An investigation into the environmental sustainability of buildings in South Africa with a focus on timber building systems

by
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DECLARATION

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

This dissertation includes two original papers published in peer-reviewed journals, and two unpublished papers currently in preparation for submission to an accredited scientific journal. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

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Abstract

Buildings are responsible for about 33% of global anthropogenic carbon dioxide emissions, high-energy consumption and other environmental resource uses. Numerous studies over the past 20 years showed that wood-based constructions have lower environmental impacts in terms of energy use, global warming potential, air pollution, water pollution and solid waste production than steel and cement-based systems. However, there are still questions about the accuracy of green building rating tools.

The objectives of this research were to

(1) critically examine established international green building rating tools and methods to measure environmental impacts of buildings,

(2) to investigate and quantify the environmental impact of selected building systems, components, and processes (including transport) relevant to the South African context, and

(3) to develop a local environmental impact base and comparison models for timber-based building and future resource demand in South Africa.

A review of green building rating tools indicated that the well documented environmental benefits of using wood was not sufficiently reflected in these rating systems. Life cycle-assessment is recognized as the best way to holistically evaluate the environmental impacts of a building. However, there is a critical need for local life cycle assessment based research in South Africa and other developing countries on building products and processes.

At present, more than 70% of all sawn timber in South Africa is used in buildings, mainly in roof structures. A comparison between several roof truss systems (South African pine, Biligom and light gauge steel) using the life cycle assessment method showed that the two timber systems had overall the lowest environmental impact. Although the difference between the timber systems was small, light gauge steel had a 40% higher normalised impact over all assessed environmental impact categories.

In a modelling analyses where different future building market scenarios in South Africa were compared, it was shown that if wood based residential buildings increase its market share to 20%, the embodied energy and global warming potential of the sector decrease by 4.9% from the current

levels. If all new constructions is wood based, the total embodied energy and global warming potential of the residential building sector will decrease by 30.4%. It was shown that with the use of wood resources currently exported as chips, as well as planting trees in areas that have been earmarked for afforestation, it will be possible (in the long term) to sustain a future residential building market where all constructions are wood based.

A decision support tool was developed to compare the environmental impact of timber transport in and to South Africa. Transport linked to local and international timber sources and markets were modelled for global warming potential and primary energy impacts. It was shown that the Johannesburg, Nelspruit and Durban markets were well located within current local truck networks and showed lower global warming potential (GWP) values per ton kilometre compared to Cape Town and Port Elizabeth markets. Results also illustrated that importing timber from regions such as Cacador, Brazil to the Cape Town and Port Elizabeth areas using container shipping will have a lower global warming potential impact than using timber from the Nelspruit area with truck transport.

Opsomming

Geboue veroorsaak tot 33% van globale antropogeniese koolstofdioksiedvrylatings, hoë energie gebruik en ander omgewingshulpbron eise. Talle studies oor die afgelope 20 jaar toon dat houtgebaseerde konstruksie laer omgewingsimpakte het in terme van energiegebruik, globale verwarmingspotensiaal, lugbesoedeling, waterbesoedeling en vaste afvallewering in vergelyking met staal- en sementgebaseerde sisteme. Nogtans is daar steeds vrae oor die akkuraatheid van groenbou graderingstelsels.

Die doel van die navorsing was om

(1) die bestaande internasionale groenbou graderingstelsels en -metodes om die omgewingsimpak van geboue te meet, krities te ondersoek,

(2) om die omgewingsimpak van sekere bousisteme, komponente en prosesse (insluitend vervoer) relevant tot Suid-Afrika te ondersoek en te kwantifiseer en

(3) om ‘n plaaslike omgewingsimpak basis en vergelykingsmodelle vir houtgebaseerde geboue en toekomstige hulpbronvraag in Suid-Afrika te ontwikkel.

‘n Analise van groenbou graderingstelsels toon dat die omgewingsvoordele van houtgebruik nie goed gedokumenteer is nie en ook nie voldoende in die graderingstelsels aangetref word nie. Lewensiklus-analise word erken as die beste manier om die omgewingsimpak van geboue holisties te evalueer. Nogtans is daar ‘n kritiese behoefte aan plaaslike lewensiklus-analise gebaseerde navorsing in Suid Afrika en ander ontwikkelende lande oor bouprodukte en -prosesse.

Tans word meer as 70% van alle saaghout in Suid-Afrka gebruik in geboue, hoofsaaklik in dakstrukture. ‘n Vergelyking tussen verskillende dakkapsisteme (Suid Afrikaanse denne, Biligom en ligte staal) met behulp van lewensiklus-analise metodiek, het getoon dat die twee houtsisteme ‘n algehele laer omgewingsimpak het. Alhoewel die verskil tussen die onderskeie houtsisteme klein was, het die ligte staal ‘n 40% hoër as genormaliseerde impak getoon.

In ‘n modelleringsanalise waar verskillende toekomstige scenarios van die boumark in Suid-Afrika vergelyk word, toon dit dat as houtgebaseerde residensiële geboue se markaandeel toeneem tot 20%, die opgesluite energie en globale verwarmingspotensiaal van die sektor daal met 4.9% teenoor die huidige vlakke. As alle nuwe konstruksie houtgebaseer is, sal die opgesluite energie en globale verwarmingspotensiaal van die sektor met tot 30.4% daal. Verder is daar getoon dat genoegsame hulpbronne beskikbaar sal wees om ‘n slegs hout residensiële mark volhoubaar te ondersteun oor

die kort- en langtermyn. Dit sal vereis dat huidige houtspaanders, wat tans uitgevoer word, plaaslik gebruik word en bome aangeplant word op die voorgestelde areas.

‘n Besluitnemingsmodel is ontwikkel om die omgewingsimpak van die vervoer van hout in en na Suid-Afrika te vergelyk. Vervoer na plaaslike en internasionale houtbronne en -markte is gemodelleer om opgesluite energie en globale verwarmingspotensiaal te ondersoek. Daar is bevind dat die Johannesburg, Nelspruit en Durban markte goed geleë is ten opsigte van die huidige padvervoer netwerke, en het laer opgesluite energie en globale verwarmingspotensiaal getoon as Kaapstad en Port Elizabeth markte. Die bevindinge toon ook dat om hout in te voer van Cacador, Brasilië na Kaapstad en Port Elizabeth areas deur middel van skeepsvervoer, laer opgesluite energie en globale verwarmingspotensiaal toon, in vergelyking daarmee om hout vanaf die Nelspruit area per vragmotor te vervoer.

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All my colleagues, friends and family

My heavenly Father for the opportunity to learn and the Grace to persevere

Table of contents

Chapter 1. Introduction

Buildings are responsible for about 33% of global anthropogenic carbon dioxide emissions (Allwood et al. 2010). The construction and use of buildings involve high energy consumption, environmental pollution, and other environmental resource uses (UNEP 2009). There is no doubt that the way future towns and cities are developed will be a key to moving closer to environmental sustainability on earth. There are various ways to evaluate or measure the environmental sustainability of buildings. In South Africa the Green Building Council, established in 2008, performs "green star" ratings on buildings (GBCSA 2015). The SANS 10400 XA standard, to govern environmentally sustainable design, was implemented in 2011 and the EcoStandard South Africa in 2013 to rate building materials against environmental standards (SANS 10400 XA 2011; EcoStandard SA 2015). An increasing number of building and development companies and building material suppliers use “green-marketing” strategies to promote business. According to a global review of green building trends by McGraw Hill-Construction (2013), the South African building market shows the fastest growing green building activity rate in the world.

However, scrutiny of the measurement systems used in rating tools suggests that there might be room for improvement (Zuo & Zhao, 2014). For instance, there are few incentives in terms of the scoring methods in SA rating tools (as well as in many international rating tools) for selecting timber as a sustainable building material over steel or concrete. This is despite numerous international studies showing that wood-based constructions display lower environmental impacts in terms of energy use, greenhouse gas emission, air pollution, water pollution and solid waste production than steel and concrete systems (Koch 1992; Petersen & Solberg 2005; Werner & Richter 2007; Upton et al. 2008; Sathre & O’Connor 2010). There are two perceived problems. It seems existing scientific data on the environmental impacts of building systems has not been transferred into building rating tools and little data exist quantifying environmental impacts in South African or other developing country building systems.

Results from developed countries (especially from the Northern Hemisphere) cannot necessarily be applied in the South Africa industry, as both the manufacturing and in-use conditions are different in South Africa and other developing countries. The primary energy mix and operational residential energy demand various significantly, due to extremely cold climatic conditions as well as social and economic implications, compared to some Southern Hemisphere and developing countries. Life cycle assessment has been used in the building sector since 1990 and since then has developed into an important tool to evaluate the potential environmental impact of buildings (Ortiz et al. 2009). Based on the number of studies published in the last 15 years it is apparent that incorporation of

LCA in construction decision making is becoming more and more important in the United States, Europe and Asia (Singh et al. 2011).

Currently, every year about 2.3 million m^3 of sawn timber is produced in South Africa of which more than 70% is used for structural applications – mostly for roof trusses (Crickmay and Associates, 2017). Timber frame housing or other types of wood based residential constructions constitute an estimated 1% or less of the total residential housing market (Slabbert, W, 2017, email communication, November 28). There is a negligible percentage of industrial or commercial structures from timber in South Africa. One way of reducing the environmental impact of the building sector could be to increase the relative market share of timber based buildings. However, there are several aspects that need scrutiny if the market share of timber based buildings is to be increased based on expected environmental impacts. These include, amongst others, (a) quantifying the environmental impacts of different timber building market share growth scenarios, (b) the question of whether there is enough wood resources in South Africa to support significant growth in timber based building, and (c) the environmental impact of importing timber for building purposes.

The main objectives of this research were:

- To critically examine established international green building rating tools and methods to measure environmental impacts caused by timber and alternative building systems in South Africa.
- To investigate and quantify the environmental impact of selected building systems, components, and processes (including transport) relevant to the South African context.
- To develop a local environmental impact base and comparison models for timber-based building and future resource demand in South Africa.

Layout of the dissertation

This dissertation follows the accepted format of a set of published and unpublished papers. It consists of an introduction (Chapter 1), followed by two published papers (Chapter 2 and Chapter 3) and two unpublished papers (Chapter 4 to 5), each covering a specific objective within the research question. The two unpublished papers are in preparation for submission to an accredited scientific journal. Chapter 6 contains a complete summary of the main research outcomes.

Appendix A display the signed declarations by the candidate and co-authors regarding the nature and extent of contribution to each paper. This study was performed using numerous building and environmental literature and datasets, obtained from national and international sources. In each paper, the best available data was gathered concerning scope, time and resources. The following section briefly explain each paper's contribution to meet the research objectives.

Chapter 2

Crafford PL, Blumentritt M, Wessels CB. Sustainability and wood constructions: A review of green building rating systems and life-cycle assessment methods from a South African and developing world perspective. Published in: Advances in Building Energy Research (2018)

- This study reviewed current green building rating systems and literature on life cycle assessment methods in the building sector. Apart from rating systems and life cycle assessment, the importance of geographical origin of data and technological advancement in building development was investigated.

Chapter 3

Crafford PL, Blumentritt M, Wessels CB. 2017. The potential of South African timber products to reduce the environmental impact of buildings. South African Journal of Science. 113 (9/10), Art. #2016-0354.

- Currently, about 70% of all sawn timber produced in South Africa is used in roofing structures. In this paper three different roof truss systems were compared and assessed using adjusted life cycle assessment methodology. The study resulted in important environmental impact findings concerning the current South African truss and building industry.

Chapter 4

Crafford PL, Wessels CB. Unpublished. The potential of timber building systems to reduce global warming potential and embodied energy in residential housing structures in South Africa.

- The study investigated the potential for market growth in wood based building systems in South Africa and modelled the environmental impact of different growth scenarios. The study predicts current and projected national global warming potential and embodied energy impacts, based on several development scenarios. The potential of new wood resources to support the modelled timber building growth scenarios were also investigated.

Chapter 5

Crafford PL, Wolf C, Blumentritt M, Wessels CB. Unpublished. Environmental decision support tool for South African timber transport and supply.

- A concern for the timber building sector is the limited supply of sawn timber resources in South Africa in the short term. Significant growth in timber building might require imports. This paper described the South African timber market and life cycle assessment transport models for predicting the global warming potential and primary energy impacts, between truck and shipping. The paper reported the breakeven global warming potential distances, between importing timber by ship compared to local truck supply options.

The slight difference in format between Chapters 2-5 were as result of the journals they appear in or will be submitted to, for review.

Chapter 2.

Sustainability and wood constructions: A review of green building rating systems and life-cycle assessment methods from a South African and developing world perspective

Published in: Advances in Building Energy Research (2018)

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Abstract

This study reviews, from a South African and developing world perspective, green building rating tools and life-cycle assessment methods with a focus on wood constructions. Based on existing studies, it seems as if the well documented environmental benefits of using wood is not sufficiently reflected in the green building rating systems reviewed. Although life-cycle-assessment is recognized as the best way to holistically evaluate the environmental impacts of a building, it is resource intensive, can be highly complex, and is dependent on the availability of accurate data. The life-cycle assessment research results on which green building rating tools were based, were mostly from colder, northern hemisphere developed countries. This might result in an over-emphasis on the operating energy requirements of buildings at the expense of embodied energy and the importance of material choices. We therefore conclude that there is a critical need for local life cycle assessment based research in South Africa and other developing countries on the environmental impacts of different building products and processes.

Keywords: wood, green building, rating systems, life cycle assessment, developing world

1. Introduction

Green building (GB) is the 'practise of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life cycle from design, construction, operation, maintenance, renovation and deconstruction' (U.S. EPA 2014, p 1). According to Hwang and Tan (2012) GB should address ecological, social and economic sustainability of a building in the context of its community. The GB definitions above are well integrated in the following vision statement of the Green Building Council of South Africa (GBCSA) to 'lead the transformation of the South African property industry to ensure that all buildings are designed, built and operated in an environmentally sustainable way that will allow South Africans to work and live in healthy, efficient and productive environments' (GBCSA 2014b, About us section).

According to the United Nations Environmental Protection Agency (UNEP), in South Africa, the total embodied and operational energy consumed in construction, including both residential and non-residential buildings is about 27% of the national annual energy consumption (Milford 2009). A similar figure was stated in the UNEP report on the carbon dioxide (CO_2) emissions created by the building industry in South Africa. However, these figures seem quite conservative compared to other literature. For instance the UK construction industry accounts for approximately 50% of CO_2 emissions, including life cycle processes of the construction work and the use phase of the building, and is responsible for almost a third of all industry related pollution occurrences (BIS 2010). In the United States buildings account for 38% of CO_2 emissions and up to 41% of the annual electricity usage (EIA 2015). Lower emissions related to buildings in South Africa compared to international averages are partly due to the fact that more than 30% of the population lives in small informal and low emission impact housing (Milford 2009). The total number of residential homes in South Africa, "amounted to about 12.5 million units in 2006 of which about 8.5 million are formal units and about 4 million units are backyard properties, informal and squatter units, and traditional housing" (Milford 2009). Informal and squatter units are typically constructed from corrugated iron, are smaller than $80m^2$ and have no or limited municipal services. Traditional houses are usually constructed from earth and branches and have grass or thatch roofs. This high percentage of informal housing units is representative for developing countries (Drakakis-Smith 1981).

According to a global review of GB trends by McGraw Hill Construction (2013), the South African building market shows the fastest growing GB activity rate in the world. Sixty percent (60%) of newly planned commercial buildings have GB plans, making this the most reported sector, and up to 36% of firms report green activity for low-rise residential projects. South Africa is one of few countries with a high level of green activity in residential markets – this may reflect an environmental conscious approach to building in the country. However, it is also one that is motivated by economic considerations since developers and realtors can use an estate's GB credentials as a selling point to attract investors and to add value to the property (McGraw Hill Construction 2013). Windapo (2014) investigated the key drivers of green building in the construction industry in the Western Cape Province of South Africa. The study found that these were rising energy costs and the associated need to reduce building operating costs, as well as the availability of an appropriate rating tool, i.e. the Green Star South Africa (Green Star SA) rating system used by the GBCSA, which can be used as a competitive advantage and a new marketing tool. The increasing focus on 'greening of industry' places the emphasis on business responsibility and accountability on a variety of stakeholders (Morris & Dunne 2004). In a study by Murru et al. (2013) the importance of green architectural design of low-cost housing developments in developing countries, like South Africa was demonstrated. According to the study green architectural design can help reduce fossil fuel dependency and expensive, unsatisfying municipal services.

1.1 Wood as a green building material

Wood has played a major role throughout human history as construction material for buildings, tools, and ships but also as fuel. Wood has the advantage over many other materials of being a sustainable and renewable natural resource. Next to its natural beauty, wood is characterized by a high strength per weight ratio while being easy to work with (Tsoumis 1991). It also often serves multifunctional purposes, for example a wooden wall can have structural, aesthetical and insulating purposes. In terms of insulation, wood is 400 times better than steel and 10 times better than concrete (per volume) in resisting the flow of heat due to its low conductivity and good insulating ability, which can lead to significant energy savings (Stalnaker & Harris 2013). Wood has predictable behaviour in fire and in some instances has advantages over steel in terms of fire ratings possible for building (Dinwoodie 2000). Wood is bio-degradable and can reduce the pollution at landfill sites and surrounding environment (Wang et al. 2014). Trees absorb CO_2 from the atmosphere, release oxygen and store the carbon in their stems, branches, leaves and root-systems as part of the photosynthetic process. Trees that die or decompose release this carbon back into the atmosphere. However, when trees are harvested and manufactured into timber and other forest products, these products continue to store carbon for the lifetime of their use, while the regenerated forest once again begins absorbing CO_2 (reThink Wood 2014). Since recovered wood can easily be reused and recycled, or can be used as a bioenergy source, burdens on the environment caused by disposal of construction materials in landfills can be avoided (Lippke et al. 2011).

Already in 1992, research showed that structural wood products had consistently lower carbon balances compared to other non-wood substitutes such as steel, aluminium, concrete and brick (Koch 1992). In the same decade Schlamadinger and Marland (1996) studied the role of wood products in the global carbon cycle by looking at storage of carbon in the biosphere, storing carbon in forest products and use of wood products as alternative to other materials requiring more fossil energy in production. More recent research shows that wood-based constructions display in most cases lower environmental impacts in terms of energy use, greenhouse gas emission, air pollution, water pollution and solid waste production than steel and concrete systems (Petersen & Solberg 2005; Werner & Richter 2007; Upton et al. 2008; Sathre & O'Connor 2010). According to Upton et al. (2008) significant savings of greenhouse gas emissions and energy use can be realized by the use of more wood-based building materials in residential developments in the USA.

Life cycle assessment (LCA) performed by Gustavsson et al. (2006) of the primary energy and climate impacts of a four storey timber-framed apartment building showed that a negative life cycle net CO_2 emission could be achieved using a wood-based construction and biomass-based energy supply system. Another study performed a systematic comparison on the environmental impact of three building systems where, wood, steel and concrete were analysed using the Athena Eco-Calculator, a well-known LCA tool (Lippke et al. 2004). The system boundaries included: raw material extraction, primary and secondary manufacturing, transport along the production chain and to site, and finally building construction. The theoretical two storey building had a total floor area of 3720m^2 and assumed a concrete foundation for all three building types. Another study by Lippke et al. (2010) looked at steel vs. wood construction and found environmental impacts associated with steel mostly 30% to 60% greater, with a range of 2% to 200% higher, depending on the environmental impact category. Impacts associated with concrete ranged from 90% to 480% greater compared to the wood building type. The wood building showed the lowest impact across all the environmental categories. However, different system boundaries might result in slightly different and even better answers for wood buildings. For example, if one would include the forest cycle, long-term carbon storage and renewability metrics of the wood life cycle, the steel and concrete LCA environmental impact might be far greater. Research performed by Upton et al. (2008) showed that a slight increase of wood use from 7.8% to 10.1% per mass unit in a wood based house compared to a steel based house, decreased fossil fuel consumption by 16% and global warming potential with 20% across the 100 year life cycle. Additionally, the study looked at increasing wood from 7.4% to 15.1% per mass in a wood construction and compared it to a concrete based house, with similar thermal capacity, and found a 15% decrease in fossil fuel use and 50% decrease in global warming potential for the wooden house. Wood is often considered as carbon neutral, because carbon can be released back into the carbon cycle after the end of life of a product. However, landfilling of wood products can be problematic. While material that does not decompose can function as carbon storage, emissions from the portion of the wood that does decay under anaerobic conditions (approx. 23% of landfilled wood) are mostly CO_2 and methane, with methane contributing approx. 21-times as much to global warming potential (GWP) than CO_2. Continued improved emission recovery from landfills could result in increased levels of long term carbon storage with no negative greenhouse gas effects in landfills (Lippke et al. 2011).

In other regions of the world like North America and Scandinavia, wood has a long tradition as building material and a significant share in construction of one and two family houses (Gustavsson et al. 2006). In South Africa the use of wood in construction is not widely spread but is anticipated to increase with increasing pressure from international role-players and climate mitigation commitments such as the Intergovernmental Panel on Climate Change (IPCC) and United Nations Climate Change Conference in 2011 (COP17), as well as increasing public knowledge of the environmental benefits of wood as a building material.

1.2 Wood as a building material in South Africa

South Africa is approximately 90% self-sufficient regarding forestry products and has a huge positive trade balance in this sector (Louw 2012). Only 30% of the annual South African plantation roundwood production (≈5.6 million m^3) is used for solid wood production, the remainder being mostly used by the pulp, paper and paperboard industries (Godsmark 2014). Seventy percent of all sawn timber in South Africa is used in construction, mainly as roof and truss material (Crickmay and Associates 2015). Timber frame homes also comprise a valuable market share of sawn timber and in 1982 the Timber Frame Builders Association was established to govern the quality and standard of timber building in South Africa (Rudd 2006). The South African National Standards (SANS) also provides a specific code of practice SANS 10082:2007 for the design and construction of Timber Framed Structures (SANS 2007). However, on average each person in South Africa uses about $0.33m^3$ of industrial roundwood per year (FSA, 2015). Other developing countries such as China and India use less than 0.1 m^3 per capita. This is far less compared to developed countries such as the USA $1.02m^3$) and Australia ($1.05m^3$) and only slightly higher than the global industrial roundwood consumption average of 0.24 m^3 (FAO 2010). Still, with improving living standards of developing countries an increase in the per capita wood use seems certain.

1.3 Aim of this study

The objectives of this study were (1) to review existing green building rating systems with a specific focus on the evaluation of wood and wood based materials, (2) to review research results where wood based constructions were compared to alternative building systems using life-cycle assessment (LCA) methods and (3) to relate the findings to specific challenges and opportunities present in the context of a developing country such as South Africa.

2. Green Building rating systems

2.1 International GB rating systems

The last decade saw increasing environmental awareness and recognition of the potential impact buildings and constructions can have on climate change (Wang et al. 2014). Since the 1990's the building industry recognised the significant demand it has on energy and resource depletion and numerous international environmental rating systems were designed to evaluate the impacts of buildings. Most international GB rating systems and standards have originated in developed countries, except for one from China. Most prominent are the Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) systems (Haapio & Viitaniemi 2008; Banani et al 2013). BREEAM was introduced in 1990 in the UK. According to Banani et al. (2013) BREEAM is one of the most widely used GB assessment systems and has made a global impact, with Canada, Australia, and several other countries using the BREEAM framework in developing their own GB assessment methods (Ding 2008). LEED has been develop since 1994 in the USA and is used in the USA, Canada, Spain, China and India (Haapio & Viitaniemi 2008).

GB rating tools consist of both prescriptive and performance based indicators (Fenner & Ryce 2008). Prescriptive requirements are based on the specifications of particular materials or configurations. Whereas performance based rating in this case can be described as rational analysis or design that meets code (Fenner & Ryce 2008). Performance based analysis provide quantitative performance indicators, such as energy use or global warming potential which can be used as basis for alternative design options and further comparisons. The main benefits of prescriptive based analyses are usually the ease of use and that it is relatively quick to perform. However, the major drawbacks of following this (ticking all the boxes) path is that (1) it is only valid for a specific set of conditions and, (2) the prescribed conditions inherently discourage innovation such as using alternative methods, materials and designs. In the case of purely performance based rating tools (e.g. Gabi, Autodesk Revit and Design Builder), design and material alternatives can be compared to create the best local solution per project. Considering only the above mentioned rating types, prescriptive vs. performance one can anticipate the potential limitations and differences in many green building rating systems. However, complete building energy modelling will be part of the future for most building projects (Yellamraju 2010). Most GB rating systems are dynamic and open for improvement, even prescriptive tools, and undergo continual development. For example, the GBCSA invites users of their website to become part of the development of the rating system by joining a technical working group or sponsoring a rating tool (GBCSA 2014b).

2.2 GB governance and guidance in South Africa

The South African government states that it is dedicated to reducing greenhouse gas emissions through increasing green technologies and mechanisms such as green building. This commitment was made at the COP17 climate change meeting in South Africa in 2011 (Windapo 2014). South Africa aims to reduce its greenhouse gas emissions by 34% by 2020 and 42% by 2025 (Milford 2009). In 2011 the government adopted a National Framework for Green Building in South Africa as its official green building framework. The aim of the framework was to develop GB regulations and standards for the country (van Wyk 2012). The government has endorsed the mandatory SANS 10400-XA:2011 in the National Building Regulations to guide the design and construction of green buildings in South Africa (SANS 2011). Compliance to the SANS 10400-XA regulations also means compliance with the requirements of part XA of the National Building Regulations, issued in terms of the National Building Regulations and Building Standards Act, 1977 (Act No. 103 of 1977). The aim of this standard is to restrict energy usage to a minimum for every building type in the different climatic zones of South Africa. The standard was developed to restrict operational energy of buildings but does not address the energy utilised to create, maintain or demolish the building. Most GB rating systems on the other hand consider both the embodied and operational energy present in buildings in their evaluations. The GBCSA and the progressive development of their Green Star SA rating system, with established GB "standards and clear guidelines on what comprises a green building, have provided the local industry with an initial framework for financing, developing and investing in sustainable buildings" (Windapo 2014). Green Star SA is currently the most important GB rating system employed in South Africa. South Africa was the first African country to use the internationally recognised Green Star rating system and is part of the world GB council (Reed et al. 2009).

2.3 Comparison of selected GB rating systems

In this section the two most important international rating systems (BREEAM and LEED) and the only national rating system (Green Star SA) are further investigated and compared.

BREEAM

The Building Research Establishment Environmental Assessment Methodology was first published by the Building Research Establishment. BREEAM is arguably the world's most prominent environmental assessment method and rating system for buildings, with about 250 000 buildings certified with this system by 2014 (reThink Wood 2014). BREEAM assessment has rating systems for ten different building types each consisting of ten environmental categories. For example, BREEAM New Construction (NC) is the standard against which the sustainability of new, non-residential buildings is assessed. The overall rating of a building is determined by adding scores across all categories along with evidence of compliance with specific requirements. The assessment can only be performed by a registered BREEAM assessor (BREEAM 2015).

Each BREEAM rating scheme has its own set of environmental section weightings as determined from a combination of consensus based weightings and ranking by a panel of experts. Environmental weightings are fundamental in any GB rating system as they provide a means of ranking the relative impact of environmental concerns. Different weighting options and impact categories are used across the different rating systems and tools – they are location and building type specific. According to its developers, the primary aim of any BREEAM rating scheme is to mitigate the negative impacts of buildings on the environment and to improve the social and economic impacts of the building over its lifetime (BREEAM 2015).

Compared to BREEAM the following two GB rating systems have very similar scoring formats and methodology.

LEED

The Leadership in Energy and Environmental Design rating system was developed by the U.S. Green Building Council. It was launched in 1998 and provides third-party verification that a building or community was planned and built in accordance with specified prescriptive and performance measures within the different categories (reThink Wood 2014). Complying with required specifications, numerical scores and credits across all categories are used to determine the overall building rating. LEED standards have been applied to more than 54,000 building projects across 135 countries, covering more than 0.9 billion m^2 of development area (USGBC 2015). LEED rating systems are voluntary, consensus-based and market driven. Similar to BREEAM, different LEED rating systems are available for different building types and each consists of several credit categories. The rating systems evaluate environmental performance from a whole building perspective, considering a building's life cycle and provide a definite standard of what constitutes a green building in design, construction and operation (Yellamraju 2010).

Green Star SA

The Green Building Council of South Africa developed Green Star SA in 2008, based on the Green Building Council of Australia's Green Star rating system, BREAAM and LEED and customized their rating systems for South Africa (GBCSA 2014b). The Green Star SA rating systems provide an independent assessment of a building's green status. Different systems (also called 'tools' in this case) exist to address different building types and building stages such as offices, retail centres, multi-unit residential and public buildings. The tools consist of nine environmental categories: Management, Indoor Environmental Quality, Energy, Transport, Water, Materials, Land Use and Ecology, Emissions and finally Innovation. Similar to BREEAM and LEED, different categories are weighted in terms of credits. Points are awarded based on credits across all categories and an overall star rating is determined. Green Star SA rating systems use a zero to six star rating scheme of which a 6 star rating equals the best possible rating or green building leadership (GBCSA 2014b).

The degree of similarity between arguably the most used GB rating systems, BREEAM and LEED is conspicuous. The Green Star SA's resemblance towards the other two was expected since it was partly based on these systems. LEED does not make use of direct environmental category weightings. In the case of LEED the sum of credits related to each environmental sub-section is the actual weighting of the environmental category since all credits are equally weighted (Reed et al. 2009).

All three GB rating systems aim to provide internationally recognized GB standards, based on the latest scientific understanding of how building and construction impacts the social and natural environment. Due to their international recognition and current position in the GB market, BREEAM and LEED significantly influence the further development of the GB movement and standards. At this point different priorities and varying sets of categories and indicators within GB rating schemes will result in different assessments of the same building. Therefore, a standardized assessment and certification scheme would be of great value to produce comparable results (Reed et al. 2009; Dirlich 2011). The three most recognised rating systems, "BREEAM, LEED, and Green Star, are planning to develop common metrics that will help international stakeholders to compare buildings in different cities" (Kennett 2009).

2.4 Wood in GB rating systems

There are two ways in which the use of wood is rewarded in GB rating systems. Firstly, all three rating systems (BREEAM, LEED and Green Star SA) reward the use of legally harvested and traded timber. Credits are awarded for wood that has been third-party certified as coming from sustainably managed forests (reThink Wood 2014). In the case of BREEAM, certified wood is a minimum requirement for achieving a rating (for any rating level). Different GB rating systems recognise different independent certification programs. The Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC) are two certification bodies recognized by most rating systems. In South Africa the forest industry has informally standardised on FSC certification and in 2007, 97.8% of all industrial roundwood produced in South Africa was FSC and ISO certified (GCIS 2014). As a country South Africa has the largest area of certified exotic plantations in the world. According to reThink Wood (2014) literature, "rating systems commonly reward building projects that use certified wood, they do not require any demonstration that competitive materials such as concrete, steel, or plastic have come from a responsible mining origin".

Locally sourced materials are also credited in LEED and BREEAM systems (see Material sub-sections 11 in **Table 1**). However, considering only transportation distances ignores very important factors such as type of transportation, efficiency, and manufacturing impacts. Sea freight of materials, for instance, has an environmental footprint that is orders of magnitude lower than air freight (Borken-Kleefeld et al. 2010). In terms of indoor air quality the rating systems limit or prohibit added urea formaldehyde and have strict limits on the use of products that contain volatile organic compounds (VOC's). BREEAM and Green Star SA reward use of construction alternatives when there is proof that lower quantities (mass/volume) of building materials are required for the same project. The BREEAM system offers a credit for employing advanced wood framing systems and Green Star recognises designs that produce a net reduction in the total amount (volume) of material used (BREEAM 2015; GBCSA 2014b). Green Star also encourages designs that minimise the embodied energy associated with the building phase and end-of-life stage.

As discussed, materials used in construction are major contributors to greenhouse gas emissions, energy use and resource depletion. GB rating systems have different categories and materials is only one. Different categories are weighted according to the impact each category has on the environment. The environmental weighting factor of the materials category, depending on GB rating system and project phase, varies between 1st and 4th highest of all categories. Energy is usually weighted as one of the top two categories. In the latest BREEAM NC system up to 8.7% of the total project credits can be obtained by using wood (BREEAM 2015). In the Green Star SA system about 4% of total project credits available can be achieved if all possible credits obtainable for wood are achieved. These include credits from the Material sub-sections 3, 4, 8, 9 and 10 in **Table 1**, but points may vary across different Green Star rating tools. However, these percentages do not include potential innovation credits (GBCSA 2014b).

In the case of LEED, sustainable timber products can include reclaimed products such as finger-jointed studs, medium-density fibreboard, and insulation board (LEED 2015). In the latest LEED system v4, 9.5% of the total points can be obtained by using wood products in different ways (e.g. by showing material life cycle comparisons) (Bowyer et al. 2014).

Table - 1: GBCSA Material credits and selected Indoor Environment Quality credits (GBCSA 2014a)

Credit Number	Credit name	Aim of Credit	Tools
Mat-2	Building Reuse	To encourage and recognise developments that reuse existing buildings to minimise materials consumption.	All tools
Mat-3	Reused Materials	To encourage and recognise designs that prolong the useful life of existing products and materials.	All tools
Mat-4	Shell and Core or Integrated Fit-out	To encourage and recognise base building delivery mechanisms that eliminate the need for immediate tenant refits.	Office v1
Mat-8*	Sustainable Timber	To encourage and recognise the specification of reused timber products or timber that has certified environmentally-responsible forest management practices.	All tools
Mat-9	Design for Disassembly	To encourage and recognise designs that minimise the embodied energy and resources associated with demolition.	All tools
Mat-10	Dematerialisation	To encourage and recognise designs that produces a net reduction in the total amount of material used.	All tools
Mat-11	Local Sourcing	To encourage and recognise the environmental advantages gained, in the form of reduced transportation emissions, by using materials and products that are sourced within close proximity to the site.	All tools
IEQ-13	Volatile Organic Compounds	To encourage and recognise specification of interior finishes that minimise the contribution and levels of Volatile Organic Compounds in buildings.	All tools
IEQ-14	Formaldehyde Minimisation	To encourage and recognise the specification of products with low formaldehyde emission levels.	All tools

*1 point is awarded where 50% (by cost) of all timber products used in the building and construction works have been sourced from any combination of the following: Reused timber, Post-consumer recycled timber OR Forest Stewardship Council (FSC) Certified Timber. An additional point is awarded where 95% (by cost) of all timber products used in building and construction satisfy the abovementioned sourcing criteria.

In general it seems as if the environmental benefit of using wood is not sufficiently reflected in the GB rating systems reviewed – the least so in the case of the South African rating tool Green Star SA. According to the Green Star SA rating system, approximately 4% (rating tool dependent) of the overall project credits can be achieved by utilizing sustainable timber in the best possible manner. This value seems quite low, if one compares it to most LCA results on the superior performance of wood compared to steel and concrete building constructions, where wood performed 40% - 200% better in terms of global warming potential and fossil fuel use (Upton et al. 2008; Lippke et al. 2010). In the case of BREEAM one can argue that not specifying wood in a building might be easier, since no evidential proof in terms of responsible sourcing is required for any other materials at this point.

GB rating systems, which mostly use an integrally static (prescriptive based) rating tool which does not have the flexibility of a performance based approach, often use a single indicator, such as locality or recycled content, with the hypothesis that an positive environmental impact comes from it. The findings and discussion in the first two sections clearly highlight the need for alternative or additional methods of evaluation and comparing the sustainability of buildings and construction. However, "life-cycle assessment takes away much of the assumptions by calculating potential outcomes based on quantifiable indicators of environmental impact, such as global warming potential, resource use, embodied energy, air pollution, water pollution and solid waste" (Haynes 2013).

3. Life cycle assessment to determine environmental and economic impacts of timber building products

3.1 LCA application of wood in building construction

Life cycle assessment has been used in the building sector since 1990 and has since then developed into an important tool to assess buildings (Ortiz et al. 2009). Based on the number of studies published in the last 15 years it is apparent that incorporation of LCA in construction decision making is becoming more and more important in the United States, Europe and Asia (Singh et al. 2011).

In 2005, Petersen & Solberg (2005) published a review of environmental and economic impacts of wood products and alternative materials in buildings from analyses conducted in Norway and Sweden (mostly published in Scandinavian languages only) dating back to 1990. They found that in all studies considered, wood outperforms alternative materials in terms of greenhouse gas emissions and is also cost competitive in those studies where a cost analysis was included. Compared to alternative materials wood was found to produce less waste and also performed better in other impact categories, with the exception of preservative treated wood. The authors pointed out the need to combine traditional LCA with economic analysis for better decision support for policy makers.

Werner & Richter (2007) compiled a literature review of wooden building products in comparative LCA, including studies on building materials and components like windows, doorframes, insulation and flooring materials, wall constructions and furniture, as well as whole buildings. For LCAs on whole buildings they found that many studies focus on greenhouse gas emission and that some are documented in a rather simplified way. Overall their review shows that wood products, if appropriately installed, tend to have a favourable environmental profile compared to functionally similar alternative materials.

Several more general reviews on sustainability and environmental impacts in the construction industry based on LCA were published in recent years (Ortiz et al. 2009; Ramesh et al. 2010; Singh et al. 2011; Sharma et al. 2011; Buyle et al. 2013; Cabeza et al. 2014). These studies outline the accomplishments of LCA to date, clearly showing that LCA is an innovative and appropriate decision support tool to improve the sustainability and environmental performance of building products and hence buildings. Many of the earlier studies were simplified LCAs with a focus on energy related indicators (e.g. embodied, operating, and/ or cumulative energy) whereas later studies became more complete and complex incorporating and taking advantage of recent developments in life cycle inventory (LCI) databases and software tools.

When reviewing different LCA studies on wood and wood products in the building sector it becomes apparent that results are often difficult to compare. In general LCAs in this sector can be divided in two classes, firstly, those that evaluate building materials and building components like roof constructions, frames or walls, and secondly, those that evaluate whole buildings. The various studies put emphasis on different impact assessment methods, consider different scopes and life-cycles or define their system boundaries and functional unit differently. Comparisons are further complicated by the fact that buildings are very complex objects, both in terms of design and function but also in the number of individual components and materials used that make up a building. Nonetheless, research studies largely agree that wood product substitution for other building materials reduces greenhouse gas emissions, energy use and embodied energy. However, most studies to date were conducted in developed countries with a long tradition of building with wood.

Many studies focussed on energy aspects like primary energy use, embodied energy and operating energy (e.g. Börjesson & Gustavsson 2000; Goverse et al. 2001; Petersen & Solberg 2002; Scharai-Rad & Welling 2002; Upton et al. 2008; Gustavsson et al. 2010). According to literature, “primary energy is the energy used to produce the end use energy, including extraction, transformation and distribution losses" (Ramesh et al. 2010). Consequently, the regional electricity mix has a great impact on the environmental performance of a building especially during the use-phase in form of operating energy. Operating energy is the energy required to maintain comfortable conditions and day-to-day maintenance of a building and includes energy for heating, ventilating, air conditioning, hot water, lighting and running appliances. Embodied energy is the energy utilized during the manufacturing phase of the building, including raw material extraction, building material production, transport and construction. Earlier research focused on building's life-cycle energy demand and it was recorded that 80-90% of the total energy consumption was operating energy and 10-20% embodied energy (Ramesh et al. 2010; Ortiz et al. 2009). However, due to the development of more energy efficient equipment and appliances together with innovative and more effective insulation, there is now a higher potential for savings in operational energy. In recent studies on LCA in the building sector more emphasis was placed on investigating and optimizing embodied energy of building products (Cabeza et al. 2014; Takano et al. 2015). A recent study by Hafner et al. (2012) indicated that embodied energy (i.e. the impact from the production and construction phase) of a new nearly Zero-Energy building accounts for more than 50% of the total energy impact over the buildings life span. Furthermore, more and more energy is obtained from sustainable sources e.g. from wind, hydro and solar power, further reducing the environmental impact of operational energy.

Another very important consideration to take into account is that almost all available studies where operating energy and embodied energy of buildings were considered were from developed, northern hemisphere countries. According to World Bank climate data for the past century, the mean temperature of the coldest month in the USA (-5.7 °C) and Germany (-0.4 °C) was significantly lower than that of South Africa (11.3 °C) (World Bank Group 2015). The differences in the mean warmest temperatures between these countries were much lower (USA: 19.7 °C; Germany: 17.3 °C; South Africa: 23.0 °C). Much less energy will probably be used for heating and cooling of buildings in South Africa compared to most northern hemisphere countries given both the climatic conditions and the fact that a large percentage of South Africa's population can simply not afford temperature control in their homes and workplaces. It is highly likely that the life-cycle energy demand for South African buildings will look significantly different to those of developed northern hemisphere countries. Embodied energy might thus be relatively more influential in terms of building life-cycle energy demand. No data from African studies is available but a study comparing energy requirements and environmental impacts of two residential houses in Colombia and Spain supports the argument that embodied energy will be more influential in warmer, developing countries (Ortiz-Rodríguez et al. 2010).

It is also important to note that focussing on energy only neglects consideration of other environmental impacts of embodied effects like emissions generated during resource extraction and manufacturing such as toxic releases to water and air or waste generation (Trusty & Horst 2005).

3.2 LCA tools and databases related to the building construction industry

While LCA provides a holistic cradle-to-grave approach to describe and compare environmental impacts, construction related LCA's are highly complex and face challenges because of site-specific impacts, model complexity, scenario uncertainties and indoor environmental considerations. The complexity of construction related LCA's compared to more standard LCA application to industrial products and production processes imply that it is best performed by LCA professionals (Erlandsson & Borg 2003; Singh et al. 2011). In order to simplify LCA and make it easier to understand and apply, building specific LCA tools have been and are continuously developed, mostly by research institutes, around the world. The Athena Sustainable Materials Institute proposed a three-tiered classification system for LCA tools and databases related to the construction industry based on where in the assessment process they are used and for what purpose (Haapio & Viitaniemi 2008). These include: (1) Level-1 product comparison tools (divided into tools intended for LCA practitioners (Level 1A) and those where the LCA runs in the background (Level 1B)), (2) Level-2 whole building decision support tools and (3) Level-3 whole building assessment systems and frameworks (see **Table 2**) (Trusty & Horst 2005). Another classification system categorizes building assessment tools into five categories, including (1) energy modelling software, (2) different environmental guidelines, (3) checklists, (4) product declarations and (5) certifications (IEA Annex 31 2004). There is a multitude of different tools available and some are region specific such as those in Level-2 according to the Athena classification (Haapio & Viitaniemi 2008). Caution should be taken when applying them outside the region for which they were intended for. Furthermore, not all of the tools are developed to the same level i.e. interface, quality of LCI data and the life cycle stages considered. Also, tools were and are being developed for different purposes, for example, research, consulting, decision making and maintenance, and the required outputs do not necessarily coincide. Investors, for example are more interested in economic performance, whereas tenants are more interested in health and comfort related issues. It should be noted that seemingly similar tools can complement each other based on their intended function (Haapio & Viitaniemi 2008; Trusty & Horst 2005; Singh et al. 2011). **Table 2** gives a non-comprehensive overview of some of the more popular and recognized LCA based assessment tools according to the Athena classification.

Table 2: Functionality of LCA tools (compiled from: Trusty & Horst 2005; Haapio & Viitaniemi 2008).

	Country	Comment
Level 1: Product Comparison Tools		
Level 1A Tools		
SimaPro	Netherlands	Tools are designed for and best used by LCA practitioners. They can be used globally by selecting or incorporating the appropriate data and are not building specific.
GaBi	Germany	
Umberto NXT	Germany	
Team™	France	
Level 1B Tools		
BEES	USA	Combines LCA and life cycle costing. Includes both brand specific and generic data.
LCAiT	Sweden	Streamlined LCA tool for product designers and manufacturers.
Level 2: Whole Building Decision Support Tools		
Athena Environmental Impact Estimator (EIE)	Canada/USA	All of these tools use data and incorporate building systems that are specific to the country/ regions for which they were designed. Many aim to be implemented from an early design stage.
BRI LCA (energy and CO_2)	Japan	
EcoQuantum	Netherlands	
Envest 2	United Kingdom	
LISA	Australia	
Level 3: Whole Building Assessment Systems and Frameworks		
BREEM	United Kingdom	Uses LCA results from Level 2 Green Guide.
SBTool	International	Experimental platform that accepts LCA results or performs rudimentary LCA calculations using build-in calculators.
Green Globes	Canada/ USA	Assigns a high percentage of resource use credits based on evidence that a design team has conducted LCA using a recognized Level 1 or 2 tool.
LEED v4	USA	Credits can be obtained for a life-cycle approach in designs and building material choices.

As mentioned, performing an LCA at building level is very complex. Environmental product declarations (EPD) were developed to communicate standardized LCA information in a way that is meaningful to people who may not be familiar with LCA. An EPD is a verified document that summarizes the environmental impacts associated with producing and using a product or service and other relevant information in accordance with the international standard ISO 14025 (Bergman & Taylor 2011; Bergman et al. 2014). An EPD enables architects and clients to select and compare building materials per application and can help with scoring best possible GB ratings for materials in a simplified way. EcoStandard South Africa was officially launched in 2013 and is the first South African ecolabel (an EPD like standard) for building products and is recognised by the GBCSA as a third party independent ecolabel (EcoStandard SA 2015).

3.3 Challenges of LCA methodology related to the green building construction industry

According to Zhang (2013) "although LCA is widely recognized as the best way to holistically evaluate the environmental impacts of a building it is not yet a consistent requirement of green building rating systems and codes". This is despite the fact that embodied energy and other life cycle impacts are critical to the design of environmentally responsible buildings. However, compared to other products, buildings are more difficult to evaluate in a life-cycle context because they are large in scale, complex in material and function and temporally dynamic due to limited service life of building materials and changing user requirements (Cabeza et al. 2014). While the overwhelming part of LCA studies assessing wood as a building material concluded that wood constructions on average used less energy and emits less greenhouse gas emissions, it needs to be emphasized that spatial, temporal and technological differences can significantly affect the energy and CO_2 balances of material production. LCA is also greatly dependent on the primary energy source that is used in a specific place and the conversion efficiency of materials production processes. Meil et al. (2009) found that manufacturing energy intensity can vary greatly between individual countries and regions. Developing and emerging countries furthermore often rely heavily on fossil fuels for their electricity production and also mainly use electricity for heating, ventilating, and air conditioning (Ramesh et al. 2010). Previous reviews clearly identify the need to better evaluate activities and emissions of small and medium enterprises and the lack of LCA studies on buildings in developing countries (Ortiz et al. 2009; Ramesh et al. 2010). Studies to date were mostly conducted in developed and/or cold countries, which not only differ in climatic conditions, but also in the source and use of primary energy. There are no studies from Africa and only a few from South America. Ortiz-Rodríguez et al. (2010) compared two houses, one in Spain, a developed country and one in Colombia, a country under development. They found that both energy consumption and environmental impacts differ significantly between the two countries, largely based on location specific factors, like architectural styles, technologies used and conditions such as household size, climate, geography and energy sources. Contrary to studies conducted in Europe and the USA, where the use phase of a building contributes the most to GWP, due to a high energy use especially for heating, ventilating, and air conditioning, in Colombia significant overall reductions in GWP could be realized by reducing the environmental impacts from building materials (Ortiz-Rodríguez et al. 2010).

In developing and emerging countries LCA capacity in general is low, and interest from industry and government is typically also low. LCA activity is usually only at an academic or research institute level and consequently original LCI data is still lacking and data from European and North American studies has to be used (Brent et al. 2002; Ortiz et al. 2009; Ossés de Eicker et al. 2010). As many developing and emerging "countries supply resources to developed countries, there is increasingly the recognition that LCI databases need to include the products and services from developing countries" (Colodel 2008). Currently, most available LCI data, including those for forest and wood products, and other construction materials and processes only represent conditions in industrialized countries (e.g. North America, Scandinavia, central Europe, Australia and New Zealand) (Oliveira et al. 2013). It is important to use and develop location specific LCI data since environmental impacts can vary significantly from country to country. Furthermore, most currently available life cycle impact assessment methods were developed for developed countries not considering environmental impacts that are of major importance in developing countries, e.g. water and land resources (Brent et al. 2002; Brent 2003). For forestry and wood products those could be due to differences such as local climate, forestry practices, timber densities, species and construction, and manufacturing practices and processes (Lippke et al. 2011; Nebel et al. 2008). Furthermore, the two other pillars of sustainability, social and economic indicators, often play a major role in developing countries and should be considered when possible (Ortiz et al. 2009).

3.4 Status of LCA in South Africa

South Africa is a major exporter of raw materials like metals and minerals, manufactured products such as motor cars and components, but also agricultural products such as corn, fruits, sugar, wood pulp, and wool. Therefore, the external demand for LCI data from South Africa is increasing, since the materials enter cycles of production and consumption in countries where LCA information is required (Brent et al. 2002). There is increasing potential for greater coordination of LCA efforts in South Africa. Although a few South African universities and research institutes have been active in LCA for over fifteen years, South African industry and government have been slow to realise the benefit of LCAs (Brent et al. 2002). In order to meet consumer demands for environmentally friendly products and also to increase the productivity and competitiveness of green building materials the use of LCA needs to be fostered, especially in developing countries (Ortiz-Rodríguez et al. 2010). Currently, efforts are being made to provide LCI data for South Africa, with data for electricity and some mining activities already being available in the latest ecoinvent 3.1 LCI database (Weidema et al. 2013).

It is apparent that more research and education is required to establish a common understanding of the environmental impact of resource extraction, material manufacturing, building erection and disposal of different construction materials and to make this information available and accessible to decision makers in a standardized concise format.

4. Conclusions

Globally, the building industry contributes significantly to greenhouse gas emissions, resource depletion and landfill pollution. With rising awareness of the environmental impacts of buildings, green building activity has grown rapidly, with the South African market showing the fastest GB activity rate in the world.

Current GB rating tools such as BREEAM, LEED, and Green Star SA use mainly prescriptive rating methods. Whilst it is easy to use, it discourages innovation and the use of new methods, materials, and designs. Based on existing studies, it seems as if the well documented environmental benefits of using wood is not sufficiently reflected in the GB rating systems reviewed.

It is generally agreed that LCA is an innovative and appropriate decision support tool to improve the sustainability and environmental performance of building products and buildings. According to literature in this study, LCA is recognized as the best way to holistically evaluate the environmental impacts of a building, however, it is resource intensive, can be highly complex, and is dependent on the availability of accurate data. Most LCA studies found that wood products and constructions tend to have a favourable environmental profile compared to functionally similar products and buildings.

Earlier LCA studies from mostly developed countries found that the operating energy required over a building's life-cycle dwarfs the embodied energy of the building. However, recent advances in renewable energy production, better building insulation, and more efficient use of energy will result in the reduction of operational energy impacts from buildings. It is also unlikely that the operating energy required from buildings from a developing country such as South Africa with a relatively warm climate will be as high as buildings from developed, northern hemisphere countries where most LCA studies were conducted. Thus it is highly likely that building material related embodied energy and subsequently material choices will be more influential in terms of environmental sustainability in South Africa than current studies from developed countries would suggest. Existing GB rating tools also base their scoring and weighting methods on available LCA research results from these developed countries. This might result in an over-emphasis on the operating energy requirements of buildings at the expense of embodied energy and the importance of material choices. There is, therefore, a critical need for local South African life-cycle assessment based research on the environmental impact of different building products and processes.

Geolocation information

The origin of this research is Stellenbosch, South Africa.

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Chapter 3.

The potential of South African timber products to reduce the environmental impact of buildings

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Summary

South Africa was the first country in Africa to implement a locally developed green building rating tool and has a growing number of rated green building projects. The method of life-cycle assessment can help to compare and assess the environmental performance of building products. At present, more than 70% of all sawn timber in South Africa is used in buildings, mainly in roof structures. Light gauge steel trusses have recently also been gaining market share. However, to date, no studies have been conducted that quantify and compare the environmental impacts of the different roof truss systems in South Africa. We thus compared several roof truss systems (South African pine, Biligom and light gauge steel) found in low- and medium-income house designs in South Africa using a simplified life-cycle assessment approach. Our results show that the two timber systems had overall the lowest environmental impact. Although the difference between the timber systems was small, light gauge steel had a 40% higher normalised impact over all assessed environmental impact categories. The benefit of biogenic carbon dioxide present in timber proved to play a significant positive role in the global warming potential impact and could even be further reduced if wood were used to generate energy at its end-of-life. This study demonstrates the potential advantage of using local timber products to reduce the environmental impact of the truss and building industry in South Africa.

Significance:

Timber truss systems showed overall lower environmental impact than light gauge steel trusses, with implications for green building.

Keywords: *life-cycle assessment; pine; steel; novel truss materials; green building*

Introduction

Buildings are major emitters of carbon dioxide and contribute significantly to global climate change.[1,2] A growing global awareness of the environmental footprint of buildings and the necessity to lower greenhouse gas emissions has led to the implementation of green building practices and the introduction of green building rating tools that have been used to measure the environmental impact and sustainability of buildings since the 1990s.[3] Numerous studies have shown that substituting steel, concrete and brick materials with renewable and sustainable wood products can significantly lower the environmental impact of a building over its lifetime.[4-9]

Residential roof truss construction in South Africa is the single biggest user of locally produced structural timber. According to Crickmay and Associates[10], more than 70% of all structural timber is used in the local building market. Structural timber in South Africa is mostly South African pine (various *Pinus* species). In addition eucalyptus (mostly *Eucalyptus grandis*) timber is also used in structural applications, such as laminated beams and Biligom – a new, moist, glued, finger-jointed structural timber product for truss systems.[11] Traditionally, structural steel is known for its ability to cover large spans and use in high stress applications such as reinforced concrete. Recently, light gauge steel (LGS) construction as well as LGS roof truss systems have gained a noticeable market share and offer another option as roof truss material. With steel prices currently low, many building projects and smaller roof spans with steel have become economically viable options in South Africa, and in many cases displaced wood is a preferred truss material.[12,13]

In a combined life-cycle assessment (LCA) and cost study performed by Worth et al.[14], in which softwood timber trusses were compared with imported LGS in New Zealand, the authors found that LGS requires at least 6.65 times more energy to manufacture than wood. In a study by Bolin and Smith[15], it was found that in their manufacture, use and disposal, CCA-treated wood guard rails require lower fossil fuel use, produce lower greenhouse gas (GHG) emissions and have lower environmental impacts in the acidification, smog potential and eco-toxicity categories compared with that of galvanised steel posts. Ximenes and Grant[8] assessed the GHG benefits of the use of wood products compared with those of steel-reinforced concrete in two popular house designs in Sydney, Australia. The timber frame option for the roof resulted in a net GHG emission reduction ranging from 51% to 66% compared with steel frames for the equivalent roofing material.

Governments, architects, developers and the general public are under an increasing obligation to make environmentally responsible decisions when it comes to selecting building materials and methods.[16] South Africa was the first country in Africa to implement a locally developed green building rating tool and has a growing number of rated green building projects.[17] At the same time, however, marketing is used to promote materials and buildings as green and environmentally sound without concrete evidence in support of these claims.

Nearly 70% of all sawn timber in South Africa is utilised in buildings, specifically in roof trusses. LGS trusses are also gaining market share. However, to date no studies have been conducted quantifying the environmental impacts of the different truss systems in South Africa. End-users of trusses, therefore, do not have the necessary information to make environmentally responsible choices when selecting a truss system. Additionally, manufacturers of both timber and LGS trusses have little information to guide them in reducing the environmental impacts of their processes and products.

In this study, we investigated and compared the potential environmental impact of different roof truss systems typically found in low- and medium-income house designs in South Africa using a simplified LCA approach. Environmental impacts were compared over 11 different impact categories. We present the potential environmental impact of the modelled products and discuss adjustments and assumptions made with regard to the availability of South Africa specific life-cycle inventory (LCI) data and validity of obtained results.

Life-cycle assessment is a methodical framework for estimating and assessing the potential environmental impacts of a product system or process over its entire life cycle, including raw material extraction, manufacturing, use, and end-of-life disposal and/or recycling.[18] Thus, LCA is often considered a 'cradle-to-grave' approach to evaluate environmental impacts.[19] The International Organization for Standardization (ISO) adopted an environmental management standard in the 1990s as part of its 14000 standards series, with the 14040 series focusing on establishing methodologies for LCA.[20,21] The ISO standards define a four-stage interactive framework for conducting LCA analysis. The first stage is the definition of the goal and scope of the study including the establishment of the functional unit, system boundaries and quality criteria for LCI data. Life-cycle inventory, the second stage, deals with the collection and synthesis of information of system inputs and outputs of material and energy flows and associated environmental impacts in all stages of the life cycle. During the life-cycle impact assessment (LCIA), the third stage, these environmental impacts are assigned to different environmental impact categories and by means of characterisation factors, the contribution of each constituent is calculated for different environmental impact categories (e.g. global warming potential, human toxicity, acidification, resource depletion, land use). The final stage is the interpretation of the results from both LCI and LCIA.[20,21]

Goal and scope

Objective

The goal of this study was to assess the potential environmental impact associated with the manufacture, use and disposal of timber and light gauge steel roof truss systems commonly found and used in South Africa. We compared three different truss materials – South African pine (S5), LGS and Biligom – in two house designs (Table 1). Biligom is a new sawn timber product made from green finger-jointed *E. grandis* wood. A 42-m^2 Reconstruction and Development Programme (RDP) house and a 168-m^2 single-story family house were chosen to represent commonly found house sizes in the South African lower- and middle-income market. Concrete tiles were selected as the roof cover material.

Table 1: Experimental design summary

Alternative	Truss material	Number of trusses	Cover material	House footprint
1	SA pine S5	10	Concrete tiles	42 m^2 (6x7 m)
2	Biligom	10	Concrete tiles	42 m^2 (6x7 m)
3	Light gauge steel	7	Concrete tiles	42 m^2 (6x7 m)
4	SA pine S5	16	Concrete tiles	168 m^2 (14x12 m)
5	Biligom	16	Concrete tiles	168 m^2 (14x12 m)
6	Light gauge steel	12	Concrete tiles	168 m^2 (14x12 m)

Limitations

A significant portion of the overall life-cycle energy requirements of buildings is from occupational energy use. However, owing to time and data constraints, occupational energy consumption over the design life of the roof and associated building was not considered in this study. In reality, different roofing materials will have, next to their own embodied energy, an impact on the energy usage required for space heating and ventilation and further investigation is necessary to address this issue properly. The assessment of the roof configurations is limited to the environmental factors associated with each type of roof truss system, excluding the cover material (i.e. concrete tiles) and the supporting building structure. Costing was also not included in the analyses.

Methodology

A detailed description of the LCA methodology and framework is available in the ISO 14040 Environmental Management series.[20,21] Many of the recommendations set out in these documents are above and beyond the scope of the current study; however, the sections of these guidelines relevant to this study were followed.

The functional unit, as defined in ISO 14041, was chosen for this study as the quantity of materials required to construct the roof truss system of a house with a predefined footprint (i.e. 42 m^2 or 168 m^2). Both theoretical house designs have cement block walls. All structural components required that make up the roof structure were considered (namely truss material, bracing material, battens, purlins, nails and screws). The cover material (i.e. concrete tiles) and insulation material were not included, but were considered for the design (e.g. in terms of load-bearing capacity of the roof structure). The roofs were designed with a 17.5° pitch and for a 50-year service life in the Western Cape Province of South Africa. The roof structures were calculated and designed by MiTek South Africa (Pty) Ltd engineers (Cape Town) according to national timber construction standards. MiTek design software provided a detailed material and cutting list for all structural components per design, either per mass or per volume (Table 2). Waste produced from cutting standard lengths to size was not accounted for. We assumed that no maintenance work or replacements would be necessary over the design lifespan.

Biligom structural timber is 25–35% stronger than South African pine structural grade S5 in terms of flexural properties, i.e. bending strength and stiffness[11]. In this theoretical comparison, because of current design constraints and data availability, Biligom was assumed to be equal in volume/dimensions to South African pine (S5).

Table 2: Roof truss systems with the mass and volume per material category for each alternative

	SA pine (S5)		Biligom		Light gauge steel
Alternative	**m³**	**kg**	**m³**	**kg**	**kg**
1	1.33	598.5			22.5
2			1.33	798.0	23.5
3					167.8
4	6.05	2722.5			180.6
5			6.05	3630.0	186.6
6					1094.0

Notes: Wood density is taken as air dry density for South African pine (450 kg/m^3) and partially wet density for Biligom (600 kg/m^3).

Both high strength (ISQ 550-3T) and low strength (ISQ 300) components are used in MiTek truss systems. The steel is similar in production and treatment across the entire manufacturing process. Here it is assumed that the same type of steel is used for all components. All light gauge steel material is galvanised at 200 g/m^2.

End-plates are used as part of the Biligom product at 0.96 kg/m^3 Biligom and both timber systems make use of nail plates as truss component connectors.

Life-cycle inventory

In this study, openLCA 1.4.2 modelling software was used to determine the LCI. The materials used in the LCIs were assumed to be sourced and processed locally. As there is little to no LCI data available for South Africa, global data sets from the ecoinvent database 3.1 (Weidema et al.[22]) were used.

Timber

We assessed two types of timber: South African pine in grade S5 and Biligom. Plantation forestry for pine and eucalyptus is practised In South Africa. LCI data from the Australian life-cycle inventory database (AUSLCI) was used and integrated into the ecoinvent database to model the softwood forestry process, as it reasonably represents local conditions. Sawmilling, drying and planing of the timber were modelled using ecoinvent processes for softwood, but adjusted to use South African specific conversion factors and electricity.

Biligom is a recent development of finger-jointed moist glued eucalyptus timber and original LCI data were gathered from BILIGOM® International (Pty) Ltd. The AUSLCI process for hardwood (eucalyptus) forestry was used to model the forestry process. Both product systems were modelled in openLCA using the ecoinvent database for background data.

Depending on the region in South Africa, both pine and eucalyptus timber used in load-bearing applications need to be preservative treated to comply with national building codes. Biligom uses TanalithE as preservative and copper chromated arsenate (CCA) was chosen for pine, as it is widely used in South Africa. Original LCI data on the chemical composition of both preservatives used locally were provided by Arch Wood Protection (SA) Pty Ltd and modelled in openLCA using the ecoinvent database for background data on chemicals, preservative production and pressure treatment.

Light-gauge steel

Light-gauge steel is made from galvanised sheet material, on continuous zinc coating lines from either cold-rolled (thickness range of 0.27 mm to < 2.0 mm) or hot-rolled (thickness of 2.01–3.0 mm) steel in coil form. It is produced to the requirements of a range of national and international standards as well as Mittal Steel South Africa's ISQ standards.[23] Continuous zinc-coated cold-rolled sheet metal, also known as LGS, and the machining thereof was modelled based on rest-of-world (RoW) steel data, available in the ecoinvent database 3.1, including processes for steel production, sheet rolling, metal working and zinc coating. The RoW data are assumed to closer reflect local process conditions than are European or global data sets, especially in terms of the primary energy mix as it was not feasible to adjust all background processes included in LGS production to use South African electricity data.

The selected system boundaries in this study included a 50 year life cycle from cradle to grave – forest/mine to final fate. The South African wood and timber industry is approximately 100% plantation supplied and 100% FSC certified. The plantation area covers only 1% of the national land area – as is the case the past 40 years. South Africa also has well-established cement and steel (iron, coal, silica, lime etc.) mining and manufacturing operations – which also need to adhere to environmental legislation and safeguard. Land use change impacts was not considered as a part of the analyses and time horizon of this study. However, land use change impacts is significantly relevant in virgin mining and afforestation projects.

Transportation

Transportation of materials to the processing facilities and from there to the building site in the Western Cape was included. We assumed that the LGS was sourced from the major steel production area, the Gauteng Province, Biligom from the plant in Tzaneen, Limpopo and pine timber was standard averaged and originated in the Southern Cape and Limpopo Provinces. At the end-of-life, it was assumed that all materials were transported 50 km to their respective final destination (e.g. for incineration, landfilling or recycling).

End-of-life

Formal recycling and burning of wood waste for energy was not considered as it is currently not common practice in South Africa. According to the South African Wood Preservers Association's treated timber guidelines, treated timber should be disposed of at a registered landfill site.[24] However, in South Africa, significant amounts of waste wood are used in peri-urban and rural areas as fuel for cooking and heating. A study performed by Niyobuhungira[25] showed that more than 50% of the residential fuel wood used in peri-urban areas in the Western Cape was CCA treated. In this study we chose disposal of timber by incineration, modelled with processes from the ecoinvent database as the most likely final fate scenario.

For the LGS, no recycling benefits were considered in the disposal phase as locally manufactured galvanised LGS is mainly produced from virgin material and the majority of steel scrap is exported and reused outside South Africa.[26] According to Galvanizers Association[37], end of life for galvanised steel is usually incineration/smelting by electric arc furnace (EAF). This enables the re-use of remaining zinc and other metals to include in producing new galvanized steel material. South Africa produces mostly virgin steel products and only a small percentage of raw-material is obtained from recycled steel. In Europe a mere 10-15% recycled zinc content is estimate and obtained from the EAF process.

Life-cycle impact assessment

All inputs and outputs considered in the cradle-to-grave analyses, and intermediate steps, were analysed in openLCA 1.4.2 with the CML baseline impact assessment method version 4.4 as of January 2015 (GreenDelta[27]) including normalisation data for different countries and years and using physical allocation. Additionally, impact category GWP_{100} was calculated without including biogenic carbon dioxide sequestration and emissions, thus assuming carbon neutrality of biogenic carbon dioxide.

Results and discussion

The potential environmental impact of the three roof truss assemblies was assessed and compared. Both cradle-to-gate and cradle-to-grave results are presented below. Table 3 shows the cradle-to-gate results of the 42-m^2 and 168-m^2 houses. Over all categories, Biligom has the lowest impact in most categories, closely followed by pine, and LGS has the highest impact. The difference between the two timber alternatives is small compared to the differences between them and LGS. The order of impact in the individual categories is the same for the larger truss assemblies. The impact in the individual categories is on average 4.5 times higher for the two timber alternatives and 6.5 times higher for LGS between the 42-m^2 and 168-m^2 house sizes. These differences are explained and directly correlated to the material volume ratio, required per material alternative as displayed in Table 2. It is interesting to note that although the timber alternatives use more trusses per house, the LGS system mass ratio is higher between the two house design footprints (Table 1).

Table 3: Cradle-to-gate roof truss alternative impact assessment summary for the two roof designs

	42-m^2 house			**168-m^2 house**			
Impact category	**Pine (1)**	**Biligom (2)**	**Light gauge steel (3)**	**Pine (4)**	**Biligom (5)**	**Light gauge steel (6)**	**Reference unit**
Acidification potential	3.43	3.13	9.28	19.93	18.63	60.53	kg SO_2 eq.
GWP_{100}	-919	-1224	988	-3721	-5100	6445	kg CO_2 eq.
Depletion of abiotic resources – elements, ultimate reserves	0.04	0.02	0.11	0.22	0.14	0.74	kg antimony eq.
Depletion of abiotic resources – fossil fuels	3301	3229	8918	19175	18923	58145	MJ
Eutrophication	1.20	1.14	3.50	7.10	6.85	22.82	kg PO_4--- eq.
Freshwater aquatic ecotoxicity	268	233	1035	1706	1552	6751	kg 1,4-dichlorobenzene eq.
Human toxicity	8193	813	2640	38503	4956	17218	kg 1,4-dichlorobenzene eq.

Marine aquatic ecotoxicity	7.02E+05	5.87E+05	2.28E+06	4.26E+06	3.75E+06	1.49E+07	kg 1,4-dichlorobenzene eq.
Ozone layer depletion	3.61E-05	3.21E-05	5.84E-05	1.90E-04	1.70E-04	3.80E-04	kg CFC-11 eq.
Photochemical oxidation	0.26	0.95	0.43	1.37	4.53	2.77	kg ethylene eq.
Terrestrial ecotoxicity	18.68	10.97	69.26	117	82.77	451	kg 1,4-dichlorobenzene eq.

Only the global warming potential (GWP) has negative values indicating a positive impact at the gate. More specifically, the results indicate the amount of carbon dioxide equivalents sequestrated in the material at this stage minus carbon dioxide emissions from processing and excluding emissions from end-of-life. Table 4 shows the same results as in Table 3 from cradle-to-grave. As expected, there is mostly a small increase in all categories and the timber alternatives are better than LGS. The most significant change can be seen in the GWP_{100}, which is a result of the inclusion of emissions from wood incineration at the end-of-life of the timber systems. A significant increase in fossil fuel depletion and eutrophication for the wood alternatives and aquatic ecotoxicity for LGS must also be attributed to the end-of-life treatment as well as transportation processes.

Pine showed significantly higher human toxicity impact values compared to the others because of the CCA treatment process. According to the LCA process contribution analysis, chromium oxide production is responsible for more than 90% of the human toxicity impact of pine from cradle-to-gate. The higher photochemical oxidation impact value for Biligom is again because of the carbon monoxide emissions created by the forest management process. The forest management LCI data used in the Biligom LCA (the best available data) are from an Australian-based hardwood management process which used natural gas as part of their energy mix, which was responsible for 88% of the photochemical oxidation impact.

Table 4: Cradle-to-grave roof truss alternative impact assessment summary for the two roof designs

	42-m^2 house			168-m^2 house			
Impact category	**Pine (1)**	**Biligom (2)**	**Light gauge steel (3)**	**Pine (4)**	**Biligom (5)**	**Light gauge steel (6)**	**Reference unit**
Acidification potential	4.21	4.46	9.52	23.60	24.81	62.07	kg SO_2 eq.
GWP_{100}	85	164	1038	873	1242	6769	kg CO_2 eq.
Depletion of abiotic resources – elements, ultimate reserves	0.04	0.02	0.11	0.23	0.14	0.74	kg antimony eq.
Depletion of abiotic resources – fossil fuels	5237	6513	9556	28281	34165	62308	MJ
Eutrophication	1.59	1.72	3.97	9.08	9.72	25.85	kg PO_4--- eq.
Freshwater aquatic ecotoxicity	737	744	4344	5379	5447	28328	kg 1,4-dichlorobenzene eq.
Human toxicity	8284	967	2790	38983	5726	18191	kg 1,4-dichlorobenzene eq.
Marine aquatic ecotoxicity	8.88E+05	8.27E+05	3.32E+06	5.59E+06	5.34E+06	2.17E+07	kg 1,4-dichlorobenzene eq.
Ozone layer depletion	6.05E-05	7.25E-05	7.33E-05	3.10E-04	3.60E-04	4.80E-04	kg CFC-11 eq.
Photochemical oxidation	0.29	1.00	0.44	1.51	4.76	2.85	kg ethylene eq.
Terrestrial ecotoxicity	19.28	12.44	69.62	120	89.62	453	kg 1,4-dichlorobenzene eq.

Over the last decade, carbon sequestration, carbon footprints and carbon emissions have become globally familiar terms. GWP is often one of the key impact factors when assessing the environmental performance of building materials. Timber is unique in the sense that trees sequestrate carbon dioxide during growth. By using wood in long-lived products, the re-emission can be delayed; additionally, by using wood products and by-products for energy generation, emission associated with fossil fuels can be avoided. Furthermore, wood products generally require less energy for manufacturing then equivalent alternatives.[7,28-30] There is an ongoing debate in the research community on how to treat biogenetic carbon emissions.[31,32] While the assumption of carbon neutrality is true given a long time perspective, climate neutrality is a different matter. In order to better understand the climate change impact of using wood compared to LGS in this study, Figures 1 to 3 present a more differentiated view of the GWP and associated carbon dioxide streams.

Figure 1 shows the cradle-to-grave GWP incline for the three materials and the two house sizes. The graph clearly indicates that the two timber alternatives follow a similar flat GWP impact ratio, whereas the LGS system shows a sharp increase between the small and bigger house footprints – however more data points (house sizes) would be required to perform further analysis. Once again, this increase can be explained by the higher material mass ratio required to scale up the LGS systems from the 42-m^2 to the 168-m^2 house design, compared to the timber alternatives. Note that because only two house footprints were analysed, the gradients in this graph are not equitable, but rather show a trend.

The rest of the analyses will focus on the 42-m^2 house roof designs.

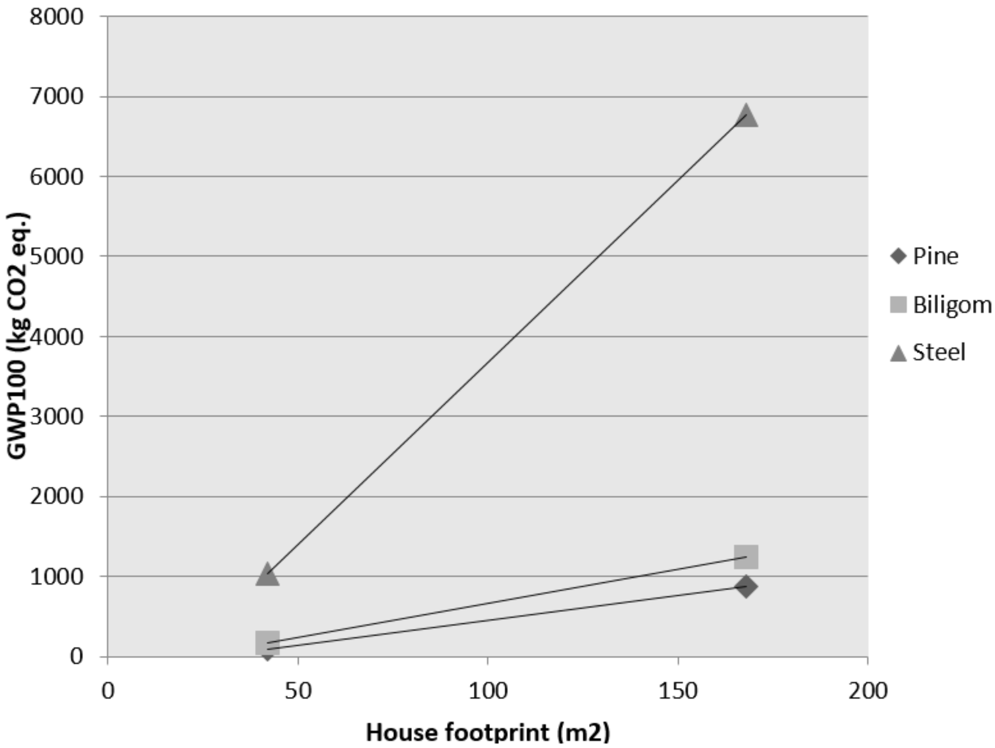

Figure 1: Global warming potential ratios for South African pine, Biligom and light gauge steel for 42-m^2 and 168-m^2 house designs.

Global warming potential is expressed in kilograms carbon dioxide equivalents (kg CO_2 eq.) and represents the impact of a number of gases (e.g. carbon monoxide, carbon dioxide, methane, HFC) standardised with their lifespan in the atmosphere to a unit of carbon dioxide. Anthropogenic carbon dioxide emissions are produced from various sources, such as fossil fuel use, waste material decomposition and organic material burning. The carbon dioxide flows over the life cycle of South African pine and Biligom are displayed in Figure 2. Three major carbon dioxide flows were captured in both GWP data reports: sequestrated carbon dioxide from the air and biogenic and fossil-derived carbon dioxide emissions. According to the US Environmental Protection Agency:

> *Biogenic CO_2 emissions are defined as CO_2 emissions related to the natural carbon cycle, as well as those resulting from the production, harvest, combustion, digestion, fermentation, decomposition, and processing of biologically based materials.*[33]

The sequestrated carbon dioxide in the air is a negative value because of the carbon that is stored in the tree through photosynthesis during growth. The biogenic carbon dioxide emissions in Figure 2 are 99% attributed to the incineration process whereas the fossil-derived carbon dioxide emissions are mainly attributed to manufacturing and transport processes. The difference in the magnitude of the carbon dioxide flows between the two timber systems is interesting to note. The lower biogenic carbon dioxide levels for pine can be explained by the lower material density. The slightly lower fossil carbon dioxide level for pine is mostly as a result of the shorter transportation distance to the building site and also a lower density (smaller mass to transport). Fossil fuel impact breakdown per alternative from the manufacturing stage, transport and disposal can be seen in Figure 4 to accentuate the transportation impact.

In theory, adding sequestrated carbon dioxide from the air and the biogenic carbon dioxide emission should be close to a net result of zero. By analysing the flows for both materials visually, it is evident that these two carbon dioxide flows do not exactly match up, but show a slight negative carbon dioxide net result. The most likely explanation for this negative net result is a difference in wood volume in the forestry background data, compared to the wood used in the trusses and the wood used in the modelled, Swiss-based, incineration process. Furthermore, the incineration process does not emit all the carbon contained in the wood as pure carbon dioxide$_2$. Although timber sequesters carbon dioxide in the growing phase, by adding the three types of carbon dioxide flows as seen in Figure 2, both pine and Biligom still result in a small positive carbon dioxide footprint.

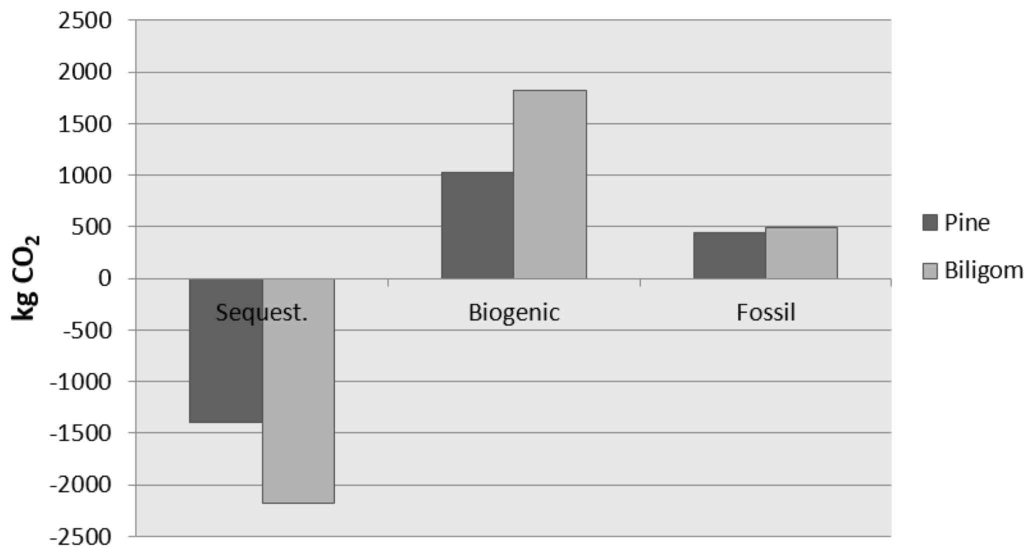

Figure 2: Carbon dioxide flow of South African pine and Biligom for the 42-m^2 roof design.

Therefore, under a general simplified assumption of carbon neutrality of biomass, a closer look at the GWP (excluding biogenic carbon monoxide, carbon dioxide and methane flows) can help in the understanding of the global warming impact of the truss alternatives (Figure 3). This time not considering carbon dioxide, the net GWP impact of the LGS truss system is only about double the two wood alternatives. Both wood alternatives have a large contribution attributed to truck transportation-associated emission from the factory to the building site. This finding highlights the importance of the transportation method and resource location. Although alternative transportation methods – i.e. shipping and rail – might be more environmentally efficient compared to truck, it was not part of the scope of this study. The final stage (i.e. site to grave) includes incineration of all three truss systems and shows a non-significant overall non-biogenic impact contribution compared to the cradle-to-gate and cradle-to-site impact.

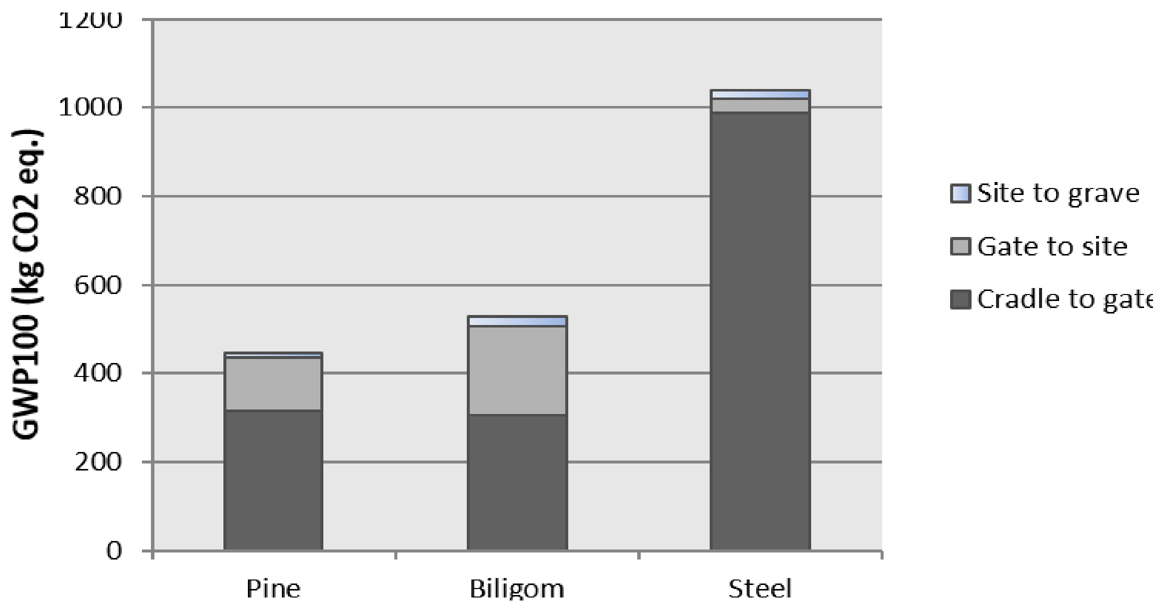

Figure 3: Global warming potential (GWP), excluding biogenic carbon monoxide, carbon dioxide and methane impact per life-cycle stage for the 42-m^2 roof design.

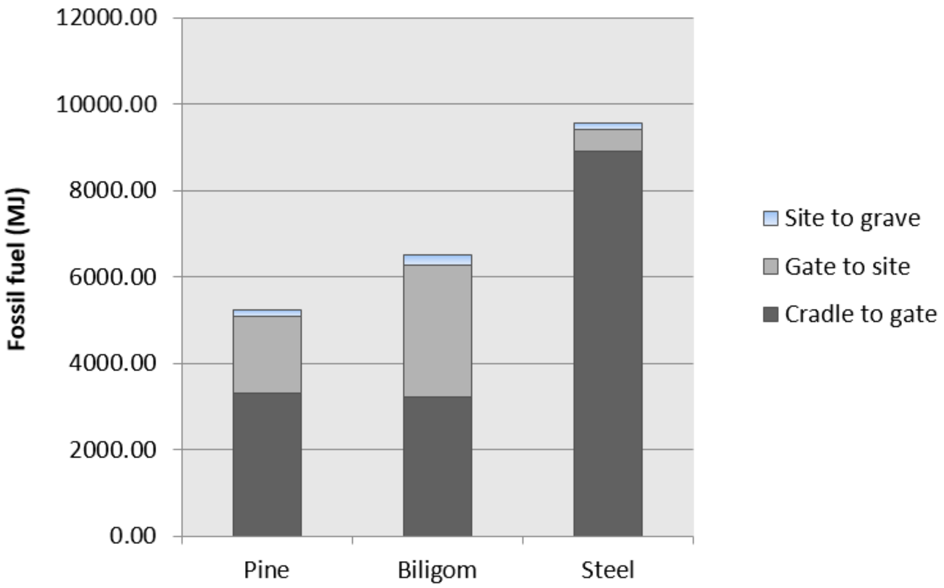

Figure 4: Depletion of abiotic resources/ fossil fuel (MJ) per life-cycle stage for the 42-m^2 roof design.

Figure 4 displays the fossil fuel depletion per life-cycle stage. A similar trend to the contribution profile for the non-biogenic GWP (Figure 3) can be seen, with a large contribution from transportation to the wood alternatives, especially for Biligom.

While GWP and fossil fuel depletion are important and relatively easy to understand impact factors, to assess the largely fossil fuel based climate change impact of building products, other environmental indicators need to be considered for a holistic evaluation of the potential environmental impact of building materials beyond GWP. In the following section, normalisation was used to evaluate the overall environmental impact between truss systems based on the 11 baseline impact categories. Normalisation is a simple technique to equate different categories and magnitudes by adjusting values measured on different scales to a notionally common scale. In Table 5, normalised indices of each cradle-to-grave impact category for all three truss systems are displayed. In each case, the LGS impact was set as one and the remaining two in relation to one. Finally, the combined or pooled normalised impact was computed by repeating the process using the total normalised values per truss system. Equal weighting was used to compute the compiled impact.

This method indicates that the overall environmental performance of the two timber systems is about 40% better than that of the LGS system. It also shows that one should be cautious of considering only one impact category to evaluate materials. For example, considering only climate change or human toxicity potential will portray a skewed picture. However, considering all impact data and results presented in this study, both timber truss systems outperform LGS but indicate a similar or higher impact in the human toxicity, ozone layer depletion and photochemical oxidation categories.

Table 5: Combined cradle-to-grave normalised impact per alternative material

Normalised impact for 42-m² roofs	**Normalised indices**		
Impact category	**Pine**	**Biligom**	**Steel**
Acidification potential – average Europe	0.44	0.47	1
Climate change – GWP_{100}	0.08	0.16	1
Depletion of abiotic resources – elements…	0.34	0.17	1
Depletion of fossil fuels	0.55	0.68	1
Eutrophication – generic	0.40	0.43	1
Freshwater aquatic ecotoxicity – FAETP inf	0.17	0.17	1
Human toxicity – HTP inf	2.97	0.35	1
Marine aquatic ecotoxicity – MAETP inf	0.27	0.25	1
Ozone layer depletion – ODP steady state	0.82	0.99	1
Photochemical oxidation – high No_x	0.66	2.29	1
Terrestrial ecotoxicity – TETP inf	0.28	0.18	1
Total	6.98	6.14	11
Average normalised impact	**0.63**	**0.56**	**1**

Sensitivity analysis

Process contribution, end-of-life modelling and data uncertainty were identified as important independent variables that could impact the dependent variables and thus overall LCIA under the system assumptions. Adjustments were made to existing processes in the ecoinvent database when possible to better represent local conditions (e.g. by using local electricity data available in ecoinvent or adjusting conversion factors). However, according to the Ecoinvent dataset v3, the average efficiency of the global hard coal plants (0.322) compares very close to the South African (0.332) electricity generation efficiency (Treyer and Bauer[36]).

Data uncertainty and availability

Data uncertainty with a likely significant impact on results is the lack of LCI data for the wood preservation chemicals. A local timber treatment expert provided chemical composition and quantities of treatment required per cubic metre of timber but impacts that could possibly occur when the treated product is disposed of were not accounted for. Similarly, no detailed LCI data were available for galvanised LGS. Global steel manufacturing processes in ecoinvent, including steel production, sheet rolling, zinc coating and metal working were combined and adjusted to approximate a local LGS product model. Metal working was included to represent the machining and press factory processes which produce profiled LGS truss components. This process contributes 36% to the LGS GWP and might be a slight overestimate as a result of the difference in general metal machining and LGS.

Although the Australian forestry models used reasonably represent local conditions, in order to better assess the impact of forestry on local land and water use, local LCI data would be required. In general, global LCI data are good enough for a general comparison, to assess trends and identify weak points in a system, but the calculated numbers should not be taken as absolute values. The work by Nebel et al.[34], on adapting European data for use in New Zealand, highlights the difficulty of using data from one country or region for another country that does not share common manufacturing resources. The latter can be especially difficult to assess in terms of appropriateness for an LCA practitioner.

End-of-life scenario discussion

Only one scenario was considered in this study: 100% material waste incineration. The assumption satisfies the reality of local wood waste treatment and scrap steel disposal. However, a study done by Blengini[35] showed that building material recycling has the potential to save between 18% and 35% on GWP over the building's life cycle.

Additional climate benefits of wood use can also be realised at the end of its life depending on biogenic carbon and GWP accounting approaches and by granting substitution benefits. In general, wood use can help reduce GHG effects by four main routes, which are closely interlinked: (1) carbon can be stored in forests and (2) wood products, (3) wood products can substitute for other products, thus using less fossil fuel during manufacturing, avoiding process emissions and fuel emissions through biofuel substitution, and (4) carbon dynamics in landfills.[7] Previous studies on the topic of wood substitution have found that the greatest potential for positively effecting climate change mitigation lies in increasing the amount of carbon stored in wood products and by substituting fossil fuels using wood energy or products that use a large amount of fossil fuel in their production.[28-30]

In this study, we chose a conservative approach to account for climate change benefits of wood use and substitution without accounting for carbon pools, carbon pool changes and substitution benefits to facilitate a relatively simple and easy direct comparison of the different roof truss systems and materials.

Conclusion

In both cradle-to-gate and cradle-to-grave analyses, the two timber alternatives – Biligom and South African pine truss systems – showed significantly lower environmental impact than LGS. For the smaller truss system, LGS had about twice the GWP impact of the timber systems and the normalised impact over all environmental indicators was about 40% higher. The benefit of biogenic carbon dioxide and low embodied energy present in timber proved to play a significant role in the GWP impact and could be further reduced if wood were used at its end-of-life to generate energy and substitute for fossil fuel use.

Overall, we have shown the potential advantage of using local timber products to reduce the environmental impact of the truss and building industry in South Africa. More local LCI data and research are required in order to promote and simplify direct system comparison in the local building industry and to better account for localised environmental emissions e.g. end-of-life fate of preservative treated timber. While better data would produce more reliable and robust absolute data, no changes to the general trends of this study are likely.

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Chapter 4.

The potential of wood based building systems to reduce global warming potential and embodied energy of residential housing structures in South Africa

Unpublished

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Abstract

The objective of this study was to quantify the reduction in global warming potential and embodied energy possible if building systems for new residential housing structures in South Africa change to wood based systems. In a modelling analyses where different future building market scenarios in South Africa were compared, it was shown that if wood based residential buildings increase its market share to 20% of new constructions, the embodied energy and global warming potential of the residential building sector would decrease by 4.9% from the current levels. If all new constructions is wood based, the total embodied energy and global warming potential of the residential building sector will decrease by 30.4%. It was shown that with the use of wood resources currently exported as chips, as well as planting trees in areas that have been earmarked for afforestation, it will be possible (in the long term) to sustain a future residential building market where all constructions are wood based. However, in the short term imports of wood building components might be necessary if significant growth in wood based building market share occur.

Note: wood based building systems in this paper comprise timber frame, cross laminated timber and other wood based materials such as orientated strand board or plywood.

Introduction

In less than 15 years, it is predicted that 3 in 4 people will fall into the middle-income group of the world (World Bank, 2016). That means roughly an additional 2.5 billion people will require formal housing to live in. The threat of global warming to the world is well documented (IPCC, 2014) with buildings playing a major role in the emissions of greenhouse gasses (GHG). According to Beradi (2017) the building sector in developed countries produce up to 40% of the total GHG. In South Africa it is estimated that the energy use in, and construction of buildings, are responsible for about 27% of South Africa's total anthropogenic carbon dioxide emissions (Milford, 2009).

The environmental footprint of residential buildings in South Africa could be reduced in various ways. Firstly, the building materials used could be changed from the traditional brick and mortar to lower impact materials such as timber frame or even timber panel systems. Secondly, various strategies to decrease the operating impact of buildings can be introduced. Currently, operational life cycle energy requirements of conventional buildings are far higher than the embodied energy (Chastas et al., 2016). However, as low energy and near zero energy buildings become more prevalent, embodied energy will become a larger part of the total building energy requirements (Sartori and Hestnes, 2007; Ampofu-anti et al., 2015). Our research only focussed on the reduction of the embodied impacts of buildings. In terms of the environmental impact criteria our emphasis was on global warming potential (GWP) and embodied energy (EE) of residential buildings.

Numerous studies showed that timber is not only renewable, but is also the best performer across most environmental impact factors compared to building material alternatives, such as steel and concrete with particularly good performance in terms of greenhouse gas emissions (Petersen & Solberg 2005; Werner & Richter 2007; Upton et al. 2008; Sathre & O'Connor 2010; Wang et al., 2014; Crafford et al., 2017). Trees absorb carbon dioxide during the photosynthetic process to form wood which is a largely carbon based material. Timber structures effectively store a similar mass of carbon that was removed from the atmosphere by the tree and fixed as wood. Currently an estimated 1% of new residential housing structures in South Africa can be described as wood based structures and the rest are brick and mortar or cement block with timber roof truss systems (Slabbert, W, 2017, email communication, November 28). In some countries such as the USA and Canada well over 90% (Palmer, 2000) of residential housing is timber frame.

The objective of this study was to quantify the reduction in global warming potential and embodied energy possible if building systems for new residential housing structures in South Africa change to wood based systems. We considered various future residential building scenarios for South Africa.

For each scenario, we displayed the global warming potential and embodied energy of buildings on a national level, while considering factors such as expected residential building area completed per building type such as brick and mortar, reinforced concrete compared to timber frame and cross-laminated timber (CLT) and the specific environmental impacts per system.

This study used data obtained from literature to develop models to predict global warming potential and embodied energy from new residential housing structures in South Africa. Data was required for three input areas: (a) Building system environmental impacts, (b) residential housing construction in South Africa, and (c) potential market growth of wood based buildings in South Africa. An effort was made to investigate whether local forest resources will be able to supply the required wood for significant growth in timber based residential housing construction.

Background and literature review

Building system environmental impacts

In 2014 cement based building products such as mortar, screed, plaster, concrete and paving accounted for 3.59 million tons carbon dioxide equivalent (mtCO_2 eq.) greenhouse gas emmissions or 29.4% of the emmissions of the major building product groups in South Africa. An additional 3.36 mtCO_2 eq. (27.6%) of the emmissions of the major building product groups was caused by masonry wall elements. More specific, concrete hollow blocks and clay brick production contributed 60% and 40% respectively of masonry GHG impact (Ampofo-anti et al., 2015). Concrete stockblocks require a significant amount of GHG-generating cement. Clay stock brick production requires energy intensive processess and the major GHG emissions arise from fossil fuel burning to fire brick kilns (EPA, 2003).

According to Ampofo-anti et al. (2015), 8.74 million single roof trusses were consumed in the entire South African building sector in 2014, of which 55% were steel and 45% timber trusses. The total GHG emissions for roof structures was 0.467 mtCO_2 eq. and accounts for 3.8% of the total GHG impact of the building product groups (Ampofo-anti et al., 2015). Residential markets per value in these reports represented 38% of the building sector.

Up to date, the world relied heavily on CO_2 intensive concrete development for building structures (Miller et al. 2017). On the other hand, wood based systems has been gaining market share in some areas (Alfter et al., 2017; Adamson et al., 2017) and has a comparatively lower CO_2 and embodied energy impact. Bribian et al. (2011) reports that laminated wood absorbs 582 kg CO_2 per m^3 (not incinerated at end of life), while reinforced concrete emits 458 kg CO_2 and steel 12 087 kg CO_2 per m^3. In the same way, Ferguson et al. (1996) reported rough sawn timber produce 750 MJ/m^3, concrete 4800 MJ/m^3 and steel 266 000 MJ/m^3. Although these differences are quite significant, material level values do not enable any realistic building system comparisons in terms of building area since not all building systems require the same amount and format of materials per unit area.

A building system review study by Cuchi et al. (2007) done in Spain, showed overall average GWP emissions of 500 kg CO_2 and EE of 5754 MJ for all building materials considered per building area (m^2). In another life cycle energy study of brick and timber residential buildings, Thomas and Ding (2017), compared ten standard Australian brick buildings to similar thermal and structural performing timber designs. Three life cycle stages were analysed including material and construction, maintenance, and end-of-life over a 50 year lifecycle. The material and construction phase resulted in similar EE and GWP impacts per m^2, compared to Cuchi et al. (2007) and are presented in Table 1.

Embodied energy carries an increasing importance in residential life cycle impacts. Chastas et al. (2016), performed an in depth literature review which considered 90 life cycle energy analysis case studies of residential buildings, over a 50 year life cycle, constructed the past decade. The results showed an increasing percentage of EE in the transaction from conventional to passive, low energy and near zero energy buildings. EE dominates in low energy and near zero energy buildings with a share of 26% - 57% and 74% - 100% respectively.

Embodied energy and GWP of buildings and in particular residential dwellings can be very complex to determine. Studies based on life cycle analysis methodology and newly developed product category rules (Tyrens, 2014) for buildings were selected as the most applicable data sources to derive the normalised building impacts from. Table 1 summarise the best available literature results for building system EE and GWP impact per m^2, compiled from multiple sources. Mean volume of wood (including wood-based panels) per building system was also included.

Important to note, operational, maintenance or end of life energy were not included and were assumed equal for all systems. End of life energy contributed on average less than 2% of total life cycle energy for both timber frame and brick cladded homes (Thomas and Ding 2017). In the same way, no significant differences between timber frame and brick home maintenance energy over 50 years, was evident. In terms of CLT and reinforced concrete demolition energy demands, due to lack of CLT system demolition energy data, it was assumed equal (Guo et al. 2017).

Table 1. Research study results on building system embodied energy and global warming potential impacts.

Building system	Description	MJ/m²	CO² eq/m²	Wood m³/m²	Gross floor area m²	Life cycle	Country	Year	Source
Brick	Low energy	5588	527.17[a]	0.1[b]	231	50 yrs	Australia	2017	Thomas and Ding
Timber frame	Low energy	4717	445.00[a]	0.3[b]	231	50 yrs	Australia	2017	Thomas and Ding
Reinforced concrete	Conventional	1541	308.2	-	4 floors	50 yrs	China	2017	Guo et al.
CLT	Low energy	847	-84	-	4 floors	50 yrs	China	2017	Guo et al.
Reinforced concrete	Conventional	3095.2[a]	292	-	4 floors	50 yrs	Sweden	2014	Dodoo et al.
CLT	Conventional	1208.4[a]	114	0.27[c]	4 floors	50 yrs	Sweden	2014	Dodoo et al.
Brick	Conventional	5400	509.43[a]	-	192	70 yrs	Italy	2010	Blengini and Di Carlo
Brick	Conventional	6132	578.49[a]	-	150	30 yrs	Spain	2006	Casals
Timber frame	Standard-light	2212	208.68[a]	-	94	100 yrs	New Zealand	2004	Mithraratne and Vale

a. These results were obtained by multiplying a factor from the South African primary energy production and GHG emissions ratio in 2014 (Ampofo-anti et al. 2015).

b. Brick and timber frame wood volume per m², was obtained from Pajchrowski et al. (2013), the timber frame house had an all wood-based ground floor, 1st floor and roof structure.

c. CLT showed slightly lower volume of wood per m², most likely due to reinforced concrete foundation and ground floor.

Residential housing construction in South Africa

The South African population growth rate decreased steadily from 2.8% per annum in 1972 to 1.3% in 2017 and is expected to continue decreasing in the near future (UN Department of Economic and Social Affairs, 2017). National completed residential building data indicate a rise and fall development curve over the past 17 years. Compiled building data from Statistics SA (2016) was selected as background data for further scenario modelling. This data included all completed residential buildings reported by South African municipalities. Note, not all government-subsidised low-cost housing units were included as it is reported and financed separately in many cases. This data was not available and could not be included in this study.

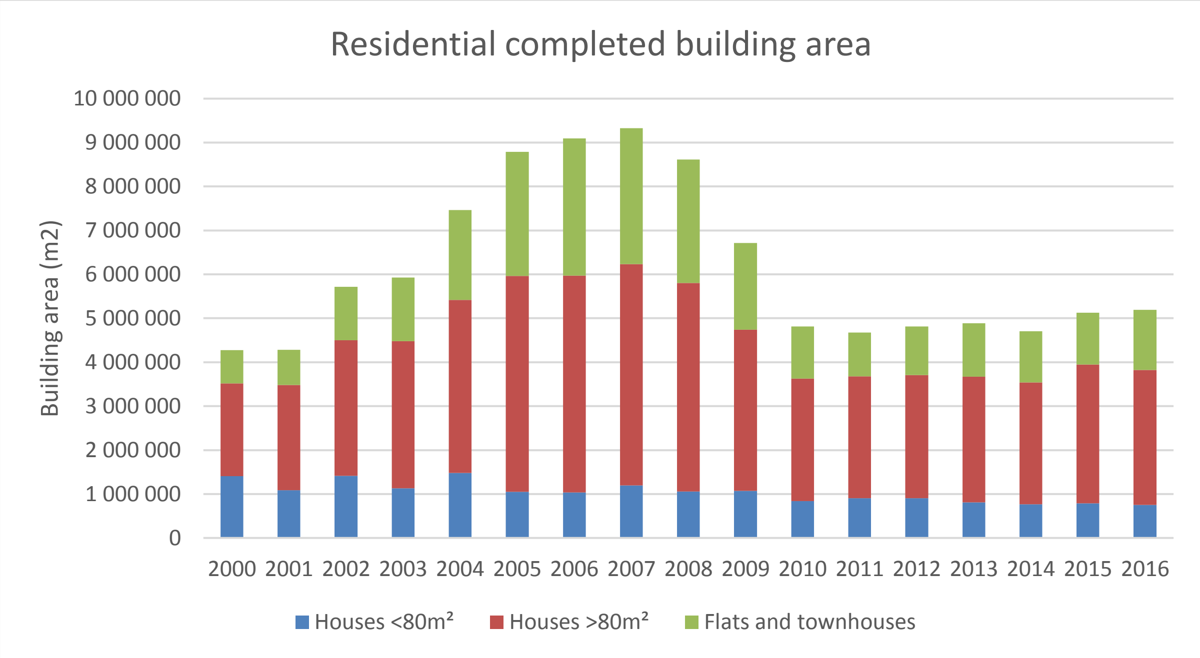

Figure 1. South Africa completed residential building area. Source: Statistics SA, 2016.

According to Statistics SA, over the period 2000 - 2016, the average house in SA was 114m^2 big and an average of 54 111 houses were constructed annually. On average 1 040 651 m^2 of houses smaller than 80 m^2, 3 436 302 m^2 of houses bigger than 80 m^2 and 1 665 624 m^2 of flats and townhouses were completed annually.

Potential market growth of wood based residential buildings in South Africa

The extent to which new building systems can increase its market share in a country is dependent on many factors. The cost, resource availability, legislation, building culture, user's perception of a building method and type, skills availability and, also the perception of the environmental credentials of the building system can play a role.

In Germany the number of new single family and two-family houses built with wood has tripled in the past 25 years from 6% of the market share in the early 1990's to 18% in 2017 (Alfter et al., 2017). The UK timber frame housing share of all new buildings reached 27.6% in 2015 and is predicted to rise to around 32% by 2018, (Adamson et al. 2017).

South Africa is a country with limited forest resources. The SA plantation forestry industry is very productive though, and despite having only about 1.8 million ha's covered with closed canopy plantations and forests, the annual national industrial roundwood production was 17.5 million m^3 in 2015 (FSA, 2015).

The requirements of wood resources for future house construction can come from either new forest plantings, a change in forest resource use, or imports. South Africa's industrial roundwood production is used mainly for the production of pulp and board products (51%), sawn lumber (24%), and chip exports to Asia (17%), (Figure 2). In 2016 sawn timber production was 2.3 million m^3 of which 70% was used in construction, mainly for roof truss material (Crickmay and Associates, 2017). Sawn timber resources are already oversubscribed and mainly used in house construction (roof trusses), therefore it is not likely that any additional timber can be sourced for future house construction from the current sawmilling resource. Table 2 provide estimates of potential future log resources available for timber based housing components such as sawn timber and board products.

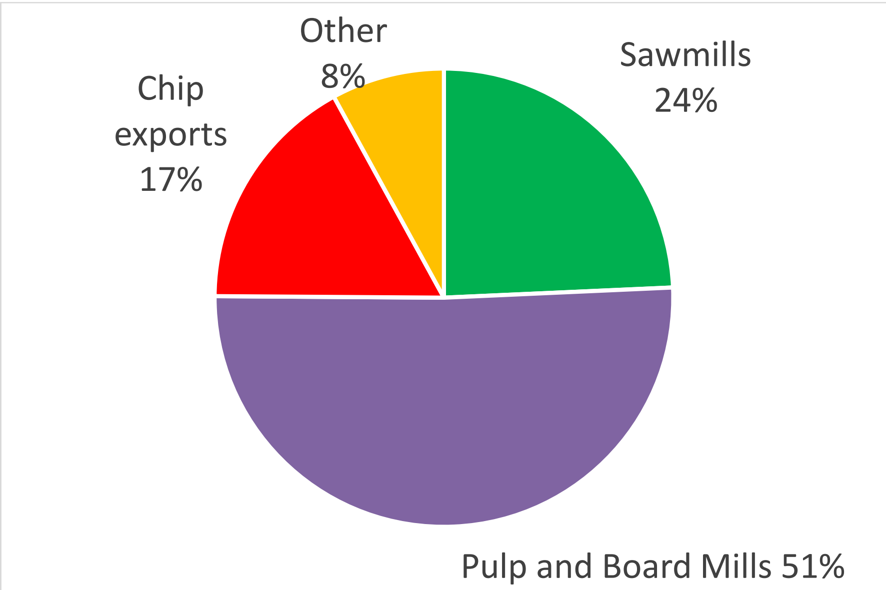

Figure 2. South African industrial roundwood consumption by different sectors (FSA, 2015)

Chip exports is the most likely available resource which could potentially be used for future house construction components. Export chips are either from eucalypt or wattle trees. Recently developed new technology such as green-gluing of eucalypt timber enable the manufacture of engineered high grade structural timber from fast grown pulp wood resources (Crafford and Wessels, 2016). CLT would offer another product solution for young eucalypt or pine pulp or wood chip trees (Pröller, 2017). According to Guo et al. (2017) CLT is a relatively new product, production increased from 25 000m^3 in 1996 to 600 000m^3 in 2014 and was estimated to reach 1000 000m^3 in 2016. CLT is a

European developed product, with an 80% installed market share in Europe, but countries like Canada, US and Australia are also showing rapid market growth (Guo et al., 2017). Other housing components that could potentially be manufactured from young pulp tree resources include products such as oriented strandboard (OSB), and possibly parallel strand lumber.

Over the past 10 years, an average of 3.5 million tons of wood chips was exported from South Africa annually (FSA, 2015). A slight decrease in chip exports was evident in 2015 with only 2.3 million tons exported. Depending on chip moisture content and sawmill recovery rates, on average 2.3 million ton chips would result in 2.6 million m^3 sawlogs or 1.04 million m^3 of sawn timber using a volume recovery rate of 40%. However, the national average sawmill volume recovery rate of softwood sawmills in South Africa is 47.4% (Crickmay and Associates, 2013). In general, smaller diameter logs such as pulp logs will result in lower volume recovery rates (Wessels, 2009). Some processors of small diameter eucalypt logs into green, unseasoned sawn timber obtain volume recovery rates of 50% - but in this case do not include a shrinkage loss as they sell products in the green state (De Kock, 2017). A volume recovery rate of 40% was assumed to be a reasonable estimation of dry sawn timber that will be recoverable. For board products such as oriented strand board or reconstituted lumber such as parallel strand lumber, the volume recovery rates will depend on the process and final product but could vary between 70-80% (Puettmann et al. 2016).

Afforestation in South Africa with fast growing plantation species is also a possibility. Although available land considered suitable for plantations is limited in South Africa, communal areas of 100 000 ha was earmarked by government for afforestation in the Eastern Cape (DEA, 2017). There are also roughly 40 000 ha private farmland available in Kwazulu Natal which could also potentially be afforested (Chamberlain et al., 2005). If successful, these afforestation plans has the potential to produce an additional annual sustainable supply of 2.07 million m^3 roundwood or about 1 million m^3 of timber within about 24 years of establishment, if destined for sawlogs only. This was calculated using a mean annual increment of 14.8 m^3/ha/year for softwood sawlogs (Kotze et al. 2012) and the national average sawmill volume recovery of 47.4% (Crickmay and Associates, 2013).

There is also potential for afforestation in areas previously not considered suitable for plantation forestry. Recent research shows the potential of dryland forestry in the Western Cape coastal areas (Du Toit et al., 2017). Von Doderer (2012) identified 175 000 hectares of potential dryland forest plantation area in the Western Cape. This area could result in a potential annual yield of 738 255 m^3 of timber (based on mean annual increment and volume recovery of 8.9 m^3/ha/year and 47.4% volume recovery respectively) within about 30 years of establishment. In addition, research by Wessels et al. (2016) showed that some species grown on the dry west coast of Southern Africa could produce high value sawn timber. There is undoubtedly also other areas in the country where trees can be grown in dry areas previously not considered suitable for forestry. However, research is required to quantify this potential.

Although it is from a socio-economic perspective not always the preferable option, import of sawn timber is also a possibility. Research from other countries showed that where shipping is used with short land transport distances the environmental impact of timber imports can even be relatively low (Liao et al. 2009). South Africa only imported 2% of its annual structural timber use in 2016 (Crickmay, 2017). Currently the three major import countries include Brazil, Chile and Zimbabwe. Past trade and most likely future countries for import include Argentina, New Zealand, Germany, Zambia and Mozambique (Stears, A, 2017, email communication, February 1). Board products such as oriented strand board, the preferred option for timber frame housing wall covering, is currently only available from imported sources. However, research will be required to quantify the transport environmental impacts of imports to South Africa.

Table 2. Potential future log resources available for timber based housing components such as sawn timber and board products.

Description	**Log volume (m^3/year)**	**Availability (years)***	**Data source**
Current chip export resource. Eucalypt and wattle logs	2 600 000	Immediate	FSA, 2015
Current pulp, board, and other log resource. Eucalypt, wattle and pine.	11 850 000	Immediate	FSA, 2015
Import logs or wood products	N.A.	Immediate	
Afforestation Eastern Cape / KZN. 140 000 ha	2 070 000	24 (8)	DEA, 2017
Dryland afforestation Western Cape. 175 000 ha	1 557 500	30 (10)	Von Doderer, 2012

*Value in parentheses is for pulpwood rotations and thinning's

From the data in Table 2 it can be seen that, excluding imports and current pulp, board, and other log resources, there could be an estimated 6.23 million m^3 of log resources available for wood house components in the future. This could be processed into between 2.9 to 4.9 million m^3 of products depending on the product type and recovery rates. If timber frame construction require on average $0.3m^3$ of processed wood based products per m^2 (similar in volume to CLT according to Table 1) it means between 9.6 and 16.3 million m^2 or between 84 210 and 142 982 houses of $114m^2$ will be possible to build, sustainably per annum - which is nearly double the amount of formal annual residential development at present. This clearly indicate the resource potential for an increase in timber based buildings in the construction market in South Africa.

Methodology

Four potential residential building scenarios were selected based on the existing international examples of growth in wood based buildings and potential local wood resources. Table 3 present these scenarios and input values for South Africa viz. Current (1% residential wood based buildings), 10%, 20% and 100% residential wood based buildings. The 10% and 20% growth scenarios were based on market growth values in wood based buildings experienced in Western European countries such as Germany and England over a time period of about two decades. The 100% scenario is an extreme value to illustrate the environmental impact of constructing only wood based residential buildings. Mean building area values for houses smaller than $80m^2$, houses larger than $80m^2$ as well as flats and townhouses were as indicated in Figure 1. Most applicable building system impacts (grey shaded in Table 1) i.e. brick and timber frame building were assigned to all houses smaller and bigger than $80m^2$ whereas reinforced concrete and CLT system impacts are assigned to the smaller flats and townhouses portion. In each case, the selected building system (i.e. brick, timber frame, reinforced concrete and CLT) impact, either best represented South African building and climate conditions or provided most conservative analyses options in terms of global warming potential. In addition, it was assumed that all houses smaller and bigger than $80m^2$ were brick or timber frame constructed and (higher level developments) flats and town houses either reinforced concrete or CLT construction.

Table 3. Four projected development scenarios.

Building system		Brick / Reinforced concrete			Timber frame / CLT		
System EE and GWP impacts		MJ/m²	kg CO2 eq/m²	m²	MJ/m²	kg CO2 eq/m²	m²
Current	<80m² and >80m²	5588	527	4476953	4717	445	0
	Flats and townhouses	3095	292	1665624	1208	114	0
10% wood	<80m² and >80m²	5588	527	4029257	4717	445	447695
	Flats and townhouses	3095	292	1499061	1208	114	166562
20% wood	<80m² and >80m²	5588	527	3581562	4717	445	895391
	Flats and townhouses	3095	292	1332499	1208	114	333125
100% wood	<80m² and >80m²	5588	527	0	4717	445	4476953
	Flats and townhouses	3095	292	0	1208	114	1665624

Building system impact values here represents embodied energy impacts for all processes required to produce and construct each building such as foundations, walls, roof, windows, and doors. These impacts include a wide range of materials and processes, for example the brick and mortar system include on average 0.1 m^3 of wood per m^2 – mostly due to the roof structure. Other, perhaps less obvious building elements that were comprised in the embodied energy impacts include maintenance, repairs, replacements and refurbishments (Chastas et al. 2016).

Projected development assumptions

The annual residential building data over the past 17 years in Figure 1 was used to calculate the mean annual building area per year – this was assumed to be the building rate for the near future. Population growth was not included as a direct parameter in the analyses, since the South African population growth is already fairly low and declining. At the current trend, our population will start declining in less than 40 years and will be at the same numbers as current in less than 80 years. However many other factors such as political instability of neighbouring countries and subsequent immigration to South Africa, diseases such as HIV and malaria, and economic growth influence population growth and building rates. Excluding growth also allowed the model to be time independent and therefore easier to apply. However, this is off course not an accurate assumption and introduces uncertainty in the model - which should be taken into consideration by the user.

Results and Discussion

The results discussed here are based on the development scenarios as defined in Table 3. Input values include building system EE and GWP impacts per building system mean area (m^2) per annum. Output values are mean annual residential EE (MJ) and GWP (t CO_2 eq) per development scenario (Figure 3). Each impact bar in Figure 3 for both embodied energy and GWP comprise four major categories, maintenance (1%), energy for construction (1%), transport (7%) and material production (91%) and differs significantly in mean embodied energy contribution (Chastas et al. 2016).

Building material and material production and thus building system choice, contained by far the biggest embodied energy quantity with transportation of goods being second. Hence, the reason for an increased wood based system introduction, as it is the best performer across most environmental impact factors - especially in terms of GWP, compared to building material alternatives, such as steel and concrete with particularly good performance in terms of greenhouse gas emissions (Petersen & Solberg 2005; Werner & Richter 2007; Upton et al. 2008; Sathre & O'Connor 2010; Wang et al., 2014; Crafford et al., 2017). It is important to note that in this study, the total embodied building system impact was selected as output values. If comparing purely building structures (excluding furnishing, painting, plumbing, insulation, etc.) an even greater magnitude order difference would be expected between wood based and other systems.

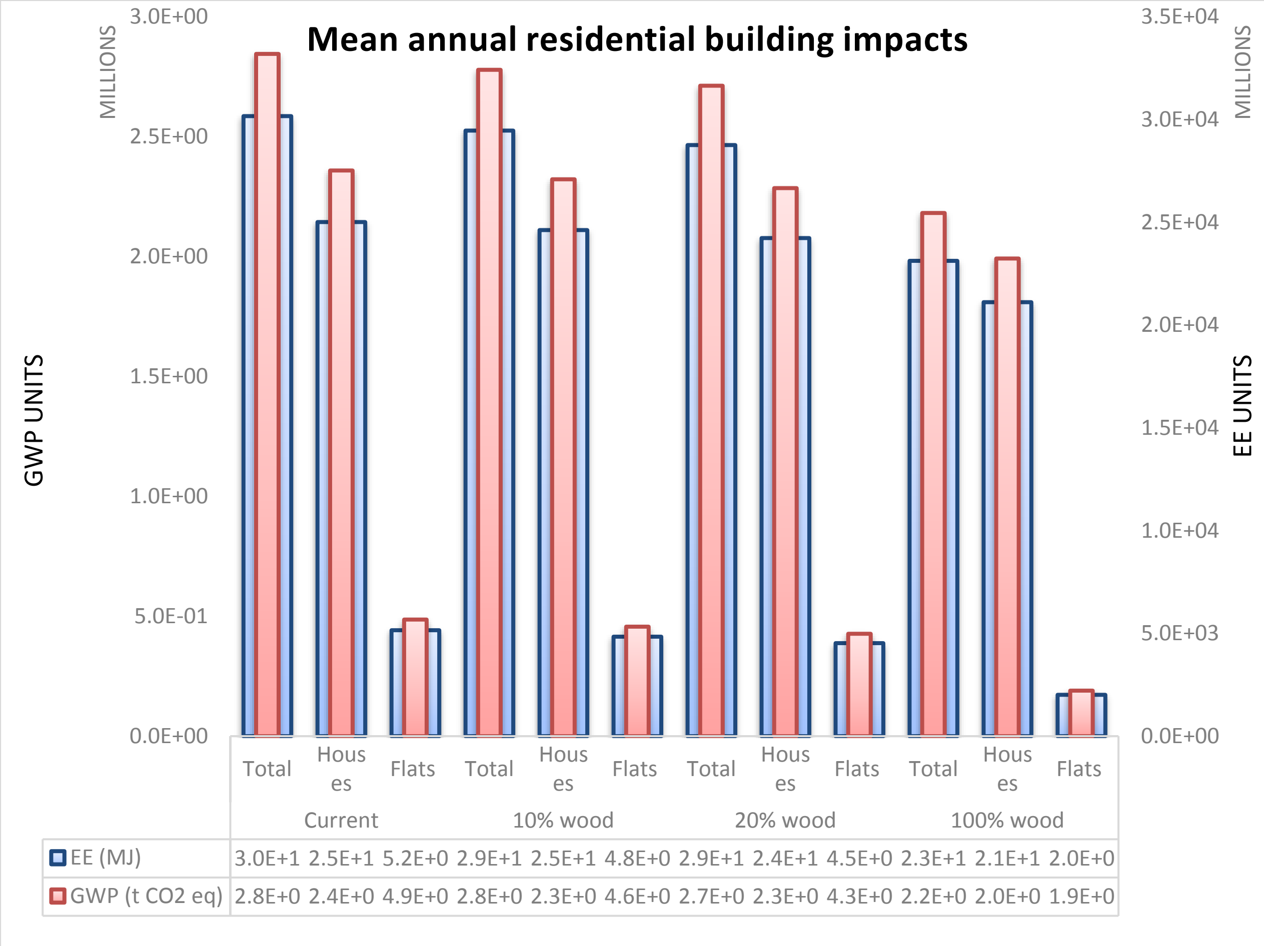

Figure 3. South African mean annual residential building GWP and EE impacts.

Brick and mortar residential homes (<80m² and >80m²) comprised the bulk of the formal residential housing market in South Africa. Brick houses represent 73 % and flats and townhouses 27 % of the total annual, formal residential development area. However the mean embodied energy and GWP impact from residential homes (<80m² and >80m²) contribute 83 % of the total annual South African footprint. This is mostly due to the smaller scale and subsequent inefficiencies as well as the building system difference compared to bigger flats and townhouses.

A 10% wood residential market increase will amount to a 2.4% savings in mean annual EE and GWP compared to the current scenario. The 20% market increase will amount to a 4.9% savings in mean annual EE and GWP compared to the current scenario. Finally an all wood market would amount to a 30.4% savings in mean annual EE and GWP compared to the Current scenario.

South Africa had an estimated total GWP of 590 million ton CO_2 eq. in 2014, an extraordinary 243 million ton more than 2006 (Ampofo-anti et al., 2015). The major building products amounted to 12.2 million ton CO_2 eq. in 2014 and represented only 2.1% of the total national GHG impact. These major building material impacts include all industries i.e. roads, commercial, government and industrial sectors. Figure 4 presents mean annual residential GWP building impacts with 5% error bars to explain likely variability for total developoment, normal houses and town houses and flats.

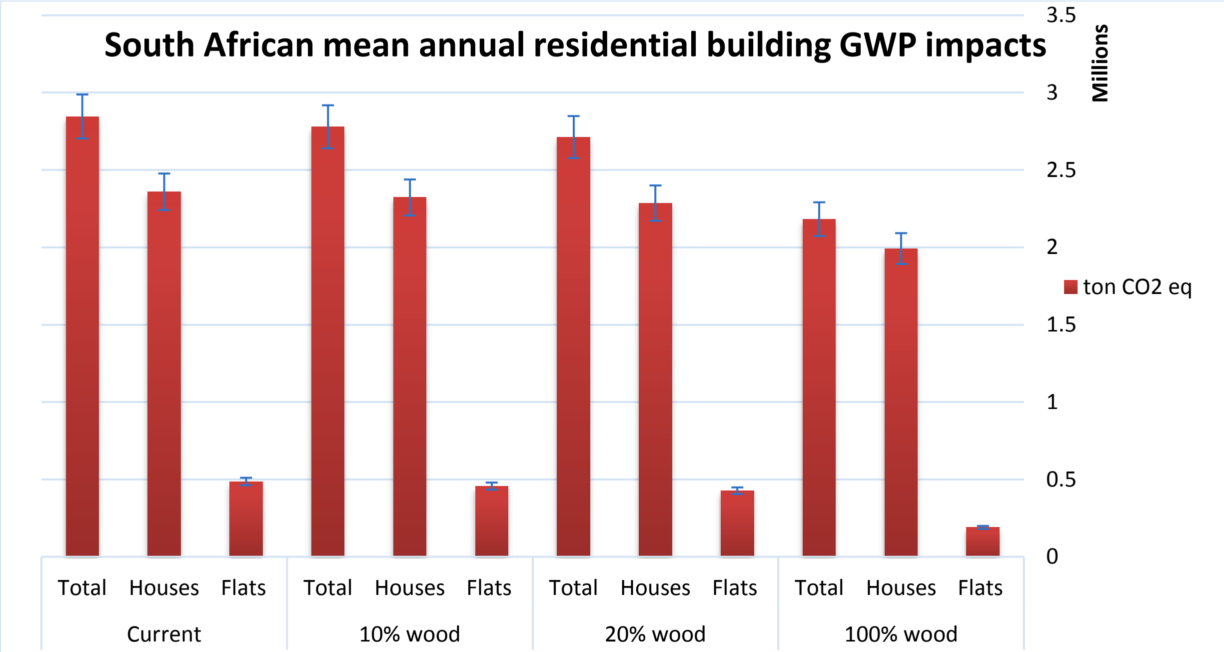

Figure 4. South African mean annual residential building GWP impacts, with 5% error bars.

As mentioned earlier, this study evaluates only residential embodied energy and not operational energy impacts. Recent studies shows that embodied energy for convential buildings contribute as low as 10% of total building life cycle energy impacts compared to operational energy impacts (Chastas et al., 2016). Although not considered in this study, wood based buildings generally also perform well in terms of operational energy efficiency. Wood is 400 times better than steel and 10 times better than concrete (per volume) in resisting the flow of heat due to its low conductivity and good insulating ability, which can lead to significant energy savings (Stalnaker & Harris 2013). However, EE can contribute up to 100% in modern near zero energy buildings and therefore plays an ever increasing role in total life cycle energy.

This modelling study showed that with market growth of wood based residential buildings similar to Germany and England (i.e. 10-20% of new buildings), there will be a moderate reduction in EE and GWP emissions of less than 5% of total residential building values. If all new residential buildings will be wood-based, the total reduction in EE and GWP will be a really significant 30.4%. Even though the potential to reduce EE and GWP in the short to medium term seem to be fairly moderate, it will still be an important contribution to climate change mitigation. The wedges theory of Pacala and Socolow (2004) showed that it will not be possible to reduce GWP to acceptable target levels with a single initiative or technology. Many different industries, sectors, and technologies will all have to contribute in order to combat global warming. If the effects of climate change result in more severe weather events, it could also be that more dramatic changes in consumer behaviour or even government intervention will result in faster and a more dramatic changes in building methods and materials such as the 100% wood based residential building scenario modelled here.

Only residential housing construction was considered in this study as it has traditionally been the market segment of choice for wood based building in other countries. New technologies and products such as cross laminated timber also make it possible to build medium rise buildings from wood based materials. An 18-storey building from mainly CLT and glulam beams has been completed in Vancouver, Canada in 2017 (Connoly et al. 2018). The commercial and industrial building sectors might therefore also in future become an attractive option for wood based buildings.

Due to the limited forest cover in South Africa the perception is often that significant increases in the market share of wood based buildings is not possible (at least from local wood resources). This study showed that this perception is not correct – current resources available in large volumes such as eucalyptus for chip export could potentially support significant growth in wood buildings. In the longer term, however, new afforestation will be required if ever wood based buildings become the norm in South Africa. In the short term supply gaps of wood building components could potentially be alleviated by imports using shipping with short land transport distances. However, research is required to quantify the environmental transport impacts from imports.

Apart from the environmental advantages of building with wood, wood-based development also has many other positive spin-offs such as job creation, technological advancement and other eco-system services (Alfter et al., 2017).

Sensitivity analyses and limitations

This study focussed on the environmental impacts of an increase in wood based residential building market share. Important impacts such as GDP generation and job creation per development scenario was not in the scope of this study. Although elements such as water availability, water quality, air pollution and economy is critical in building system comparison – this was not included in the study due to scope and resource constraints. This limit the impact of this research.

Simple cradle to gate system boundaries were selected to evaluate residential building embodied impact magnitude. End of life energy was not included and assumed equal for all direct system comparisons. However, wood in buildings can be reused or used for heat or bio-energy which all have positive climate effects. According to literature (Jambeck et al., 2007 & Ribeiro et al., 2000) CCA treated wood can be landfilled (as municipal solid waste), incinerated (waste to energy) and recycled (cleared from CCA treatment), of which proper incineration technology and methodology according to US EPA does not emit GHG's. However, incineration is not a viable/available option across South Africa (yet) and not included in the SAWPA guidelines.

Future timber resources and possible imports and transport impacts were highlighted as critical consideration to realise increased and sustainable wood based building development.

Conclusion and Recommendations

The building scenario modelling showed that incremental 10% and 20% increases in residential wood based buildings market share show a moderate environmental benefit, compared to current national GHG impacts of the residential building sector. However, the study demonstrated that a 100% increase in local timber based development will result in a significant 30.4% GWP saving in residential building impact. There is a direct correlation between GWP reduction and increased wood use in development.

It was shown that with the use of wood resources currently exported as chips, as well as planting trees in areas that have been earmarked for afforestation, it will be possible (in the long term) to sustain a future residential building market where all constructions are wood based. However, in the short term imports of wood building components might be necessary if significant growth in market share occur in wood based building.

Further research that include other environmental impacts as well as social and economic comparisons with regards to increase in wood based building is recommended. Finally, the interaction of operational energy and embodied energy of wood based buildings compared to conventional buildings in South Africa should be investigated.

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Chapter 5.

A global warming potential and energy analysis decision support tool for South African timber transport and supply

Unpublished

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Abstract

South Africa is a timber scarce country with plantations suitable for sawn timber widely distributed and often far from some of the main local markets. The objective of this research was to develop a decision support tool in order to evaluate potential local and global timber resource supply options in terms of the environmental impacts of transporting timber to the main South African market centres. Four life cycle assessment transport datasets were obtained and integrated into a single environmental decision support tool. Transport to major South African timber markets linked to local and international timber sources were modelled for global warming potential and primary energy impacts, using different transport technologies. Different supply scenarios were modelled and analysis showed that the Johannesburg, Nelspruit and Durban markets are well located for local supply of timber within current truck networks. Results also illustrated that importing timber from regions such as Cacador, Brazil to the Cape Town and Port Elizabeth areas using container shipping with current truck technology will have a lower global warming potential impact than using timber from the Nelspruit area with truck transport. If dry bulk shipping become an option for importing timber, the global warming potential of ship transport will be reduced significantly. The decision tool that was developed is relatively uncomplicated to use and can in theory be utilised to estimate the

comparative transport impacts for almost any cargo along port or road transport networks that use similar transport technologies.

Introduction

Timber from sustainable resources for construction is, from an environmental perspective, an excellent choice of material and a highly suitable alternative in terms of green building in the developing South African context (Crafford et al., 2017). Numerous international studies indicate that the use of timber in construction has a lower environmental impact compared with the alternatives, such as steel and cement (Petersen & Solberg, 2005; Werner & Richter, 2007; Upton et al., 2008; Sathre & O'Connor, 2010).

Although South Africa is approximately 90 % self-sufficient in terms of forestry products and has a positive trade balance in this sector (Louw, 2012 & Crickmay, 2017), increased demand in the building sector might necessitate greater reliance on timber imports in the future. For example, in 2008 South Africa imported large volumes of sawn structural timber to satisfy local demand. South Africa has limited timber resources with only about 1% of our land area covered with productive forests (DAFF, 2015). These forests support the production of about 5 million m^3 of sustainably produced saw logs and 12 million m^3 of logs for pulp, paper and board materials annually (FSA, 2015). The local timber plantations suitable for sawn timber are spatially far apart and are mainly located in four regions: Mpumalanga, KwaZulu Natal, Limpopo, and the Southern Cape. The areas where there are plantations are, in many cases, hundreds or even more than a thousand kilometres from the development hubs, where timber products are consumed (DAFF, 2015). The demand in most international markets as well as the supply of timber from commercial forests are on the increase, and subsequently the need for transporting timber between production areas and markets are also increasing (Crowther et al., 2015 & Carle et al., 2015).

Life cycle assessment (LCA) is a powerful tool for measuring the potential environmental impact of building products, processes and interactions (Ortiz et al., 2009 & Singh et al., 2011). In terms of life cycle assessment, studies on transport and construction, global warming potential (GWP) and primary energy demand are the most documented and relevant impact categories (Psaraftis et al., 2009 & Chastas et al., 2016). Due to the inherent low embodied energy of timber compared with other materials, the extensive transportation of timber materials is in many, if not most, cases the most significant part of the embodied environmental impact (Qarout 2017; Crafford et al., 2017). In the same way that rail transport enabled national trade and development in the past, well-established global sea freight networks have enabled the world of international trade today.

Currently, truck as well as railway transport are used to connect seaport or factory to depots, and to the final destinations. In South Africa, close to 100 % of all secondary timber transportation is by truck (Krieg, 2012).

Consumers and traders of timber products often want to make environmentally responsible choices when making purchasing decisions. Apart from selection of appropriate materials, the location or source of the material is also an important decision given the high environmental impact of transport.

Objective

The objective of this study was to investigate the potential environmental impact of importing timber to South Africa compared with the transportation impacts of local supply. Part of the objective was to develop a decision support tool based on LCA methodology and international life cycle inventory data to help analyse environmental impacts.

Note: timber in this paper is defined as structural timber or sawn timber for construction

It is important to mention that there are other very important considerations during purchasing decision-making, such as the socio-economic consequences of choices i.e. job creation, which was not considered in this study. In the South African context these might outweigh environmental considerations for some consumers. We only focussed on the environmental impacts of transport and resource decisions in our study.

Background

Global resource

Close to 30 % of the global land area is covered by forests with only 2 % being planted forests (Figure 1). Planted forest area in this sense includes “close to nature” forests and plantation forests that are used mainly for commercial purposes. In 2005 the global planted forest area was an estimated 271 million ha (of which 76 % was for productive purposes) of which South Africa plantations contributes less than 0.5%. This area represents less than 7 % of the world's forest area, but supplies 70 % of world's forest products (Evans, 2009).

According to research done by Crowther et al. (2015), using satellite images, our planet is home to more than three trillion trees. That is close to eight times more than documented in other studies done in the past and amounts to 422 trees per person living on Earth. The study highlighted areas such as Finland, Slovenia, Sweden, Brazil and Canada as increasing resource areas as well as countries such as Thailand, Vietnam, Cambodia and Laos, which are in general red zone areas where, if current forestry trends continue, the existing forests will be cleared by 2030. Studies like that of Crowther et al. (2015), next to certification systems for forests and wood products like Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC), can be used as an indication or guide for architects and clients to enable them to source timber from "green" or environmentally sustainable zones.

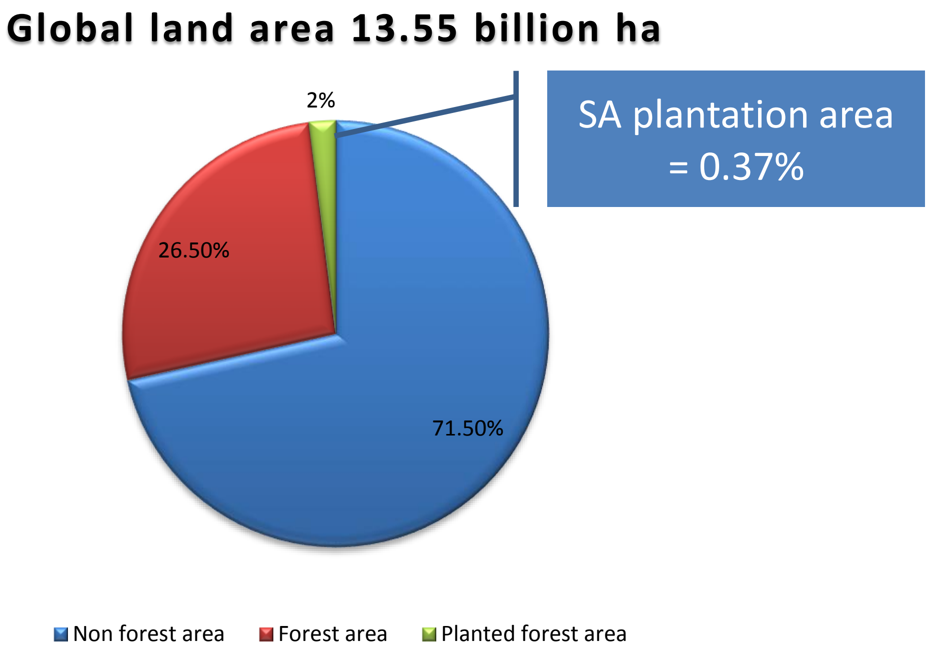

Figure 1. Global land coverage and type in hectares (Evans, 2009)

The FSC and PEFC are the biggest sustainable forest management certifying bodies in the world. Presently, the FSC and the PEFC govern third-party certification in sustainable forest management for 498 million hectares (FSC – 195.25 million ha; PEFC – 302.75 million ha) of forests across the globe (FSC and PEFC, 2016), nearly double the global planted forests area (271 million ha). In addition, China has planted significant areas over the past two decades and aims to establish 29.6 million hectares of plantations by 2020 – this will bring the country's forested area to more than 220 million hectares (FAO, 2009). This investment certainly indicates not only the environmental importance of forests currently and in the future, but also their importance in commercial trading – which is one of the main considerations for a country like China.

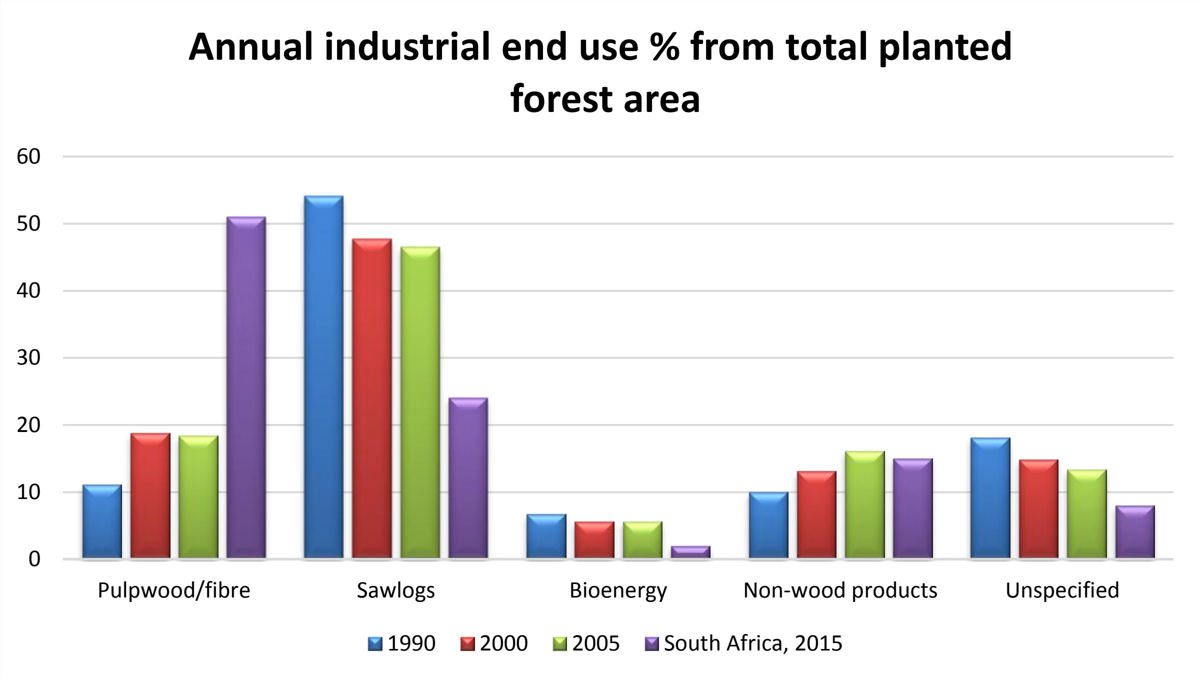

Figure 2. Global annual industrial end-use percentage from total planted forest area (Carle et al., 2009 & FSA, 2015) Note: South Africa, 2015 non-wood products (percentage) is mainly owing to log and chip exports

According to a report by Carle et al. (2009), close to 50 % of planted forests are used for saw or veneer logs, although this percentage has decreased slightly since 1990 (Figure 2). In contrast, pulpwood volumes have nearly doubled since 1990. The increase in usage for non-wood products can be attributed to the addition of data on rubber wood after 1990; also, the data on bioenergy usage does not yet reflect the latest trends in collecting biomass in plantations as a response to climate change (Carle et al., 2009).

The FAO (2015) forest products report provides the following global production of industrial roundwood: United States of America (20 %), Russian Federation (10 %), China (9 %), Canada (8 %), Brazil (7 %), Sweden (4 %). These statistics explain the existing importance of global shipping; for example, although China produces only 9 % of industrial roundwood globally, they consume 11 %. Canada, on the other hand, export 64 % of all the sawn wood that they produce (FAO, 2015). Altogether, sawlogs comprise the largest proportion of the global production of industrial roundwood although; in South Africa the largest portion is pulpwood and fibre.

Local resource

In its Global Industrial Roundwood Outlook (FAO, 2012), the FAO reports that the South African forest industry is producing only 0.94 % of the annual global industrial roundwood supply. However, South Africa is still the 19th biggest industrial roundwood producer in the world, producing almost 16 million m^3 in 2012 and 17.5 million m^3 in 2015 (FSA, 2015). Data on local timber sales illustrates a wide geographical distribution of the South African timber market (DAFF, 2015). The largest timber market (Johannesburg) is less than 500km from all of the sawmills in the largest sawn timber producing area (Mpumalanga). Cape Town, on the other hand, is more than 1700km removed from most sawmills in Mpumalanga. Both the largest sawn timber producers in South Africa, with sawmills located in Mpumalanga and KwaZulu-Natal, have got sales depots situated in the Cape Peninsula, illustrating current trade and transport routes.

Local import and transportation impacts

Currently, the three major importing countries for timber to South Africa are Brazil, Chile and Zimbabwe. Continents and countries that have been prominent in terms of trade in the past, and that will most likely continue and increase their trade in the future, include again South America, Europe, Australasia, Zambia, Gabon and Mozambique (Stears, A, 2017, email communication, February 1; Crickmay, 2017). Global trade is predominantly truck and ship dependent. A study by Liao et al. (2009) compares the CO_2 emissions of trucking and intermodal container transport in Taiwan and highlights the importance of container shipment and trucking networks for trade. The research states that significant greenhouse gas savings are possible with inter-country shipping compared with inter-country trucking, the same applies for intra-country shipping and trucking. Finally, the study highlights the lack of research quantifying shipping transport impacts.

Although South African timber truss material has a lower GWP compared with alternative materials, a large contribution to its GWP has been attributed to emissions associated with truck transportation from the factory to the building site (Crafford et al., 2017). In another international LCA study, by Bribian et al. (2011), building materials transported from the production plant to the building site, covering an average distance of 100 km, were analysed, and impact calculation coefficients for truck, rail and shipping were developed. Table 1 summarizes the primary energy demand and GWP associated with the transportation of one ton of building materials over one kilometre. Clearly, truck transportation has the highest impact on primary energy demand (MJ/km) and GWP.

Table 1. Primary energy demand and GWP impacts per transport stage from production plant to building site of one ton per kilometre (Bribian et al., 2011)

Impact category	Truck	Rail	Ship
Primary energy demand (MJ/km)	3.266	0.751	0.17
GWP (kg CO_2 eq/km)	0.193	0.039	0.011

Methodology

Life cycle analysis was selected as the environmental comparison method for truck and ship transportation impacts. Gabi software and the Ecoinvent v.3.3 life cycle inventory (LCI) provided the basis for the modelling, and more specific, the standard EURO3 and EURO6 with dataset destination; transport, freight, lorry >32 metric ton, global, for truck transport and for container shipping; transport, freight, sea, transoceanic ship. The functional unit was selected as one ton kilometre for each type of technology. According to Wernet et al. 2016, the background system (LCI) covers close to 99% of the unit processes (aggregated and/or disaggregated) in LCA product systems. This highlights the importance of the availability and quality of LCI unit process data.

Four types of technology were used to accurately represent local and international ship and truck transportation impacts. The global standard truck datasets in accordance with EURO3 (current technology) and EURO6 (potential technology) were used for modelling truck transportation. The dataset values for container shipping was adjusted by a factor of 0.44, in accordance with Psaraftis and Kontovas (2009), to represent dry bulk shipping impacts. The EURO3 dataset was assumed to represent the average South African truck (inter-link, 40 ton) impacts. This was selected as a conservative assumption and is not biased in terms of shipping or trucking and import or local trade. It is important to note that although truck transport (40 ton) and container ship transport (50 000 ton) load potentials vary significantly, this is accounted for in the functional unit (ton kilometre) and LCA modelling. The effects of improved truck and shipping technologies, i.e. the energy design efficiency index and ultra-low sulphur diesel, were considered by adding EURO6 as potential future trucking technology and dry-bulk shipping transport. This was assumed to account for potential market or trade scenarios in the next 10 to 20 years in South Africa. Climate change as well as primary energy were selected as life cycle impact assessment indicators from the International Life Cycle Data System /Product Environmental Footprint (ILCD/PEF) indicator v.1.09. Although, various standard impact assessment methods and indicators exist to evaluate and compare LCA impacts, primary energy (MJ) and GWP (kg CO_2 eq.) are the most reported impact indicators and perhaps the best-understood and climate-relevant impact indicators at present. There are many other important environmental indicators such as those related to freshwater and saltwater pollution but in order to limit the scope of this study, these were not included.

The system boundaries included all the global transport impacts over a distance of transportation of the final product per mass. Transport included fuel production, vehicle production, maintenance, infrastructure and vehicle operation (i.e. cradle to use, excluding end-of-life).

Markets and sources

Specific timber sources in South Africa, the nearest functional ports and the largest five timber markets were selected according to available data from the South African government's Department of Agriculture, Forestry and Fisheries (DAFF, 2015). Truck transport analyses included sawmill to market centre (km) by truck, whereas ship importing included sawmill to port (by truck) and port to port (km) by shipping. Specific seaport and land transport distances were obtained from Sea-distances.org (2018) and Google Maps (2018).

Although rail freight is an environmentally efficient transport method, it was not considered relevant to this study, since South African secondary transport (including for timber) by rail are not significant, compared with existing truck and road networks (Havenga et al., 2014).

Finally, no forest management operation or manufacturing impacts for roundwood to sawmill were included in this study. It was assumed that imported timber would be sourced from responsible managed sources in all countries.

Decision support tool

Based on the model output from the LCA, a decision support tool was developed to describe the impact of transport, by two truck and two ship technologies, as well as the combination thereof on GWP (kg CO_2 eq.) or primary energy (MJ) per ton kilometre, in the form of a linear equation.

Results and discussion

Model output

The two major processes contributing to environmental impacts in truck transportation are vehicle operation and diesel production. Diesel production contributes 1.06 MJ of energy when transporting one ton per kilometre, with current truck technology. Vehicle operation contributes more than 0.6

kg CO_2 eq. per ton kilometre to GWP (Figure 3). To prevent double counting, primary energy was accounted for in diesel production only and not in vehicle operation as well.

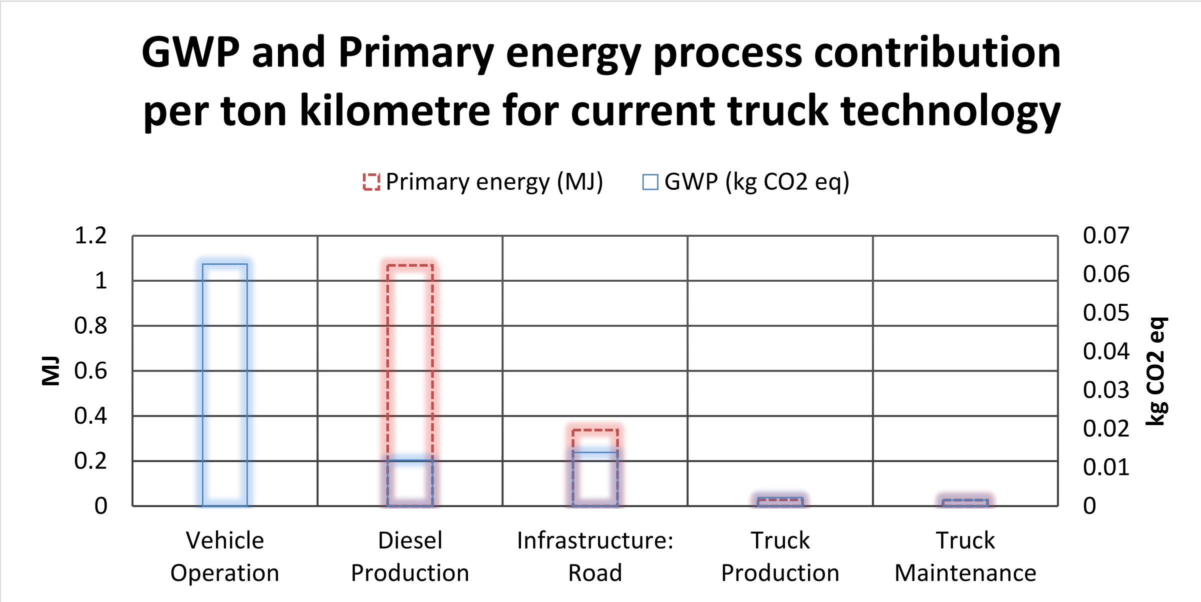

Figure 3. Process contribution to GWP (including biogenic carbon, in kg CO_2 eq.) and primary energy from non-renewable resources (gross calculated value, in MJ) for EURO 3 truck technology

Both these factors are relative to the type of production and operating technology used. In this study, we selected current truck technology and diesel production primarily from fossil fuels, as this represents the predominant global, and South African, practice. However, according to Van Vliet et al. (2009), there is a significant difference in primary energy use between oil, coal to liquid, gas to liquid and biomass to liquid diesel production. Emissions per kilometre driven by car varied greatly based on production from oil (0.18 kg CO2 eq.), coal to liquid (0.34 kg CO2 eq.), gas to liquid (0.21 kg CO2 eq.) or biomass to liquid (0.09 kg CO2 eq.) diesel. Although the findings by Van Vliet et al. (2009) are not directly comparable, it is still interesting to note the differences caused by the source and the technology used in producing diesel. Vehicle production and maintenance has a very small overall GWP and energy process contribution.

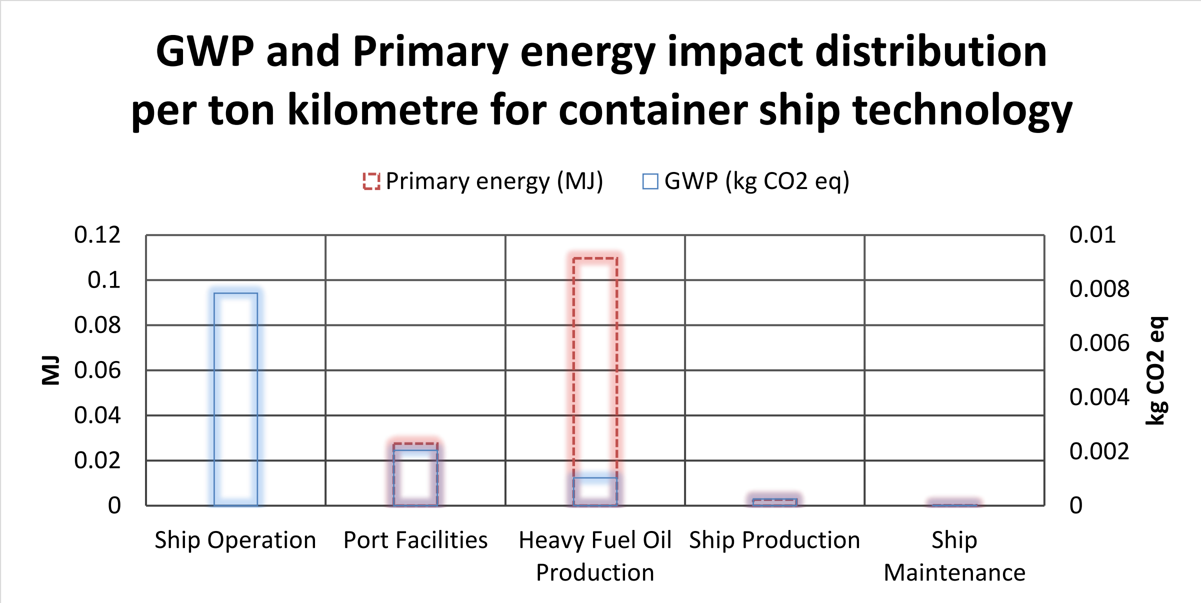

Figure 4. Environmental impact distribution for GWP and primary energy per ton kilometre for transoceanic container ship technology

Ship transportation impacts showed a similar trend to truck technology. Again, mode of operation and type of fuel production comprised the highest energy and GWP impacts, compared with port facilities, and ship production and maintenance. However, container-ship operation and fuel production contributions (0.11 MJ and 0.008 kg CO_2 eq. respectively) are approximately 10 times smaller compared with truck transportation per ton kilometre (Figure 4). This can probably be explained by the higher load capacity of ships and subsequent efficiencies achievable. Finally, ship production and maintenance is a very small process contributor over a 20-year life cycle.

It is important to note that impact categories, i.e. ship operation, vehicle operation, and port facilities all contribute towards the total environmental impacts per functional unit. For example, the total GWP per ton kilometre for container ship technology would be 0.011 kg CO_2 eq., and not only 0.008 kg. Table 2 shows the total GWP and primary energy demand per transportation option obtained from the life cycle impact assessment. The values in Table 2 will be further used as transport coefficients.

Table 2. Impact calculation coefficients for four transport technologies per one ton

Impact category	Truck – present (t_1)	Truck – potential (t_2)	Ship – container (t_3)	Ship - dry bulk (t_4)
GWP (kg CO_2 eq. /km)	0.092	0.088	0.011	0.005
Primary energy demand (MJ/km)	1.550	1.527	0.148	0.065

The transport coefficients for truck (present) are approximately 50 % less compared to those in Table 1, by Bribian et al. (2011). The ship container coefficients on the other hand are comparable. The lower truck GWP and primary energy coefficients in this study can be explained by the selection of EURO3 transporting markets, as opposed to the short hauling (100 km) used by Bribian et al. (2011).

Based on the LCA results, a model was developed to describe the impact of transport by truck and ship as well as the combination thereof on GWP (kg CO_2 eq.) or primary energy (MJ) per ton kilometre (Equation 1).

$TI = (m \times t_1 \times d_1) + (m \times t_2 \times d_2) + (m \times t_3 \times d_3) + (m \times t_4 \times d_4)$……………………………………….Equation 1

where :

TI = transport impact, in kg CO_2 eq. or MJ

m = mass, in ton;

t_i = transport technology coefficient, either GWP or primary energy;

d_i = transport distance per transport technology, in kilometres.

In theory, this relatively uncomplicated equation can estimate the comparative transport impacts for almost any cargo along port or road transport networks all over the world that use similar transport technologies.

Local transport scenarios

To compare the contribution to GWP per ton of timber transported to markets in South Africa, seven different national and international transportation scenarios to five major South African markets were compared. Actual timber resource and market data were obtained from the DAFF (2015) report on commercial timber resources and primary roundwood processing in South Africa. In Table 3 and 4, Nelspruit and Piet Retief represents the Mpumalanga North and Mpumalanga South regions and Knysna the Southern Cape plantation areas of South Africa

Table 3. Global warming potential (kg CO_2 eq.) per ton of timber, transported to five major markets in South Africa using container shipping and truck transport (present). JHB = Johannesburg; DNB = Durban; PE = Port Elizabeth; CPT = Cape Town.

Markets	Timber source							Market share (%)
	Nelspruit 30 %*	Piet Retief 15 %*	Knysna 5 %*	North Island (NZ)	Canberra (Aus)	Kolmarden (SWE)	Cacador (Brazil)	
Nelspruit	4.60	25.12	136.71	237.72	217.28	238.19	185.08	21.9
JHB	32.02	29.99	104.88	226.68	206.24	227.15	174.04	27.5
DNB	63.20	39.19	107.27	174.52	154.08	174.99	121.88	17.7
PE	125.12	112.70	24.10	176.98	156.54	167.29	114.18	10.6
CPT	160.45	148.58	44.99	183.77	163.33	159.08	106.60	16.4

*Percentage of the total SA timber supply

The GWP values per ton of timber transported to local markets varied significantly by distance and mode of transportation. As can be expected, short distance truck transportation e.g. from Nelspruit to Nelspruit had a lower impact than long distance truck transport e.g. from Nelspruit to Cape Town. The same trend can be seen for transportation by ship, the longer the distance the higher the impact.

Johannesburg, the biggest local market, consumes 27.5 % of the timber supply of South Africa (DAFF, 2015). Currently the biggest local source, Nelspruit (30 %), is closer to Johannesburg and most of the demand can be met from there. If the demand for timber continues to rise, Johannesburg would require supply from other local markets, as well as possibly importing from abroad. Importing timber from Cacador, Brazil through the Durban port to Johannesburg has only a slightly higher GWP impact than truck transport from Knysna, the local source furthest away from Johannesburg.

The following section analyse and discuss transport technology impacts and breakeven quantities over distance in kilometres in comparing shipping and local truck transport alternatives – from resource to major markets, based on the previously provided transport impact equation and the coefficients in Table 2. Transport scenarios in Figure 5 represent actual South African timber trade cases and illustrate the major markets i.e. Cape Town and Port Elizabeth.

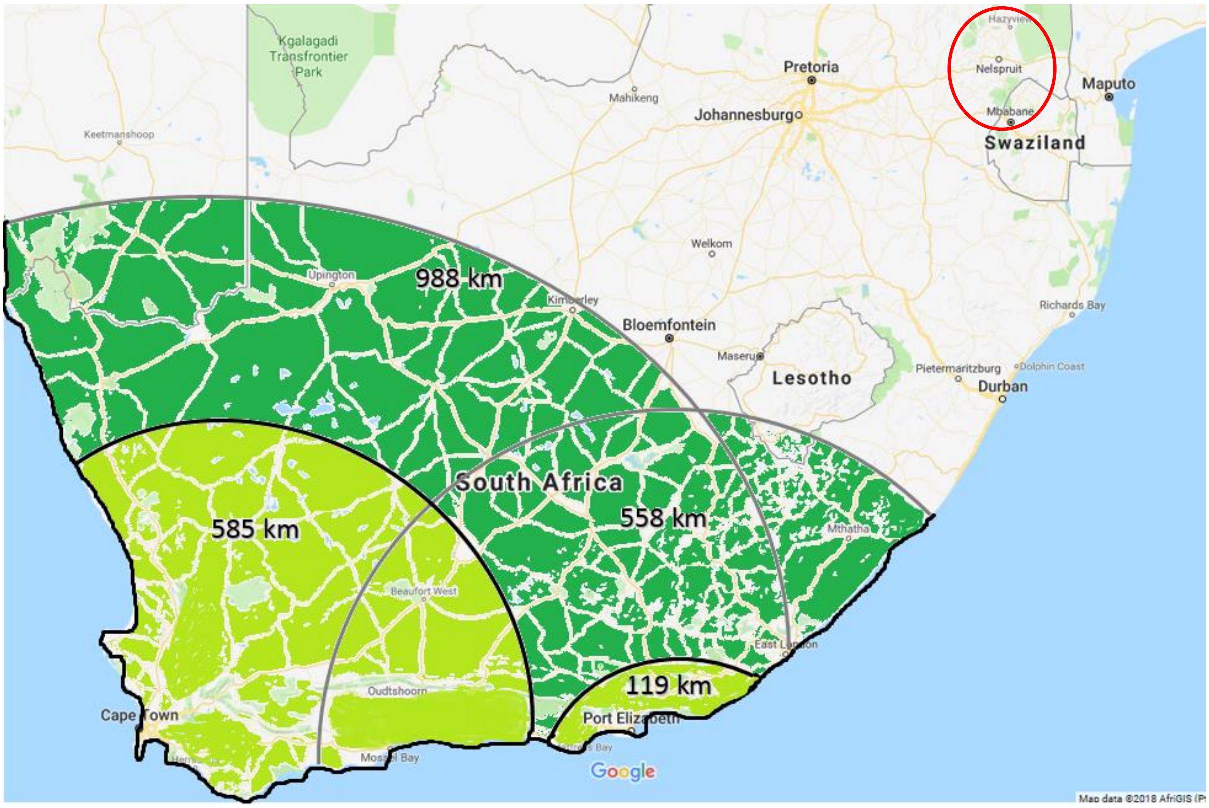

Figure 5. GWP breakeven border (in km) for shipping from Cacador (via Paranagua port) in Brazil to two important market centres in South Africa compared to the impact of local timber transport from Nelspruit. The black lines represent breakeven points for current transport technology (EURO3) and grey lines potential transport technology (EURO6 trucks and drybulk shipping). Inside the shaded area the transport GWP impact from imported Brazilian timber will be less than that of Nelspruit timber.

Figure 5 provides a comparison of GWP impacts between importing from Brazil to the Cape Town and Port Elizabeth markets compared to local supply from Nelspruit (1744 km from CPT and 1360 km from Port Elizabeth). It is evident that the transport technology plays a significant role on the GWP impact. Importing timber from Brazil to Cape Town results in 585 km net truck transport compared to local truck transport from Nelspruit (i.e. Brazilian timber can be transported an additional 585 km by truck after reaching the port in Cape Town before a breakeven in GWP impact). The use of more modern trucking technology (EURO6) would result in even greater additional truck transport distances after shipping before breakeven point is reached. The same trend can be seen for importing through Port Elizabeth, except that the additional truck transport distances after shipping are smaller due to the longer ship transport distance. It is interesting to note the significant difference in net truck transport between current and potential future transport technologies. This is mainly because of container versus dry-bulk shipping (see Table 3 and Table 4). To a lesser degree, the truck technology also affects the GWP impact when importing timber.

Using Equation 1 (and viewing the map in Figure 5), it is clear that shipping timber from Nelspruit through the Maputo harbour to either Cape Town or Port Elizabeth will clearly be a much better choice, from an environmental perspective, than either truck transport or even shipping timber from Cacador, Brazil. Currently that option is not even considered by sawmilling companies - probably due to the logistical complexity of exporting and importing lumber through another country to a local market. However, if climate change considerations start to play a more prominent role in purchasing decisions, these type of transport arrangements might become a more realistic option.

Table 4. Global warming potential (kg CO_2 eq.) per ton of timber, transported to five major markets in South Africa using dry-bulk shipping and truck transport (potential). JHB = Johannesburg; DNB = Durban; PE = Port Elizabeth; CPT = Cape Town.

Markets	Timber source							SA market share for timber (%)
	Nelspruit 30 %*	Piet Retief 15 %*	Knysna 5 %*	North Island (NZ)	Canberra (Aus)	Kolmarden (SWE)	Cacador (Brazil)	
Nelspruit	4.40	24.02	130.77	155.67	145.36	146.88	133.96	21.9
JHB	30.62	28.69	100.32	145.11	134.80	136.32	123.40	27.5
DNB	60.46	37.49	102.61	95.21	84.91	86.42	73.50	17.7
PE	119.68	107.80	23.06	96.33	86.03	82.92	70.00	10.6
CPT	153.47	142.12	43.03	99.42	89.11	79.19	66.56	16.4

*Percentage of the total SA timber supply

To transport one ton of timber from a Nelspruit sawmill to the Nelspruit market by truck currently results in an emission of 4.6 kg CO2 eq., compared with 4.4 kg CO2 eq. for transporting timber from a Nelspruit sawmill to the Nelspruit market with a potential future truck. Similarly, to transport one ton of timber from a Nelspruit sawmill to the Cape Town market with a current truck emits 160.45 kg CO2 eq., compared with 153.47 kg CO2 eq. of emission per ton for transporting it with a potential truck to the Cape Town market.

However, to transport one ton of timber by container ship from a North Island (New Zealand) sawmill to the Cape Town market emits 183.77 kg CO2 eq., compared with an emission of only 99.42

kg CO2 eq. per ton for transporting it with a dry-bulk ship to the Cape Town market. This is nearly a 50 % reduction in GWP impact for the dry-bulk shipping option compared with the container alternative. Furthermore, in the case of dry-bulk shipping, all import options to Cape Town and Port Elizabeth prove environmentally viable, compared with the two biggest local supply options.

Future transport technologies and sensitivity analysis

In comparing container shipping vs dry-bulk shipping and present truck vs potential future truck transport scenarios, it is evident that dry-bulk shipping results in a significantly lower GWP (and thus a primary energy) impact. This is primarily due to the uniform bulk nature of dry-bulk shipping, without the additional mass and volume of steel containers for protected goods. Whereas, only a small variability in ton kilometre impacts between Euro3 and Euro6 truck technology was found. However, additional transport technologies such as rail may become part of the future viable (timber) transport options in South Africa, which will then need to be included.

Due to the problems of air pollution, gas emissions and fossil fuel depletion in recent years, electric vehicles, hybrid electric vehicles, and energy efficient fuel cell vehicles will be adopted in the near future to replace the current conventional vehicles (Ehsani et al., 2018). Nykvist & Nilsson (2015) report that the past decade has shown a rapid cost reduction in battery technology for electrical vehicles. Accordingly, their findings have significant implications when modelling future transport systems and reflects a positive outlook for electric vehicles and consequently the impact of truck transportation on GWP.

Conclusion and recommendations

For this study, a novel transport impact-decision-tool, with LCA derived impact coefficients, was developed to compare the current GWP and primary energy impacts of four different international transport technologies. Particularly, the results in Table 3 and 4 indicate that major local markets, i.e. those of Johannesburg, Nelspruit and Durban, are well located within current truck networks and show lower GWP values per ton kilometre compared with those of Cape Town and Port Elizabeth. Although, the Knysna timber source (5%) offers good timber supply options to nearby markets, future and potential supply from that source might not be sufficient to meet further demands.

International shipping proves to be an environmentally viable alternative in some potential trade scenarios. More specifically, timber imports to the Cape Town and Port Elizabeth markets from some sources show up to a 55 % lower GWP impact than supply by truck transport from Nelspruit. Our data analyses and the literature presented in this study present a good environmental basis for increased international resource use, and in this case, an increase of sustainable timber supply in South Africa. In addition, the impact equation in this study can be used to compare similar supply chain alternatives across the world, based on locally adjusted coefficients.

Although the scope of this study allowed only for the investigation of four relevant transport technologies, future research should focus on electrical truck, rail transport options and other environmental impact categories. However, it is important to make decisions based on an environmentally sensible basis for both timber resource origins and transport mode. For example, exploiting certain resources (countries) might result in local damage such as erosion, water pollution, and livelihood losses.

Hence, it is recommended that other factors such as fresh water and air pollution impacts be included in future (timber) trade and transport research. Finally, and imperatively, responsible resource management as well as social and economic impacts per country should form part of purchasing decision-making. In practice, this might necessitate starting by importing only FSC, PEFC or comparable certified timber or resources.

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Chapter 6. Summary of research outcomes

The main results of the study as reported in Chapters 2 to Chapters 5 are summarised below.

- Rising global awareness of greenhouse gas emissions and resource depletion caused by the building industry resulted in increased “green building” activity. However, a review of green building rating tools indicated that the well documented environmental benefits of using wood were not sufficiently reflected in these rating systems.
- Although life-cycle-assessment is recognized as the best way to holistically evaluate the environmental impacts of a building, it is resource intensive, can be highly complex, and is dependent on the availability of accurate data. There is a critical need for local life cycle assessment based research in South Africa and other developing countries on the environmental impacts of different building products and processes.
- At present, more than 70% of all sawn timber in South Africa is used in buildings, mainly in roof structures. A comparison between several roof truss systems (South African pine, Biligom and light gauge steel) using the life cycle assessment method showed that the two timber systems had overall the lowest environmental impact. Although the difference between the timber systems was small, light gauge steel had a 40% higher normalised impact over all assessed environmental impact categories.
- In a modelling analyses where different future building market scenarios in South Africa were compared, it was shown that if wood based residential buildings increase its market share to 20% of new constructions, the embodied energy and global warming potential of the residential building sector decrease by 4.9% from the current levels. If all new constructions is wood based, the total embodied energy and global warming potential of the residential building sector will decrease by 30.4%.
- It was shown that with the use of wood resources currently exported as chips, as well as planting trees in areas that have been earmarked for afforestation, it will be possible (in the long term) to sustain a future residential building market where all constructions are wood based. However, in the short term imports of wood building components might be necessary if significant growth in market share occur in wood based building. A decision support tool, with life cycle assessment based impact coefficients, was developed to compare the environmental impact of timber transport in and to South Africa. Transport to major South African timber markets linked to local and international timber sources were modelled for global warming potential and primary energy impacts, using different transport technologies. The decision tool that was developed is relatively uncomplicated to use and

can in theory be utilised to estimate the comparative transport impacts for almost any cargo along port or road transport networks that use similar transport technologies.

- It was shown that the Johannesburg, Nelspruit and Durban markets were well located within current local truck networks and showed lower GWP values per ton kilometre compared to Cape Town and Port Elizabeth markets. Results also illustrated that importing timber from regions such as Cacador, Brazil to the Cape Town and Port Elizabeth areas using container shipping with current truck technology will have a lower global warming potential impact than using timber from the Nelspruit area with truck transport. If dry bulk shipping become an option for importing timber, the global warming potential of ship transport will be reduced significantly.

Potential impact of this research

The novel environmental impact findings, analyses and models in this research, regarding local timber building systems will help policy makers, the professional building community and clients to make scientifically informed choices and to perform policy or rating tool modifications, in terms of material choice and building system selection.

This work indicate that an increase in timber-based development in South Africa has significant environmental potential in terms of local greenhouse gas savings and sustainable resource use. In addition, growing global trade and certified resources, suggest increased timber-based development potential in South Africa.

Further life cycle assessment studies, related to increased timber-based development are recommended, to evaluate other factors such as fresh water, air pollution and social and economic impacts.

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Appendix A

Declarations of candidate and co-authors

Declaration by the candidate (Chapter 2):
With regard to Chapter 2 of this dissertation, the published paper "Sustainability and wood constructions: A review of green building rating systems and life-cycle assessment methods from a South African and developing world perspective" the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Reviewed literature - Conceptualised and wrote the paper	80 %

The following co-authors have contributed to "Sustainability and wood constructions: A review of green building rating systems and life-cycle assessment methods from a South African and developing world perspective":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
M Blumentritt	melanie.blumentritt@gmail.com	Contributed to the writing and literature of paper	15 %
CB Wessels	cbw@sun.ac.za	Contributed to the writing of the paper	5 %

Signature of candidate: Declaration with signature in possession of candidate and supervisor
Date: 16 August 2018

Declaration by co-authors:
The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 2 of this dissertation, "Sustainability and wood constructions: A review of green building rating systems and life-cycle assessment methods from a South African and developing world perspective",

2. no other authors contributed to Chapter 2 of this dissertation, "Sustainability and wood constructions: A review of green building rating systems and life-cycle assessment methods from a South African and developing world perspective" besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 2 of this dissertation, "Sustainability and wood constructions: A review of green building rating systems and life-cycle assessment methods from a South African and developing world perspective" of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signature in possession of candidate and supervisor	Stellenbosch University	16 August 2018

Declaration by the candidate (Chapter 3):
With regard to Chapter 3 of this dissertation, the published paper "The potential of South African timber products to reduce the environmental impact of buildings" the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Conceptualised and wrote the paper - Performed most of sampling and analysis work	75 %

The following co-authors have contributed to "The potential of South African timber products to reduce the environmental impact of buildings":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
M Blumentritt	melanie.blumentritt@gmail.com	Contributed to the analysis and writing of the paper	20 %
CB Wessels	cbw@sun.ac.za	Contributed to the writing of the paper	5 %

Signature of candidate: Declaration with signature in possession of candidate and supervisor
Date: 16 August 2018

Declaration by co-authors:
The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 3 of this dissertation, "The potential of South African timber products to reduce the environmental impact of buildings",

2. no other authors contributed to Chapter 3 of this dissertation, "The potential of South African timber products to reduce the environmental impact of buildings" besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 3 of this dissertation, "The potential of South African timber products to reduce the environmental impact of buildings" of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signature in possession of candidate and supervisor	Stellenbosch University	16 August 2018

Declaration by the candidate (Chapter 4):
With regard to Chapter 4 of this dissertation, the unpublished paper "The potential of timber building systems to reduce global warming potential and embodied energy in residential housing structures in South Africa" the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Conceptualised and wrote the paper - Performed all sampling and most analysis work	90 %

The following co-authors have contributed to "The potential of timber building systems to reduce global warming potential and embodied energy in residential housing structures in South Africa":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
CB Wessels	cbw@sun.ac.za	Contributed to the analysis, concept and writing of the paper	10 %

Signature of candidate: Declaration with signature in possession of candidate and supervisor
Date: 16 August 2018

Declaration by co-authors:
The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 4 of this dissertation, "The potential of timber building systems to reduce global warming potential and embodied energy in residential housing structures in South Africa",

2. no other authors contributed to Chapter 4 of this dissertation, "The potential of timber building systems to reduce global warming potential and embodied energy in residential housing structures in South Africa" besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4 of this dissertation, "The potential of timber building systems to reduce global warming potential and embodied energy in residential housing structures in South Africa" of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signature in possession of candidate and supervisor	Stellenbosch University	16 August 2018

Declaration by the candidate (Chapter 5):
With regard to Chapter 5 of this dissertation, the unpublished paper "Environmental decision support tool for South African timber transport and supply" the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Conceptualised and wrote the paper - Performed most of sampling and analysis work	88 %

The following co-authors have contributed to "Environmental decision support tool for South African timber transport and supply":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
CB Wessels	cbw@sun.ac.za	Contributed to the concept of the paper	5 %
C Wolf	Wolf@hfm.tum.de	Compiled and analysed environmental data	5 %
M Blumentritt	melanie.blumentritt@gmail.com	Contributed to the writing of the paper	2 %

Signature of candidate: Declaration with signature in possession of candidate and supervisor
Date: 16 August 2018

Declaration by co-authors:
The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 5 of this dissertation, "Environmental decision support tool for South African timber transport and supply",

2. no other authors contributed to Chapter 5 of this dissertation, "Environmental decision support tool for South African timber transport and supply" besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 5 of this dissertation, "Environmental decision support tool for South African timber transport and supply" of this dissertation.

Signature	Institutional affiliation	Date
Declaration with signature in possession of candidate and supervisor	Stellenbosch University	16 August 2018
Declaration with signature in possession of candidate and supervisor	Technical University of Munich, Wood Science	16 August 2018