into account in the discussion, since the results in papers III-V are based on current building energy standards. The energy supply system (e.g. electricity mix, space heating technology, ventilation system) significantly affects the indicators mentioned above (Dodoo 2011, Joelsson 2008). However, this aspect is not discussed in detail here as it is not within the focus of this study.

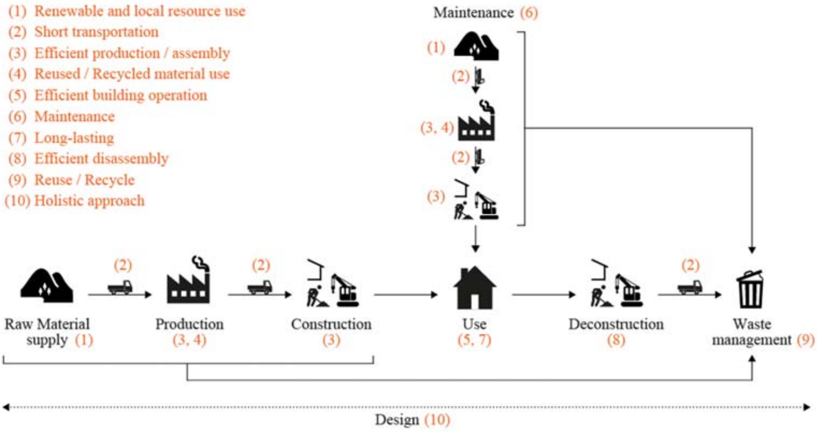


Figure 4-7. *Principles for appropriate material selection for sustainable construction*

4.2.1 Renewable and local resource use

Several social trends – rapid population growth, continuous economic development, a higher standard of living and technological change – all contribute to an increase in natural resource use. Using and processing natural resources causes environmental impacts (e.g. land, water and air pollution) and disturb the ecosystems (e.g. decrease in biodiversity). The construction industry is one of the largest consumers of natural resources (UNEP 2008). Renewable natural resources, in this context, cause less impact than non-renewable resources mainly because of their possible continuous supply (EPA 2005). Wood as a renewable construction material, thus, plays an important role in mitigating the environmental impacts of buildings.

However this idea must be considered in terms of sustainable forestry. A flow of wood products can be maintained indefinitely with proper forest management, but wood is not an infinite resource. Unfortunately, today, sustainable forestry practices have not been implemented worldwide (EPI 2010) and this means that wood cannot be regarded as a renewable resource in a global context at the moment. To solve this problem, and in contrast with commonly held beliefs, increasing the use of wood may be an effective solution since it positively contributes to maintaining and increasing forests (CEI-Bois 2014). In many cases, increasing wood use enhances the market value of forests to the local community, which is a significant incentive to preserve them. In addition, Liu and Han (2009) noted that total carbon storage in living trees and wood products in the long term could be greatest in scenarios with increased harvesting levels. In such situations, stakeholders in the construction project (e.g. client, architect or constructor) are naturally required to use wood products that are certified as being from sustainable forests. Nowadays there are more than 50 different forest certification programs all over the world, representing about 8% of the global forest area and 13% of managed forests (USDA 2010). The world's certified forests are mainly located in the northern hemisphere - North America and Europe. It would be significant to globally increase the certified area in such a way as to positively contribute to the development of a sustainable environment by using more wood in construction. An appropriate balance between the production (acquisition) from, and the consumption of, forest resources should be considered in each region, based on the annual increment.

Before industrialization, buildings were obviously constructed with local materials, since there was limited means of long distance transportation. Wood, in particular, is a location dependent material so that even wood from the same species can show different properties and behaviour if grown in different places (Nishioka 1988). Therefore, traditionally, it is noted that timber should be locally resourced (Thoma 2003). Increasing the use of local forest resources would also stimulate the local economy and proper forest management, as discussed previously. In Europe, for instance, most wood products are consumed domestically (more than 80% according to CEI-Bois 2006), so that it is often claimed that European wood products contribute less to environmental impacts because of short transport distances (CEI-Bois 2014). Morel et al (2001) noted that the embodied energy of a reference building constructed with local materials - stone masonry structure and rammed earth wall structure - could be reduced by 215% and 285%, respectively, compared to the case of a typical concrete structure due, mainly, to the difference in transportation distances. It is clear that, in general, shorter transportation distances lead to the lower impacts (This issue in relation to wood products will be discussed further in section 4.2.2.). However, it may also be argued that the use of local material is not always viable in the context of an internationalized society. For instance in Japan, the domestic forest resource accounts for less than 30% of the total annual domestic consumption (MAFF 2013), even though the domestic resource could fully satisfy demand. Most wood products are imported from all over the world over a long distance. This is mainly because of the elimination of tariffs for industrial round wood in 1951 and the trade liberalization of wood products that started in 1964 (Yamada 2012). The self-sufficiency ratio of wood in Japan has decreased as the price of domestic wood has increased. As mentioned by Morel et al. (2001), sometimes the adaptation of local materials in developed countries may also be difficult due to the loss of traditional construction skills as well as a lack of suitable building standards.

4.2.2 Short transportation

Transportation occurs in several life cycle stages of a building as shown in figure 4-7. Transportation distance should ideally be as short as possible in terms of environmental and economic efficiency. Transport at the end of life stage of a building tends to be short, since the waste management of deconstructed materials are in general conducted in local plants in order to optimize the cost. On the other hand, transport in the production and construction stages seems to be case specific. Normally, loading is optimised from an economic aspect; however, transport distance is not always in proportion to the price of a product. Thus, sometimes a product can be bought from a distant country due to cheaper prices, even though the same product might be available in a neighbouring city. In the construction industry, this trend seems to be more conspicuous for wooden products compared to other materials such as concrete and steel. Concrete consists of cement, aggregates and water, which are globally available. Cement is primarily consumed close to the area of production because of the availability of the raw materials and the high cost of transport relative to its value, particularly over land. Only 5.8% of world production is traded, with 40% of this trade between regions. In the steel market, about 30% of world production is traded. Nevertheless, the major proportion of trade is between neighbouring regions (Watson et al. 2005). Since these are very common construction materials, concrete and steel mills can be found in many parts of the world. Thus, the secondary processing of these materials is normally carried out near to the construction site.

On the other hand wood is, as mentioned before, a location dependent material because the availability of suitable wood species differs from region to region. Trade in wood-based products has been active mainly between Europe, North-America and Asia and recently the global trade volume of wood products has been growing. About 30% of sawn timber produced is nowadays traded (FAO 2013b). This ratio is even higher in the European Union (FAOSTAT 2015). In addition, the international trade in secondary processed wood products (SPWPs) is rapidly increasing (FAO 2007). For instance, about 20% of the world production of wood-based panel products are traded (FAOSTAT 2015) and this figure is likely to increase even more in the future because of increasing demand and the higher profits of SPWPs to manufactures (FAO 2007). SPWPs require greater manufacturing skill than primary products (e.g. logs and sawn timber). Thus, the mills for SPWPs tend to be unevenly distributed in certain regions.

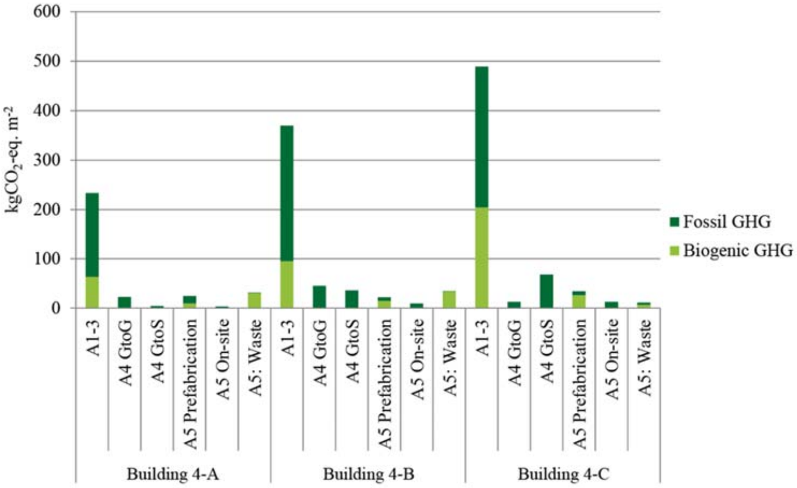


Figure 4-8. *Greenhouse gas emissions for module A. A1-3: Product stage, A4 G to G: Transport of building components from product factory to prefabrication factory, A4 G to S: Transport of building components from prefabrication factory to construction site, A5 Prefabrication: Prefabrication work in the factory, A5 On-site: Construction work on the site, A5 Waste: Waste management process (Adapted from Paper V)*

Figure 4-8, which shows the GHG emissions (from both fossil and biogenic sources) in the production and construction phase (module A) of the three multi-storey wooden residential buildings (reference buildings 4-A, B and C (Table 3-1)) clearly displays this trend (Paper V). The transport (module A4) has a relatively high share in the construction stage (module A4-5), approximately 30% in the case of building 4-A and more than 50% in the case of buildings 4-B and C. It is remarkable that the transportation of building components results in higher GHG emission than the actual construction work, module A5, in buildings-B and C. This result mainly stems from the long delivery distance of the CLT panels. For instance, the CLT used in building 4-B was delivered over 2300km by truck and ferry. There seems to be great potential to mitigate the environmental impacts from the transport of building components and elements, which has also been noted by Cole (1999). In particular, the transport process of the wooden building components seemed to have greater potential for mitigating emissions than the actual construction work. Considering this point in the material selection process would be a relevant point for improvement. For instance in Japan, it has been demonstrated that the construction of an ordinary detached house (approximately 130m^2) with either local wood or domestic wood could reduce the GHG emission from the transport of wooden components by about 93% or 82% respectively compared to construction with wood imported from Europe (Takiguchi 2006).

4.2.3 Efficient production/assembly

The material production phase is, in general, the second most important in terms of the life cycle environmental impacts of a building. In addition, the construction process is appreciably influenced by the building material selection (Gerilla et al. 2007, Eriksson 2003, Cole 1999). Wood products are normally regarded as contributing less to the environmental impact in the production and construction phases compared to other common construction materials (UNEP 2007, Eriksson 2003). In principle, more processed materials consume more energy in the production process and light-weight structures (e.g. wood and steel frames) require less energy in the construction process compared to heavy-weight structures (e.g. concrete and brick frames).

Figure 4-9 shows the assessment results of reference building 2 (table 3-1) in the production stage with the six alternative frame materials for the eight indicators (Paper III). The figure is displayed as the relative relationship between the alternative frame materials (difference index). A notable point here is that the cross laminated timber (CLT) frame shows the poorest results in terms of the non-renewable embodied energy and material cost, even though it is wood construction. This result can mainly be

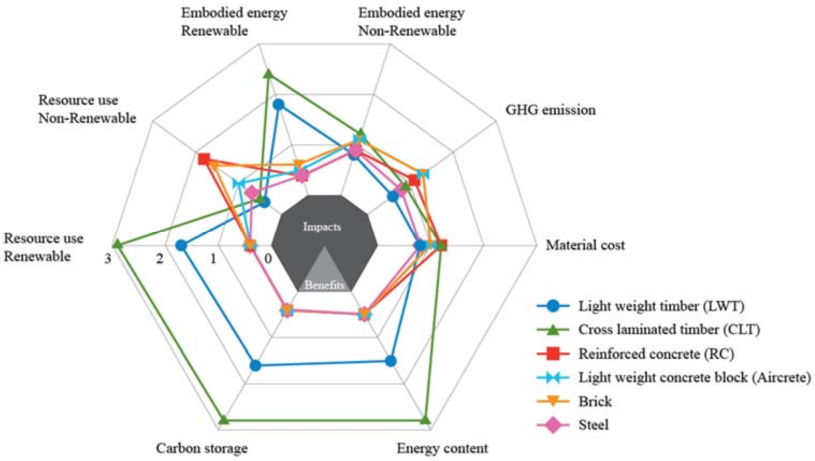


Figure 4- 9. *Difference index of the reference building 2 with the six frame materials on the indicators (Adapted from Paper III)*

explained by the following; 1) relatively high production energy per kg, 2) large quantity used and 3) inefficient configuration of building elements. The composition of the CLT framed building is normally quite similar to that of a concrete framed one, consisting of as massive structural layer plus some additional functional layer (e.g. insulation, wind barrier, exterior cladding). In addition, when fire protection is required on the interior cladding, the interior CLT surface needs to be covered by a fire proofing board, like gypsum board. In short, the CLT framed building tends to have duplicate layers, although the CLT as such may cover these functions.

Traditional vernacular buildings had a very simple composition due to the limited resources and technology. For instance, the log cabin introduced in section 2.5 consisted of just a single massive wooden layer, which had multifunction. After modernization (at the beginning of 20th century), buildings became more complex by increasing the number of layers in the envelope in response to the functions required. However, CLT, as an advanced massive timber structure which can fully exploit the physical properties of wood (e.g. low thermal conductivity, thermal/moisture buffering property, fire retardancy), may have the possibility to again simplify and rationalize the composition of a building by incorporating several functions. CLT may alone be able to form the exterior wall, for instance, if its properties could be developed so as to comply with building regulations (e.g. fire regulation, thermal performance) (figure 4-10). This sort of product development would enhance the environmental and economic sustainability of wood construction.

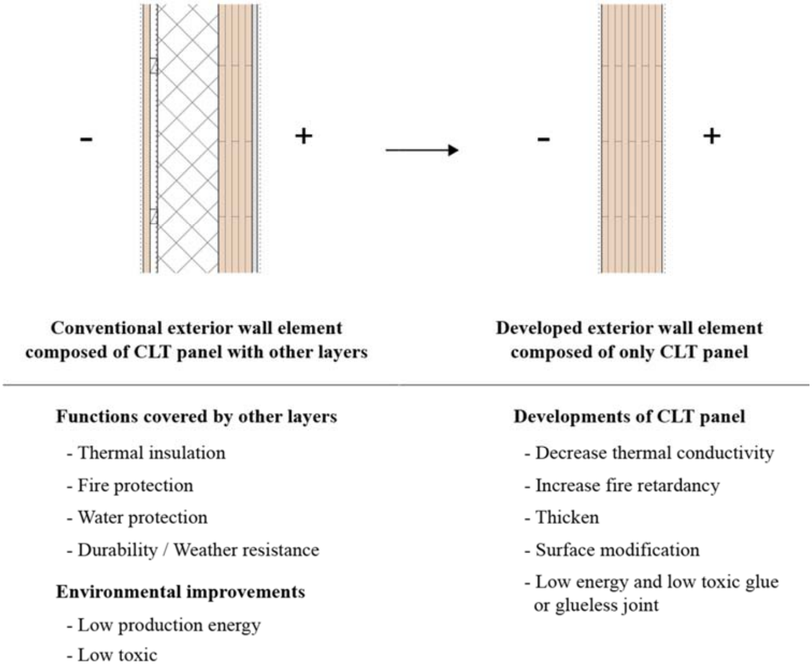


Figure 4- 10. *Simplification of the exterior wall element based on the multifunctionalization of CLT panel*

For every indicator the differences between the other alternative materials are, in general, relatively minor, although the light weight timber frame (LWT) shows the best results in many cases. However, the order of magnitude between the frame materials varies depending on the indicators. Understanding such materials' characteristics would be significant for proper decision-making. In addition, it should also be noted that variation in the material cost between the alternatives is minor compared to the other indicators, as shown in fig. 4-9. This is the same trend that Yasantha Abeysundara et al. (2009) found, meaning that the environmental parameters should be considered more than economic factors in decision-making.

Although the influence of material selection on the construction process has not been investigated in this study, the effect can be studied from previous studies (Cole 1999, Cole and Kernan 1996, Eriksson 2003). Althouh these studies are rather dated, they do show that light-weight structures (e.g. wood and steel), in general, contribute to less energy consumption and GHG emission than heavy-weight structures (e.g. concrete) in the construction process. Low weight would be advantageous during the transportation and handling of building elements.

The difference between a prefabrication oriented system and an on-site oriented system for wood construction with regard to the GHG emission was studied in Paper V. As shown in figure 4-11, the on-site construction process tends to generate more waste than prefabrication, which means more building components are required for the on-site oriented system. In the construction process (module A5: Prefabrication and On-site), the prefabrication system shows slightly smaller emission values than the on-site system on the basis of fossil GHG emission. This finding is consistent with the results of a previous study (Quale 2012). In the prefabrication system, space heating energy for the factory, which was generated by a biomass boiler, accounted for a significant share. On the other hand, diesel for operating construction machines was the dominant energy source in the on-site system. This difference in the energy source between the systems is a notable point. The possible use of biomass fuel seems to be a positive feature of the prefabrication of wood-based building elements, since residues from the wood process can be utilized directly. Although it would be difficult to draw any definitive conclusions from this result alone, due to the small sample size and the assumptions made, prefabrication seems to be a more efficient construction method compared to on-site work.

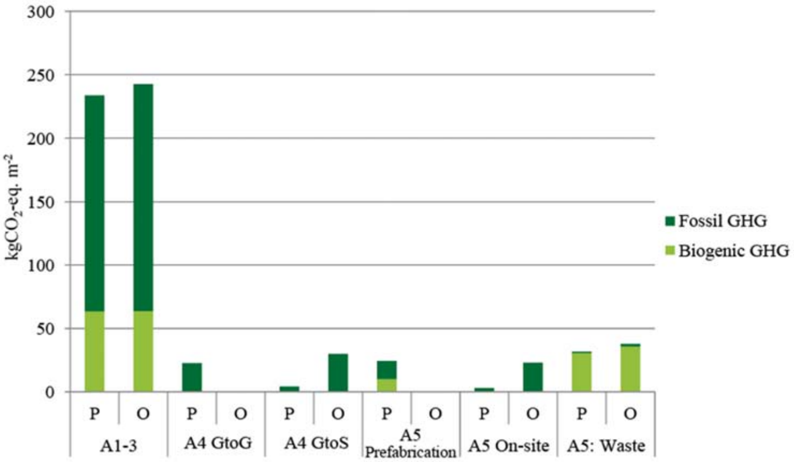


Figure 4- 11. *Comparison of the prefabrication oriented system (P) and the on-site oriented system (O) in terms of greenhouse gas emission for module A1-5 based on the reference building 4-A. A1-3: Product stage, A4 G to G: Transport of building components from product factory to prefabrication factory, A4 G to S: Transport of building components from prefabrication factory to construction site, A5 Prefabrication: Prefabrication work in the factory, A5 On-site: Construction work on the site, A5 Waste: Waste management process(Adapted from Paper V)*

4.2.4 Reused/Recycled material use

Traditionally, valuable construction materials from buildings that had been dismantled were reused in new construction (Kimura et al. 1999). The reason for this was simply that the availability of resources was limited and the value of building materials was much higher than now. For instance, harvesting a large tree from a forest with hand tools was definitely heavy labour, so that harvested wood had to be utilized as fully as possible. On the other hand, nowadays, functional materials are available at reasonable price. Therefore new, rather than reused or recycled, materials are normally selected for the construction, unless there is a significant difference in function or cost.

The use of more reused/recycled material in construction now, however, could give environmental and economic savings, at least in the short-term. In particular, the potential environmental benefits have widely been investigated. For instance, recovered wood used as a secondary material could give several direct effects such as saving natural resources, reducing production energy and construction waste, and delaying carbon emission (Sathre and Gustavsson 2006, Thomark 2000 and 2006, Nakajima and Futaki 2001, Hiramatsu et al. 2002, Peuportier 2001, Obata et al. 2006, Dodoo et al. 2012). Recovered wood is normally dried sufficiently to ensure that its moisture content is in equilibrium with the surroundings which, in principle, can lead to improved dimensional stability and strength (Miyazaki et al. 2003). For example, it has been demonstrated that the compression strength of recovered wood is generally higher than that of virgin wood (Hirashima et al. 2004, Yamasaki et al. 2005). Moreover, the Young’s modulus of recovered wood is, in many cases, higher than that of virgin wood although bending and shear strength seem to vary depending upon wood species (Ooka et al. 2011, Hirashima et al. 2005, Chini and Acquaye 2001).

Although, for instance, in most cases post-use wood is either chipped into particles or incinerated for energy generation in the EU at the moment (Leek 2010), there is deemed to be good potential to enhance the reuse/recycling of post-use wood in relatively large dimensioned products. For instance, if structural strength and adequate dimensions are secured in recovered wood from the deconstruction of buildings, an application through reprocessing into smaller dimension, such as batten or stud may be assumed at a reasonable price. Some special wood species or large dimension timber may have a high resale value if they can be carefully removed from a building by hand. There are certainly barriers to the use of reused/recycled material in construction due to economic and market factors, industry-wide reluctance, lack of information and a long habit amongst customers to use new material (Horvath 2004). In addition, the recycling of preservative-treated wood depends on several factors (USDA 2010).

Some preservatives used in the past may, for instance, include severely toxic substances that affect human health. Thus, preservatives should be carefully distinguished and need to be treated properly when reusing/recycling such treated wood. In spite of these obstacles, however, the application of secondary products should be increased as reuse/recycle becomes universal. Clear classification of the recovered materials in terms of dimension and quality linking with proper applications could be a good starting point maximising their additional values. In addition, it may be a good approach to create a building code, which regulates, for instance, the proportion of reused/recycled material to be used in a building.

4.2.5 Efficient building operation

Although the operational energy demand of a building mainly relates to the thermal performance of building envelopes, the building service systems used and the occupants' behaviour (Santin 2013, Martani et al. 2012), this study has focused on how material selection affects the operational energy of a building from both physical and psychological aspects. A typical example would be how thermal mass affects space heating/cooling energy demands. Figure 4-12 shows the life cycle primary energy balance of the reference building 3 (table 3-1) with the six structural frame materials and three alternative frame material combinations (table 3-2). Both renewable and non-renewable primary energy (PER and PENR, respectively) consumptions and ben-

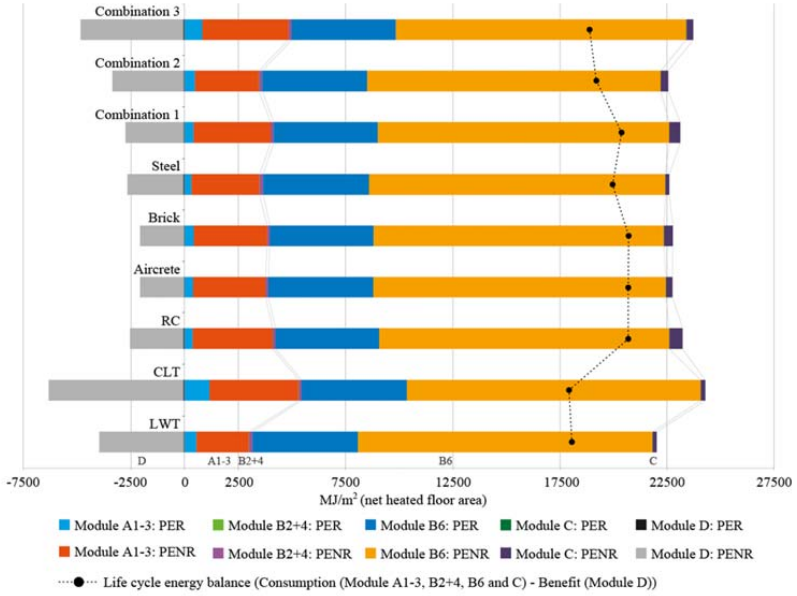


Figure 4-12. *Life cycle energy balance of the reference building 3 with the six frame materials and three alternative combinations (Module B6 includes only space heating energy use) (Adapted from Paper IV)*

efits are described according to the life cycle stages studied. As discussed in paper IV, the heavy-weight structures (RC, Aircrete and Brick) showed slightly lower space heating energy demands than the light-weight structures (LWT, CLT and steel). In addition, CLT shows a slightly lower demand than even the lighter structures - LWT and Steel. This can be understood as the energy saving benefit due to the thermal mass effect of the structural frame materials. The energy savings benefit of the heavy-weight structures in relation to the case of the highest space heating demand (steel frame) is 1.1-2.0% (fig. 4-12). This thermal mass effect can also be observed even in the structural frame combinations (1-3) shown in fig. 4-12 in which the RC elements are partly combined with the wooden (LWT and CLT) structures (table 3-2, Paper IV). Even though the life cycle primary energy consumption becomes worse when the RC elements are combined with LWT, in comparison to the original LWT, space heating energy demand decreased slightly as the amount of RC increased. These results are consistent with previous studies (Ståhl 2009, Dodoo et al. 2012, Jokisalo and Kurnitski 2005), which found space heating energy savings due to thermal mass to be around 0.7-2.0% for Nordic buildings.

Figure 4-13 shows the effect of material selection for the interior claddings (sheathing) on the primary energy balance of reference building 3 (table 3-1), according to the life cycle stages (Paper IV). In general, the influence on space heating (module

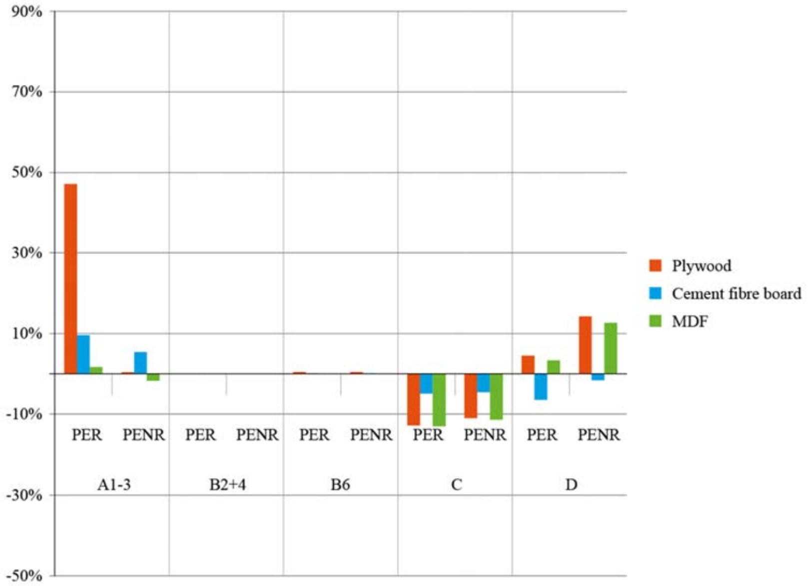


Figure 4-13. *Percentage relative differences in the assessment results of the reference building 3 caused by the different sheathing materials (Reference is a gypsum board. Module B6 includes only space heating energy use) (Adapted from Paper IV)*

B6) is not particularly noticeable from the perspective of thermal mass. This would mainly be because of the thickness of each material, since the effect is related to the heat capacity of the materials and their relative volumes. The results shown before indicate that the thermal mass effect seems to be minor in space heating energy savings; however, effective thermal mass design can be found in traditional buildings. For instance, it was said that the inside of the pit dwellings was quite warm and normally there was no need to light a fire in the fireplace (Hasegawa 1987, Nomura and Utagawa 2004). As mentioned in section 2.5, the traditional Finnish log cabin was heated by a stove and the smoke released into the cabin. The cabin would be heated for only a couple of hours per day and would be a very energy and resource efficient heating method compared to modern stoves (Huttunen 2012). It is obviously not realistic to directly incorporate this type of heating system into a modern building due to current building regulations and living style, however, there may be some useful ideas to be gained from this traditional solution. For instance, the stove, typically made of stone, was relatively large in comparison to the room size (figure 2-2, 4-14); therefore, it could store a large amount of heat even after a couple of hours firing. In addition, the cabin consisted of large cross-section logs, which would provide good thermal insulation as well as thermal mass. In short, it could be thought that the whole structure of the cabin afforded significant thermal mass. This measure might be developed to make up for any inadequacy in the thermal performance of the building envelope and space heating system, which might tend to cause uneven heat distribution in a room. As may be learned from these traditional building systems as well as the study conducted in Paper IV, the amount of thermal mass compared to the volume of space would be an interesting topic for further study. A reasonable balance between thermal insulation

Figure 4-14. *Heating a smoke cabin with a large stove. (Salio 2011)*

and thermal mass of a building may give a new approach to efficient building operation. Thermal mass is important especially in light-weight structures, like wood construction. In this sense, massive timber structures (e.g. CLT and log) seem to have potential for further development.

The interaction between space heating/cooling energy demand and building materials should be discussed from other aspects as well. For instance, the indoor surfaces of exposed massive wood, like CLT, provide moisture buffering effects that can passively mediate the indoor climate resulting in a reduction in space heating energy consumption (Hameury and Lundström 2004, Orosa and Oliveira 2009, Osanyintola and Simonson 2006). For instance, Osanyintola and Simonson (2006) noted that the interior use of hygroscopic materials with well-controlled HVAC systems might reduce heating and cooling energy demands by up to 5% and 30%, respectively. In addition, although CLT exhibits a lower thermal mass effect than heavy-weight structures, as mentioned above, in general, people feel “warm” with massive wooden interior surfaces thanks to its haptic and visual impressions (Höppe 2002, Masuda 1999). With these wood effects, the occupant may feel warmer than the actual room temperature and thus the setting of the indoor temperature may be lower, resulting in operational energy and cost savings.

Moreover, it was noted that wooden interior spaces could reduce the fatigue and stress of occupants more than vinyl and concrete interior surfaces (Saito et al. 2009, Kitta et al. 1992). These kinds of psychological effects that wooden interior surfaces have may change the meaning of the building operation. For instance, the concept of therapeutic architecture, that can heal occupants, may be designed for. If a building can promote the occupant’s health, medical expenses may reduce and an attachment to the building may be formed. These new aspects would be particularly promising topics for the further development of wood products.

4.2.6 Maintenance

The maintenance of a building includes cleaning, painting, component repair/replacement and large-scale refurbishment. These activities vary depending on several factors such as the properties of a material, its location in a building, building location, detailing and occupant’s behaviour. For instance, carpet flooring may last about 10 years under normal use, whilst stone flooring may last for more than 100 years even under heavy use. Although maintenance is a complex issue, it should be an important aspect for sustainable construction, directly relating to the physical service life of a building. Traditionally, buildings were continuously maintained and renovated due to the reasons discussed in section 4.2.4. For instance, Japanese traditional wood construction was periodically maintained according to the material's durability and location/function. Typically the repair of the timber frame occurred every 100-200 years, whilst the replacement of surface components, such as roofing and cladding, every 25-30 years. In addition, the buildings were constructed in such a way as to ease the maintenance (e.g. easy disassembly systems with all-timber connections, the possibility of partial replacement and repair). By incorporating these measures, buildings could have centuries' long lives (Uchida 2009, Kimura et al. 1999).

Figure 4-15 shows an overview of the influence of surface and inner component material selection on the life cycle energy balance of reference building 3 (table 3-1, Paper IV) in the same way as figure 4-12. On the whole, the differences between the alternatives are minor compared to the structural components (fig. 4-12), but differences can be seen at some points in the maintenance stage (module B2+4). As shown in figure 4-16, the primary energy consumption in the maintenance of flooring materials varies between the alternatives (Paper IV). Since the floor is the part of the building that wears quickly in daily use, maintenance is an important aspect. For instance, PVC flooring sheet requires higher primary energy in module B2+4 compared to the refer-

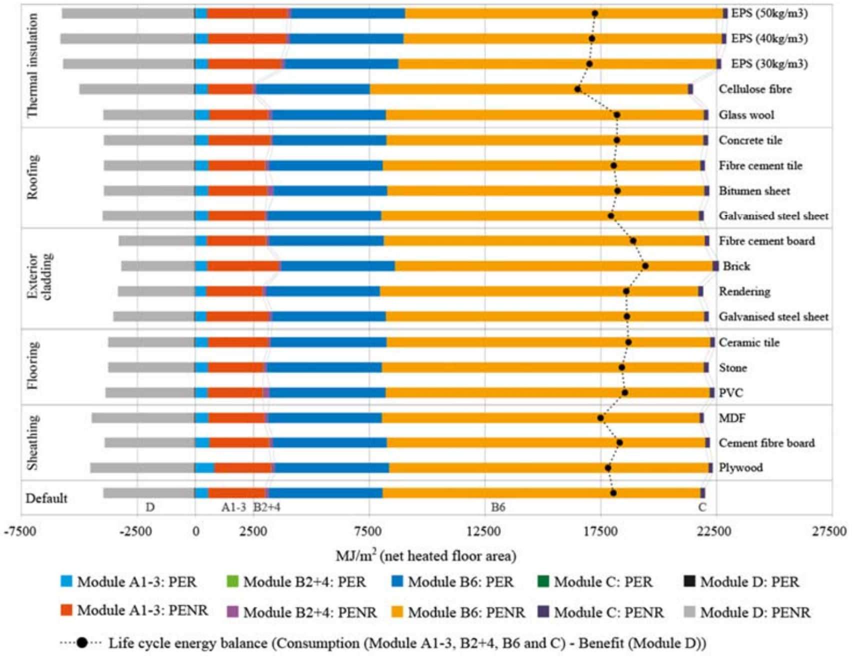


Figure 4-15. *Life cycle energy balance of the reference building 3 with the alternative materials in the surface and inner components (Module B6 includes only space heating energy use) (Adapted from Paper IV)*

ence case (wood plank flooring) due to its higher maintenance demand. Although it consumes less energy in the production stage, this option ends up with a higher life cycle energy balance than the reference (fig. 4-15). This result is just about the energy balance, but the same issues can be considered in a different way.

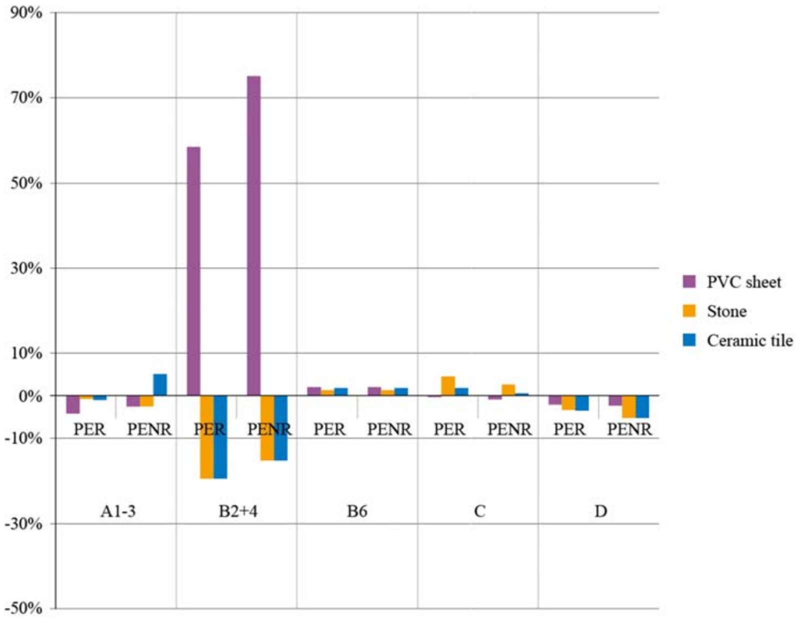


Figure 4-16. *Percentage relative differences in the assessment results of the reference building 3 caused by the different flooring materials (Reference is wood planking. Module B6 includes only space heating energy use) (Adapted from Paper IV)*

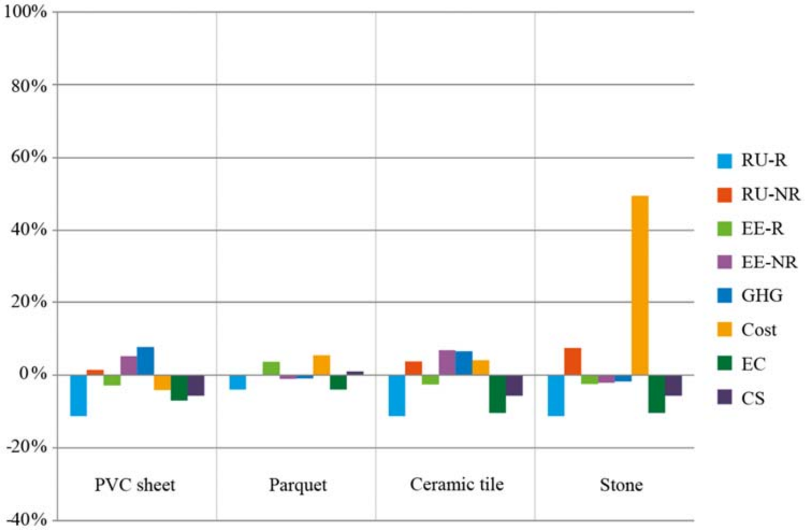


Figure 4-17. *Percentage relative differences in the assessment results of the reference building 2 in the production stage caused by the different flooring materials (reference is wood planking) (Adapted from Paper III)*

Figure 4-17 shows the effect of flooring material selection in reference building 2 (table 3-1) on several indicators: renewable/non-renewable resource use (RU-R/RU-NR), renewable/non-renewable embodied energy (EE-R/EE-NR), GHG emissions in the material production stage, material cost, energy content and carbon storage. As can be seen form the figure, PVC flooring sheet is a cheaper option than wood plank flooring at the production stage, but it will cost even more afterward due to the maintenance activities. On the other hand, although the initial cost of stone flooring is about 50% more than wood plank flooring, it requires less energy for maintenance, which would result in lower maintenance costs as well. Exterior and interior claddings are also important building parts to be properly maintained. Since they are exposed to heavy use conditions and weather in daily life, physical deterioration will be faster than other building parts. In addition, such building surfaces directly relate to the visual quality of a building. Maintenance of the claddings thus has multiple roles (e.g. to keep functionality, visual impression) on building conditions. As mentioned before, the influence of maintenance activities may be negligible in the life cycle energy of a building, but it should be considered from several aspects because of its significance in sustainable construction.

The life span of wood products can be as long as centuries under ideal conditions, as has been demonstrated throughout history. However, wood can also deteriorate easily if exposed to conditions that favour the development of wood-degrading organisms (USDA 2010). Therefore, wood tends to have the reputation of being a maintenance intensive material. The major organisms that attack wood are fungi and insects. Serious decay caused by fungi strongly correlate with the moisture content of wood. Therefore, in the first place, it is fundamental to keep wood dry (e.g. moisture content of 20% or less). In that sense, it is important to: 1) select a suitable wood product (species) for the chosen location in a building, and 2) ensure proper detailing to keep wood dry and promote drying when it gets wet. Chemical preservation (e.g. preservatives) and modified products (e.g. thermally modified wood, densified wood) should also be considered according to the conditions and concept of a building. Combination with non-wood products is, of course, a basic approach. On top of the proper design of a building, the occupant’s awareness is important for the maintenance. Maintaining wood products in a building may be thought of as being similar to growing a flower or plant. Wood products are natural materials so that their expression will change in accordance with level and way of maintenance. If an occupant can find joy in maintenance activities, like cultivating plants, affection in the building may be born. That will definitely extend the life span of the building. Appropriate design leading to ideas about how to live with a building should be considered in order to stimulate this tendency in an occupant.

4.2.7 Long-lasting

A primary factor in sustainable construction is the design and building of long life structures. Due to limitations imposed by the building technology prevailing at the time, traditional buildings had simple configurations and were composed of homogeneous structural members. However, such simplicity was also the result of long improvement (Murakami 2008). In addition, the service life of a building mainly related to physical factors (e.g. aging, deterioration), which could be mitigated by proper maintenance, as discussed in the previous section. In the context of traditional vernacular buildings, there might be no conscious sense of the end of a building's life cycle. In the modern age, building service life is subject to several factors, not only physical factors but also functional, technical, economic, legal and social obsolescence (König 2010). Therefore, it is not easy to attain long life in buildings even if that is the original intention.

Physical obsolescence is mainly caused by the initial quality of a building and poor maintenance. Good quality requires initial investment, which is not normally preferable for clients. The maintenance issue can be tackled relatively easily since the problem is normally clear and controllable. Functional and technical obsolescence could, in principle, also be accommodated by designing adaptability and renewability of the building's program and building service systems. For these points, a regular inspection strategy would be important. Economic value loss is the most common reason for demolition (König 2010), which stimulates scrap and build activities. This aspect also relates to legal obsolescence. Naturally, it is necessary to update buildings in accordance with new building regulations. However, it is normally difficult to meet that requirement in a building that has already lost economic value. It is also quite natural that during its life cycle, the style of a building falls out of vogue. Long life cannot be expected if a building's atmosphere conflicts with an epoch. At present, it is a challenge to realize long-lasting buildings due to these complex factors. History, however, at least teaches us that a building with essential functionality and beauty possibly has timeless value. Such buildings could be loved by people beyond logic and time, and become a permanent fixture. This kind of building can give rise to movements like Docomomo (1988), whose main missions are to conserve the architectural heritage of the modern movement and to foster interest in heritage over economic value. Of course not every building can achieve this level of quality, but at least a building should be designed and built based on such sustainable consciousness.

In that sense, wood may have an advantage over other common construction materials because it may hold charm as it ages. As a wood surface changes its visual expression over time – as it darkens with age, for example – people may find this pleasing. As discussed previously, wood also has several other properties (e.g. haptic, olfactory, warmth, antibacterial, etc.), which differs according to the species. These diverse characteristics of wood could be a key to producing a building that is loved. In general wood construction physically ages faster than other construction systems, like concrete and steel. However, wood buildings can have an even longer service life than the others with proper periodical maintenance and repair, as has been historically demonstrated. The forest can grow in parallel with the maintenance period, so that traditionally a semi-permanent resource circulation and building service life could be realized in wood construction (Uchida 2009).

Building reuse, in general, creates less environmental impact than new construction in the case of the same building size and functionality (e.g. operational energy performance). For instance, a previous study (NTHP 2012) noted that the environmental savings from building reuse could be from 4 to 46% over new construction, depending on the building type, location and assumed level of energy performance. In addition, the study also found that new building with 30% more energy efficiency takes from 10 to 80 years to overtake average-performing existing building in terms of life cycle energy. The authors concluded that even the reuse of an average level building consistently offers immediate reduction in environmental impact compared to the new construction of a more energy efficient building. In addition, Liu and Han (2009) found that the carbon stock in living trees and wood products was about 10% less in the case of a 50 year product life span compared to a 100 year life span, as the stock in the product pool becomes lower when the service life is shorter.

4.2.8 Efficient disassembly

As shown in figure 4-12, heavy-weight structures (reinforced concrete (RC), Aircrete and Brick) seem to require higher energy than the light-weight structures (light weight timber (LWT), cross laminated timber (CLT) and steel) in the end of life stage of a building (Paper IV). This is the same trend as discussed in section 4.2.3. In that sense, although wood construction has an advantage, optimization of the disassembly process contributes to a further reduction in the environmental and economic impacts of the stage and enhances the reuse/recycling potential of post-use construction materials. As previously discussed, traditional vernacular buildings were simply composed of a single or a few materials so that it was easy to disassemble the building with little damage to the materials, a large proportion of which could be then be reused. As is well known, Japanese traditional wood construction was basically built with only all-timber joints (Nishioka 1988, Uchida 2009), therefore, it was easy to disassemble a building component-by-component. In contrast, in the modern age, the configuration of a building became complex and industrial products were often developed as composites with several different materials in order to meet the functional requirements (Kimura et al. 1999). For this reason, the disassembly of a building became difficult and the degree of material recycling dropped, then as a result, the amount of waste increased. Thus design for disassembly is very important and should be included in the initial building design phase (Crowther 2003, Guy 2003, Thormark 2001). Efficient disassembly based on proper design would maximise the potential for the reuse/recycling of post-use materials, as demonstrated in traditional building practice.

Disassembly design has been widely studied and has been suggested by several researchers (Nordby 2009, Crowther 2005, Guy and Ciarimboli 2008, Thormark 2001). Common guidelines include the use of mechanical joints rather than gluing to increase the removability of components, and to simplify the configuration of a building, reducing the number of materials used. Moreover, documenting the inventory of materials used in a building is fundamental. Considering the jointing method would naturally be effective in a construction system consisting of a number of connections, like a light weight timber frame system (e.g. post and beam structure, timber framed panel structure). The simplification of the building configuration could be developed in a massive timber system (e.g. CLT panel structure, log structure). As discussed in section 4.2.3, it would be an ideal case for disassembly as well if, for instance, the exterior wall of a building could be composed solely of a CLT layer. This would possibly be a unique development for massive timber construction.

In order to stimulate the disassembly design of wood construction in practice, regional recycling chains of post-use wood would need to be established in the construction material market. Several related factors, such as an extension of the reused/recycled materials application as discussed in section 4.2.4, rationalization of their price compared to the virgin materials and a trade system for post-use wood between the building owner, demolition companies and product manufactures, should be developed.

4.2.9 Reuse/Recycle

The amount of construction and demolition waste (C&DW) in the European Union (EU), for instance, accounts for about one third of the total waste (by weight) generated by economic activities (Eurostat 2015). The amount of C&DW has recently been increasing in parallel with active construction activities, and its harmful impacts on the environment have been widely discussed. Following this trend, increasing the recycling ratio of C&DW is one of the main issues facing society nowadays (Toji and Fischer 2011). As noted by Höglmeier et al (2013), for instance, there seems to be significant potential for the stock of wood products in existing buildings to be cascaded.

In many cases, post-use wood products are reused or recycled as a fuel or secondary products. Thanks to its inherent properties (e.g. carbon storage, energy content), the reuse of post-use wood products may give significant environmental benefits. Reusing post-use wood as a secondary product simply extends the carbon storage period in the product. Burning post-use wood as a fuel contributes not only to energy recovery but also to a reduction in net GHG emission, through the substitution of fossil fuel use. As can be seen in figure 4-12 and 4-15, the energy benefits (module D) becomes relatively high in the case of wood products used due to the reasons discussed above. Here it was assumed that 90% of post-use wood is recycled as a fuel. EPS insulation, which was also assumed to be reused as a fuel, shows higher energy benefits than in the case of wood-based insulation (cellulose fibre). However, since EPS is a fossil-based material, cellulose fibre would still be a preferable option if both energy and GHG aspects are taken into account.

Basically the entire tree can be utilised either as product or as fuel and this is an advantage of wood compared to other building materials. Therefore, co-products and process waste generated in the construction process of wooden building are also useful resources. The recycling of wood should be important because such biomaterials are considered to be a key player in the material economy of a sustainable society. Hoogwijk et al. (2003) has noted that the demand for biomaterials and biomass fuel is expected to increase significantly during the coming 50 years. Although forest resources are renewable, they are finite as well. Therefore, it is significant to use the available wood resources efficiently, and in such context, cascading utilization, which is defined as the sequential use of resource for different purpose (Haberl and Geissler 2000), should be taken into consideration further in the future. As Börjesson and Gustavsson (2000) studied, there would be good balance in the application of post-use wood, between burning as a fuel and reusing/recycling as secondary product, on the life cycle energy and GHG balance of buildings.

A cascade chain could be more conceivable when large dimension products (e.g. CLT panel, glulam) were used. The large products can be made into smaller products by cutting them up. The small products (e.g. 2x4 sawn timbers) could also be cascaded by, for instance, gluing them together into a glue-laminated product. In any event, wood products can finally be incinerated with energy recovery, so it would be advantageous to utilize wood as many times as possible as a product beforehand. Such cascading wood may possibly create new business opportunities, stimulating the wood product industry.

4.2.10 Holistic approach for building material selection

As discussed, material selection for sustainable construction is a complex issue. Wood especially is a more diverse material than other common building materials such as concrete and steel. Factors associated with wood (e.g. moisture content, strength, dimension, carbon storage, energy content, visual and haptic quality, fragrance) vary from piece-to-piece and from time-to-time. Thus, it would be important to utilize wood according to the purpose and its features on a case-by-case basis. Since there is no perfect material in every sense, all materials need to be fairly handled. The idea “the right material in the right place” developed in history should be recalled.

Nevertheless, in many cases cost has priority over the other aspects. In reality, for now it would be very difficult to consider, for instance, the environmental impacts on equal terms as the material cost when selecting materials. Thus, it would be significant to develop a system that could connect economic aspects to the other aspects and enable several factors to equally considered in the decision making process. For example, if there is a discount system in proportion to the environmental impacts of products in the market, there are more choices than ever before. The CO_2-Performanceladder (Termeer and Vastbinder 2012), which is a procurement tool to encourage companies to be aware of their CO_2 emissions, is a good example that brings a notional discount on the tender price in proportion to the CO_2 performance of their product or service. This is an instrument developed for sustainable procurement. A new tax system on building materials, like a carbon tax (CIE 2011), may also be one measure. As discussed in section 4.2.8, a post-use material purchasing method wouldbe effective in promoting recycling system, as it has worked nicely in, for instance, the car industry.

5. Conclusions

Traditional vernacular architectures were based upon a deep understanding of the surroundings and the features of locally sourced building materials. This wisdom was translated into a rational building composition and appropriate material usage, and supported the attainment of adequate living conditions and a proper building life cycle, without any advanced technologies. Recently, a reduction in the environmental impact of a building during its life cycle has been intensively discussed. Material selection especially has a significant role to play in sustainable construction since a building is a complex system consisting of many different components. In such a context, wood products have lately attracted considerable attention as promising construction materials due to their unique environmental properties. In many cases, simply the use of wood is often regarded as a sustainable building solution and in general this would be correct. However, little work has been conducted on how wood in construction can be further developed from a life cycle perspective for the sustainability of buildings. In order to tackle this question, this study referred to the traditional building solutions in conjunction with the core results of the appended papers.

This thesis basically dealt with two topics; a discussion of methodological issues for the assessment of wood products and wood construction, and a comprehensive discussion about wood in sustainable construction over the building life cycle. Firstly, methodological issues were studied based on the current normative standards and assessment data. The results indicated the significance of the number of appropriate product data and a clear statement of the assessment basis for a fair and comparative assessment. It has been highlighted that, since wood has more diverse environmental characteristics and production process than other common building materials such as concrete and steel, an appropriate description of these features in product data as well as the building assessment result is important.

Secondly, wood in construction was discussed based on the results of the comparative studies regarding the relationship between the material selection and the sustainability of a building (mainly the environmental aspects), with reference to traditional building solutions. The discussion was arranged according to ten principles in terms of appropriate building material selection over the building life cycle. It was found that there are both strengths and weaknesses in the use of wood depending on the life cycle stages. In this sense, the importance of diverse perspectives to building materials has been highlighted. In particular it was found that although a massive timber structure, like a CLT framed building, has certain weaknesses (e.g. high embodied energy) it would have potential for contributions to the environment in a different manner. A reduction (e.g. of resource use, energy consumption and GHG emissions) has thus far been a principle to mitigate environmental problems. However, wood products may have the possibility to contribute to the environment more positively with more use, by optimising the weaknesses (environmental impacts) and maximising the strengths (environmental benefits). For instance, as discussed in chapter 4.2.3, the multifunctionalization of a building component that was practiced in traditional buildings could be a possible means. In that case, the building composition can be simplified dramatically and the life cycle energy balance of a building will significantly change. The energy consumption in the production, construction, maintenance and EoL stages may be decreased and the energy benefits from the reuse/recycling of building materials may be increased. If this measure can be applied to a zero-energy building (zero net operational energy consumption), a net plus life cycle energy building can be even imagined. In addition, the more wood is used, the more the forest may be activated, the carbon storage pool may be increased, the substitution of fossil based fuel and products may be stimulated and so forth. This would be a paradigm shift from the current approach to the environmental problems. The environmental impacts are simply determined by the impact of an activity (unit impact) and the number of people who do it. In a situation of population growth, an idea of efficiency would not be enough. Not only optimizing the unit impact but also turning the situation (population growth) into a positive way for humans and the environment would be required. In that sense, wood seems to have significant potential. It would be important to consider a specific approach and use for wood in construction.

To achieve this goal, there is the need to learn about the characteristics of wood more deeply. Several further research topics could be found through this study. For instance, the psychological effects of wood (via its appearance, haptic feeling, fragrance, etc.) would be an important topic, since it may influence not only building operation systems but also a human’s wellbeing in a building. Further studies should also examine, from various aspects, the interaction between the materials and other factors, such as the building type, scale, geometry, location, climate condition, etc. Moreover, the effects of different material combinations would be a relevant topic for future study so as to develop “the right material in the right place” concept. The assessment of traditional vernacular buildings as such would also be an interesting topic. This study is subject to the limitation of the number of case studies including certain types of material, sustainability indicators and scenarios. Therefore, repeated case studies would be significant to generalize the information and develop a more comprehensive understanding of wood in sustainable construction in comparison with other materials, from a human oriented perspective.

References

Balaras CA. 1996. The role of the thermal mass on the cooling load of buildings: an overview of computational methods. Energy Build. 24(1): 1-10.

Basbagill J, Flager F, Lepech M, Fischer M. 2013. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. Build Environ. 60: 81-92

Bell M. 2004. Energy efficiency in existing buildings: the role of buildingregulations. In CO-BRA Proc. of the RICS Foundation Construction and Building Research Conference. September 7-8. Leeds. UK.

Börjesson P and Gustavsson L. 2000. Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land use perspectives. Energy Policy 28(9): 575-588.

CEI-Bois (The European Confederation of woodworking industries). 2014. Tackle Climate Change: build with wood. Brussel. Accessed at: http://www.cei-bois.org/files/BuildWithWood.PDF. on January 5, 2015

CEI-Bois (The European Confederation of woodworking industries). 2006. Tackle Climate Change: Use wood. Brussel. Accessed at: http://www.cei-bois.org/files/FINAL_-_BoA_-_EN_-_2011_text_and_cover.pdf. on October 10, 2014

CFP. 2013. CFP database, JEMAI CFP Program (Japanese). http://www.cfp-japan.jp/calculate/verify/data.html

Chini AR, Acquaye L. 2001. Grading and Strength of Salvaged Lumber from Residential Buildings. Environmental Practice 3 (4); 247-256.

CIE (Centre for International Economics). 2011. Effects of a carbon price on the building and construction industry. Research report. Accessed at: The existing economic system needs to be developed by linking other factors with economic value of materials. on February 11, 2015

Cole RJ and Kernan P. 1996. Life-cycle energy use in office buildings. Build Environ. 31(4); 307-317.

Cole RJ. 1999. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. Build Environ. 34(3): 335–348.

Crowther P. 2003. Design for disassembly: an architectural strategy for sustainability. Doctoral thesis. Queensland University of Technology. Brisbane.

Crowther P. 2005. Design for disassembly – Themes and Principles. RAIA/BDP Environmental Design guide. Queensland University of Technology. Brisbane.

Docomomo (documentation and conservation of buildings, sites and neighbourhoods of the modern movement). 1988. http://www.docomomo.com/mission

Dodoo A, Gustavsson L, Sathre R. 2012. Effect of thermal mass on life cycle primary energy balances of a concrete- and a wood-frame building. Appl Energ 92; 462-472.

Dodoo A. 2011. Life cycle primary energy use and carbon emission of residential buildings. Doctoral dissertation. Department of Engineering and Sustainable development, Mid Sweden University. Östersund, Sweden

EC-JRC-IES (European Commission - Joint Research Centre - Institute for Environment and Sustainability). 2010. International Reference Life Cycle Data System (ILCD) Handbook – General guide for Life Cycle Assessment - Detailed guidance. First Edition. Publications Office of the European Union, Luxembourg

ecoinvent. 2013. ecoinvent version 3. Ecoinvent center. http://ecoinvent.org/database/

Emori S. 2004. Ainu's history and culture II (Japanese). Publication group for "Ainu no rekishi to bunka". pp.114-123. Sendai

EN 15804: 2012+A1:2013. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. European Committee for Standardization

EN 15978: 2011. Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method. European Committee for Standardization

EN 16449: 2014. Wood and wood-based products – Calculation of the biogenic carbon content of wood and conversion to carbon dioxide. European Committee for Standardization

EN 16485: 2014. Round and sawn timber – Environmental Product Declarations – Product category rules for wood and wood-based products for use in construction. European Committee for Standardization

EPA (U.S. Environmental Protection Agency). 2007. Energy trends in selected manufacturing sectors: Opportunities and Challenges for Environmentally preferable energy outcomes. Accessed at: http://www.epa.gov/sectors/pdf/energy/report.pdf on November 9, 2013

EPA (United States Environmental Protection Agency). 2005. The quest for less, Activities and Resource for teaching K-8, Chapter 1.1: Natural resources, pp. Washington, DC.

EPI (Earth Policy Institute). 2010. World forest cover, 1990-2010. Forest resource assessment 2010: Global Tables. Accessed at: http://www.earth-policy.org/indicators/C56/forests_2012. on January 10, 2015

Eriksson PE. 2003. Comparative LCAs for wood construction and other construction methods: Energy use and GHG emissions. Swedish Wood Association.

Erlandsson M and Borg M. 2003. Generic LCA-methodology applicable for buildings, constructions and operation services—today practice and development needs. Build Environ 38(7):919–938.

European Commission (DG ENV). 2011. Service contract on management of construction and demolition waste – SR1, Final report Task 2. Accessed at http://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf. on September 20, 2014.

Eurostat. 2015. Eurostat statistics explained – Waste statistics (updated January 2015). Accessed at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics#Total_waste_generation. on January 19, 2015

FAO (Food and Agriculture Organization of the United Nations). 2013a. FAO Corporate document repository, Energy conservation in the mechanical forest industries. Accessed at: http://www.fao.org/docrep/T0269E/t0269e04.htm on October 10, 2013

FAO (Food and Agriculture Organization of the United Nations). 2013b. Forest products statistics, Global Forest Products facts and figures. Accessed at:

http://www.fao.org/forestry/35445-0e287e9c252335f2936d3cdc5b6bbd5ff.pdf. on January 23, 2015

FAO (Food and Agriculture Organization of the United Nations). 2007. Global wood and wood products flow, Trends and perspectives. Advisory committee on Paper and Wood Products. Accessed at: http://www.fao.org/forestry/12711-0e94fe2a7dae258fbb8bc48e5cc09b0d8.pdf. on November 11. 2013

FAOSTAT (Food and Agriculture Organization of the United Nations, Statistics division). 2015. Forest production and trade. Accessed at: http://faostat3.fao.org/download/F/FO/E. on February 4, 2015

Fava JA. 2006. Will the next 10 years be as productive in advancing life cycle approaches as the last 15years? Int J LCA 11(1):6–8.

Frischknecht R. 2006. Notions on the design and use of an ideal regional or global LCA database. Int J LCA 11; 40-48.

Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Dones R, Hischier R, Hellweg S, Humbert S, Margni M, Nemecek T, Spielmann M. 2007. Implementation of Life Cycle Impact Assessment Methods: Data v2.0. ecoinvent report No.3. Accessed at: http://www.ecoinvent.org/fileadmin/documents/en/03_LCIA-Implementation.pdf. on October 10, 2012

GaBi. 2013. GaBi 6 life cycle inventory data. GaBi Software. http://www.gabi-software.com/index/

Gerilla GP, Teknomo K, Hokad K. 2007. An environmental assessment of wood and steel reinforced concrete housing construction. Build Environ. 42; 2778-2784.

Gustavsson L and Sathre R. 2006. Variability in energy and carbon dioxide balances of wood and concrete building materials. Build Environ. 41(7): 940-951.

Guy B and Ciarimboli N. 2008. DfD - Design for disassembly in the built environment: a guide to closed-loop design and building. Hamer centre for community design. pp.132

Guy B. 2003. Building deconstruction: Reuse and recycling of building materials. Alachua County Solid Wastes Management Innovative Recycling project program. Accessed at: http://www.lifecyclebuilding.org/docs/Six%20House%20Building%20Deconstruction.pdf. on July 22, 2014.

Haberl H, Geissler S. 2000. Cascade utilization of biomass: strategies for a more efficient use of a scarce resource. Ecol Eng 16: 111–21.

Hameury S, Lundström T. 2004. Contribution of indoor exposed massive wood to a good indoor climate: in situ measurement campaign. Energy Build. 36; 281-292.

Harvey LDDD. 2009. Reducing energy use in the building sector: measures, costs, and examples. Energy Efficiency 2(2): 139-163.'

Hasegawa S. 1987. Suomalainen Puu Rakenteinen Talonpoikaistalo (Japanese). Inoue shobo. Tokyo

Hendrickson CT, Horvath A, Lave LB, McMichael FC. 1996. New markets for old materials. TR News 184:32–35

Hennigar CR, Maclean DA, Amos-Binks LJ. 2008. A novel approach to optimize management strategies for carbon stored in both forests and wood products. Forest Ecology and management 256(4): 786-797.

Hiramatsu Y, Tsunetsugu Y, Karube M, and Tonosaki M, Fujii T. 2002. Present state of wood waste recycling and a new process for converting wood waste into reusable wood materials. Material Transactions 43(3): 332-339.

Hirashima Y, Sugihara M, Sasaki Y, Ando K, Yamasaki M. 2004. Strength properties of aged wood II: Compressive strength properties, shearing strength and hardness of aged Keyaki and Akamatsu woods (in Japanese), Mokuzai gakkaishi 50: 368-375.

Hirashima Y, Sugihara M, Sasaki Y, Ando K, Yamasaki M. 2005. Strength Properties of aged Wood III: Static and impact bending strength properties of aged keyaki and akamatsu wood (in Japanese). Mokuzai gakkaishi 51: 146-152.

Höglmeier K, Weber-Blaschke G, Richter K. 2013. Potentials for cascading of recovered wood from building deconstruction – A case study for south-east Germany. Resour Conserv Recy 78: 81-91.

Hoogwijk M, Faaji A, Van den Broek R, Berndes G, Geilen D, Turkenburg W. 2003. Explanation of the ranges of global potential of biomass for energy. Biomass Bioenergy 25(2): 119-33.

Horvath A. 2004. Construction materials and the environment. Annu. Rev. Environ. Resour. 29; 181-204.

Huttunen M. 2012. Architect and Restoration master. Person interview on November 16, 2012

IBO. 2013. IBO-Richtwerte für Baumaterialien. http://www.ibo.at/de/oekokennzahlen.htm

IBU. 2013. Institut Bauen und Umwelt, Environmental Product Declarations. Accessed at: http://construction-environment.com. on December 23, 2013

IDA ICE (IDA indoor climate and energy). 2014. EQUA Simulation AB. Online at: http://www.equa.se/index.php/en/

IEA (International Energy Agency). 2011. Technology roadmaps – Energy efficient buildings: Heating and Cooling equipment. Accessed at: http://www.iea.org/ on April 3, 2013

IEA (International Energy Agency). 2013. Transition to sustainable buildings, Strategies and Opportunities to 2050, Executive summary. Accessed at: http://www.iea.org/media/training/presentations/etw2014/publications/Sustainable_Buildings_2013.pdf on November 9, 2014

ISO 14040: 2006, Environmental management – Life cycle assessment – Principles and frameworks. International Organization for Standardization.

ISO 14044: 2006, Environmental management – Life cycle assessment – Requirements and guidelines. International Organization for Standardization.

ISO 14067: 2013, Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification and communication. International Organization for Standardization.

ISO 21929-1: 2011. Sustainability in building construction – Sustainability indicators – Part 1: Framework for the development of indicators and a core set of indicators for buildings. International organization for standardardization.

Itard L, Meijer F, Vrins E, Hoiting H. 2008. Building renovation and modernisation in Europe: State of the Art Review. OTB Research institute for housing, Urban and mobility studies. Delft University of Technology. Netherlands

Joelsson A. 2008. Primary energy efficiency and CO_2 mitigation in Swedish residential buildings. Doctoral dissertation. Department of Engineering and Sustainable development, Mid Sweden University. Östersund, Sweden

Jokisalo J, Kurnitski J. 2005. Effect of the thermal inertia and other building and HVAC factors on energy performance and thermal comfort in Finnish apartment buildings. Report B79, Helsinki University of Technology. Laboratory of Heating, ventilating and Air-Conditioning, Helsinki

Karimpour M, Belusko M, Xing K, Bruno F. 2014. Minimising the life cycle energy of buildings: Review and analysis. Build Environ. 73: 106-114.

Kimura K et al. 1999. Minka no shizen energy gijyutsu (Japanese) (Energy technology in traditional residential house). Shokoku-sha. Tokyo

Kitta K, Hattori Y, Ogawa M. 1992. Effects of wooden building materials in a school building on teacher's health state and educational environment (Japanese). Aichi University of Education research report 16; 59-66.

König H, Kohler N, Kreißig J, Lützkendorf T. 2010. A life cycle approach to buildings: Principles, calculations, Design tools. Detail Green Books. Munich.

Korhonen T. 2011. The heritage of new comers – Finnish Features in the tradition. CIAV Vernadoc 2010. Suomen ICOMOS, kansanrakentamisen komitea. pp. 29-35. Helsinki.

Kuosa H. 2012. Reuse of recycled aggregates and other C&D wastes. Technical research centre of Finland VTT, research report VV-R-05984-12. Accessed at http://www.vtt.fi/inf/julkaisut/muut/2012/VTT-R-05984-12.pdf. on September 20, 2014.

Leek N. 2010. Post-consumer wood. EUwood - Final report. pp 93-96 (160 p.). Hamburg

Leroy C, Thomas JS, Avery N, Bollen J, Tikana L. Tackling recycling aspects in EN 15804. Proceedings of the International Symposium on Life Cycle Assessment and Construction – Civil Engineering and Buildings. Accessed at http://www.metalsustainability.eu/wp-content/uploads/2014/06/11-11-15-ModuleD-metals.pdf. on May 25, 2015.

Lindberg M. 2011. Structures of a Finnish Chimneyless cottage. CIAV Vernadoc 2010. Suomen ICOMOS, kansanrakentamisen komitea. pp.166-167. Helsinki.

Liu G and Han S. 2009. Long-term forest management and timely transfer of carbon into wood products help reduce atmospheric carbon. Ecological Modelling 220(13-14); 1719-1723.

MAFF (Ministry of Agriculture, Forestry and Fisheries, Japan). 2013. Forest resource supply and demand. Forest agency. Tokyo

Martani C, Lee D, Robinson P, Britter R, Ratti C. 2012. ENERNET: Studying the dynamic relationship between building occupancy and energy consumption. Energy Build. 47; 584-591.

Masuda M. 1999. Why people like wood? (Japanese). Report of Forest Products Research institute Japan. Hokkaido

Miyazaki H, Tanaka K, Inoue M, Takanashi H, Hirata M, Hano T. 2003. Recycling of timbers from wooden house by handworked demolition system, Proceedings of JSCE; 748: 81-89.

Mohammed TI, Greenough R, Taylor S, Meida LO, Acquaye A. 2013. Operational vs. embodied emission in buildings – A review of current trends. Energy Build. 66: 232-245.

Moncaster AM, Symons KE. 2013. A method and tool for ´cradle to grave` embodied carbon and energy impacts of UK buildings in compliance with the new TC350. Energ Buildings 66:514–523.

Morel JC, Mesbah A, Oggero M, Walker P. 2001. Building houses with local materials: means to drastically reduce the environmental impact of construction. Build Environ. 36: 1119-1126.

Murakami S. 2004. CASBEE: New labelling system based on Environmental Efficiency and designed to fit all lifecycle stages. The symposium on Green Building Labeling. Hong Kong

Murakami S. 2008. Environmental assessment of Vernacular Architecture (Japanese). Keio University Press. Tokyo

Nakajima S and Futaki M. 2001. National R&D project to promote recycle and reuse of timber construction in Japan, Deconstruction and Material reuse. Accessed at; http://www.irbnet.de/daten/iconda/CIB753.pdf. on April 19 2014.

Nishioka T. 1988. Ki ni manabe –Horyuji, Yakushiji no bi (Japanese) (Learn from wood - Beauty in Horyuji and Yakushiji temple). Shogakukan. Tokyo

Nomura T and Utagawa H. 2004. Ancient-Satsumon-Ainu culture in Hokkaido. Hokkaido Shimbun press. Hokkaido

Nord T. 2008. Prefabrication strategies in the timber housing industry – Case studies from Swedish and Austrian markets. Technical Report, Luleå University of Technology. Accessed at: http://epubl.ltu.se/1402-1536/2008/16/LTU-TR-0816-SE.pdf. on March 31, 2014

Nordby AS. 2009. Salvageability of building materials – Reasons, Criteria and Consequences of designing buildings to facilitate reuse and recycling. Doctoral dissertation. Norwegian University of Science and Technology. Trondheim, Norway

NTHP (national Trust for Historic Preservation). 2012. The greenest Building: Quantifying the envieonmental value of building reuse, Executive summary. Accessed at; www.preservationnation.org/information-center/sustainable-communities/green-lab/lca/The_Greenest_Building_lowres.pdf. on February 1, 2015.

Obata Y, Takeuchi K, Soma N, Kanayama K. 2006. Recycling of wood waste as sustainable industrial resources, Design of energy saving wood-based board for floor heating systems. Energy 31 (13): 2341–2349.

Ooka Y, Tanahashi H, Izuno K, Suzuki Y, Toki K. 2011. Strength and embedment properties of old wooden members used in Japanese traditional wooden buildings (in Japanese). Journal of structural engineering 57B: 335-342.

ORNL (Oak Ridge National Library). 2001. Thermal mass – energy savings potential in residential buildings; 2001. Accessed at: http://www.ornl.gov. September 9, 2014.

Orosa JA, Oliveira AC. 2009. Energy saving with passive climate control methods in Spanish office buildings. Energy Build. 41; 823-828.

Osanyintola OF, Simonson CJ. 2006. Moisture buffering capacity of hygroscopic building materials: Experimental facilities and energy impact. Energy Build. 38: 1270-1282.

Palolahti T, Kivimäki C, Mäki T. 2013. ROK – Rakennusosien Kustannuksia 2013. Rakennustieto Oy. ISBN 9789522670359

Pawelzik P, Carus M, Hotchkiss J, Narayan R, Selke S, Wellisch M, Weiss M, Wicke M, Patel MK. 2013. Critical aspects in the life cycle assessment (LCA) if bio-based materials – Reviewing methodologies and deriving recommendations. Resour Conserv Recy 73: 211-228.

Peeredoom EC, Rene K, Saul L, Sven L.1999. Influence of Inventory Data Sets on Lice-Cycle Assessment Results: A Case study on PVC. J Ind Ecol 2:109–147

Peuportier BLP. 2001. Life cycle assessment applied to the comparative evaluation of single family houses in the French context. Energy Build 33: 443-450.

Quale J, Eckelman MJ, Williams KW, Sloaditskie G, Zimmerman JB. 2012. Comparing environmental impacts of building modular and conventional homes in the United States. J. Ind. Ecol. 16(2): 243-253.

Ramesh T, Prakash R, Shukla KK. 2010. Life cycle energy analysis of buildings: An overview. Energy Build. 42: 1592-1600.

Rüter S and Diederichs S. 2012. Ökobilanz-Basisdaten für Bauprodukte aus Holz (German) (Life cycle assessment datasets for wood-based building product). Universität Hamburg, Thünen-Institute of Wood Research, Report No: 2012/01. Accessed at: http://literatur.vti.bund.de/digbib_extern/dn050490.pdf. on December 20, 2013

Sailo A. 2011. The smoke cabin of the Finnish people in Middle-Scandinavian. CIAV Vernadoc 2010. Suomen ICOMOS, kansanrakentamisen komitea. pp.122-124. Helsinki.

Saito Y, Nishimaki M, Tatsumi Y, Ono S, Konoshita M, Sasayama S, Saito K. 2009. Effects of wooden and vinyl interior finishes on stress reduction estimated by biological and psychological parameters. JWRS Journal 55(2); 101-107

Salio A. 2011. Keski-skandinavian Suomalaisten Savupirtti (Finnish). CIAV Vernadoc 2010. Suomen ICOMOS, Kansanrakentamisen komites. pp.118-121. Helsinki

Santin OG. 2013. Occupant behaviour in energy efficient dwellings: evidence of a rebound effect. J Hous and the Built Environ. 28; 311-327

Sartori I and Hestnes AG. 2007. Energy use in the life cycle of conventional and low-energy buildings: A review article. Energy Build. 39: 249-257.

Sathre R and Gustavsson L. 2006. Energy and carbon balances of wood cascade chains. Resour Conserv Recy 47: 332-355.

Sathre R and O'Connor J. 2010. A synthesis of research on wood products & Greenhouse gas impacts 2nd editions. FP Innovations (Technical report No. TR-19R). Vancouver, B.C. 117p.

Sathre R. 2007. Life cycle energy and carbon implications of wood-based materials and construction. Dotoral dissertation. Ecotechnology and Environmental Sciences, Mid Sweden University. Östersund, Sweden

Savo-seura K, Böök N, Huttunen M, Savolainen K. 2010. KANAJÄRVEN RESTAUROINTI-LEIRI 2009 (Finnish). Arkkitehtuurin julkaisuja 2010/106, Arkkitehtuurin historia ja Puurakentaminen.

Scharai-Rad M and Welling J. 2002. Environmental and energy balances of wood products and substitutes. Food and Agricultural Organization of the United Nations. Accessed at: http://www.fao.org/docrep/004/Y3609E/y3609e00.htm. on October 10, 2014

Scheurer C, Keoleian GA, Reppe P. 2003. Life cycle energy and environmental performance of a new university building: modelling challenges and design implications. Energy Build. 35: 1049–1064.

Ståhl F. 2009. Influence of thermal mass on the heating and cooling demands of a building unit. PhD dissertation, Department of Civil and Environmental Engineering, Chalmers University of Technology. Göteborg

Suikkari R. 2001. Wooden Town Tradition and Town Fires in Finland. Presentation in a workshop. Advanced research centre for cultural heritage interdisciplinary projects.

Synergia. 2010. SYNERGY Carbon Footprint tool. SYKE and Pöyry Building services Oy. http://www.syke.fi/en-US/Research__Development/Consumption_and_production_and_sustainable_use_of_natural_resources/Calculators/Synergy/SYNERGY_Carbon_Footprint_Tool_instructio%2826143%29

Takiguchi Y. 2006. Research note – 13 (Japanese). The Woodmiles forum. Accessed at: http://woodmiles.net/pdf/kn013.pdf. on February 9, 2015

Taloon. 2014. Online hardware store, taloon.com. Accessed at: http://www.taloon.com/. on January 22, 2014.

Termeer G and Vastbinder M. 2012. CO_2-Performanceladder 2.1 Handbook. Stichting Klimaatvriendelijk Aanbesteden & Ondernemen. Accessed at: http://www.skao.nl/images/cms/Handbook%20English%20concept%202.1.pdf. on May 25, 2015

The national building code of Finland, D3. 2012. Energy efficiency of buildings, Regulations and guidelines. Ministry of the Environment of Finland.

Thoma E. Dich sah ich wachsen. 2003. Über das uralte und das neue Leben mit Holz. Wald und Mond (Ki to tsukiau chie, Japanese translation). Jiyu-sha. Tokyo

Thomark C. 2000. Environmental analysis of a building with reused building materials. International Journal of Low Energy & Sustainable Buildings Vol. 1.

Thormark C. 2001. Recycling potential and design for disassembly in buildings. Research report TABK—01/1021. Lund University. Lund

Thormark C. 2002. A low energy building in a life cycle – its embodied energy, energy need for operation and recycling potential. Build Environ. 37: 429-435.

Thormark C. 2006. The effect of material choice on the total energy need and recycling potential of a building. Build Environ. 41: 1019-1026.

Toji N and Fischer C. 2011. Europe as a recycling society – European recycling policies in relation to the actual recycling achieved. European Topic Center on Sustainable Consumption and Production. Accessed at: http://scp.eionet.europa.eu/wp/ETCSCP%202per2011. on December 10, 2014

Tucker SN, Tharumarajah A, May B, England J, Paul K, Hall M, et al. 2009. Life cycle inventory of Australian forests and wood products. Report Project No. PNA008-0708. Forest & Wood products Australia (FWPA). Accessed at: http://www.fwpa.com.au onOctober 10, 2013

Uchida S. 2009. Nihon no dentoukenchiku no kouho (Japanese) (Traditional construction system in Japan). Ichigaya Shuppan. Tokyo

UNEP (United Nations Environmental Programme). 2007. Building and Climate change, Status, Challenges and Opportunities. Accessed at: http://www.unep.fr/shared/publications/pdf/DTIx0916xPA-BuildingsClimate.pdf on October 21, 2014

UNEP (United Nations Environmental Programme). 2008. Sustainable Building and Climate Initiative, Protocol for Measuring Energy Use and Reporting Greenhouse Gas Emissions from Building Operations.

UNEP (United Nations Environmental Programme). 2009. Building and Climate change, Summary for decision makers. Accessed at: http://www.unep.org/SBCI/pdfs/SBCI-BCCSummary.pdf on November 9, 2014

USDA (United States Department of Agriculture). 2010. Wood handbook, Wood as an Engineering Material. Forest Products Laboratory. Chapter 1: wood as a sustainable material. Wisconsin.

Verbeeck G and Hens H. 2010. Life cycle inventory of buildings: A contribution analysis. Build Environ. 45: 964-967.

Watson C, Newman J, Upton RHS, Hackmann P. 2005. Round table on Sustainable Development, Can transnational sectoral agreements help reduce greenhouse gas emissions? Organisation for Economic Co-operation and Development (OECD). Accessed at: http://www.oecd.org/sd-roundtable/papersandpublications/39357524.pdf. on November 9, 2013

Werner F. Taverna R. Hofer P. Richter K. 2005. Carbon pool and substitution effects of an increased use of wood in buildings in Switzerland: First estimates. Annals of Forest Science 62(8): 889-902.

Wittstock B et al. 2012. EeBGuide Guidance Document, Part A: PRODUCTS and Part B: BUILDINGS, Operational guidance or life cycle assessment studies of the Energy-Efficient Buildings Initiative. Project report. Accessed at: http://www.eebguide.eu on December 20, 2013

Wood for Good. 2013. Lifecycle Analysis datasets. Accessed at: http://www.woodforgood.com/sustainability/lifecycle-database/lca-datasets. on September 7, 2014

Yamada T. 2012. Transition of self-sufficient ratio of woor and price of domestic wood in relation to the trade liberalization. Report in upper house budget committee. Accessed at: https://www.yamada-toshio.jp/minutes/pdf/120808_02_03.pdf. on February 1, 2015

Yamasaki M, Hirashima Y, Sasaki Y. 2005. Mechanical properties of the used wood recycled from old temples (in Japanese). Journal of structural and construction engineering 588: 127-132.

Yasantha Abeysundara UG, Babel S, Gheewala S. 2009. A matrix in life cycle perspective for selecting suatainable materials for buildings in Sri Lanka. Build Environ. 44: 997-1004.

YM (Ympäristöministeriö, Finnish ministry of the Environment). 2008. Pientalon Huoltokirja (Finnish) (Single family house service book). Accessed at: http://www.neuvoo.fi/LinkClick.aspx?fileticket=vEPqO6/HHDc=. on July 7, 2014.

Yokoo N, Terachima T, Oka T. 2013. Embodied energy and CO_2 emission associated with building construction by using I/O based data and process based data in Japan. Proceedings of the Sustainable Buildings – Construction products & Technologies (SB13 Graz): 1313-1318.

Zhu L, Hurt R, Correia D, Boehm R. 2009. Detailed energy saving performance analyses on thermal mass walls demonstrated in a zero energy house. Energy Build. 41: 303-310.

Aalto-DD 97/2015

This doctoral dissertation, which is a summary of research works carried out in both the Department of Forest Products Technology and the Department of Architecture, discusses how wood in construction can be further developed from a life cycle perspective for the sustainability of buildings. In order to tackle this question, this study refers to the traditional building solutions in conjunction with the core results of the appended papers.

ISBN 978-952-60-6293-8 (printed)
ISBN 978-952-60-6294-5 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

Aalto University
School of Chemical Technology
Department of Forest Products Technology
www.aalto.fi

BUSINESS +
ECONOMY

ART +
DESIGN +
ARCHITECTURE

SCIENCE +
TECHNOLOGY

CROSSOVER

**DOCTORAL
DISSERTATIONS**