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Life Cycle Assessment of a cross laminated timber building

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Life Cycle Assessment of a cross laminated timber building

Prepared for

Forest & Wood Products Australia

by

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Executive Summary

Lend Lease is constructing a new residential building using cross laminated timber (CLT). This material is a relatively new building material in Australia, which has found increased use in multi-story residential and commercial buildings, particularly in Europe. The Centre for Design (CfD), School of Architecture and Design, RMIT University was commissioned by Lend Lease through Forest and Wood Products Australia (FWPA), to investigate the environmental performance associated with the production of the materials, along with HVAC and lighting systems, and associated operation and end-of-life of this novel building, using a life cycle approach.

This report details and compares the full life cycle of the following systems:

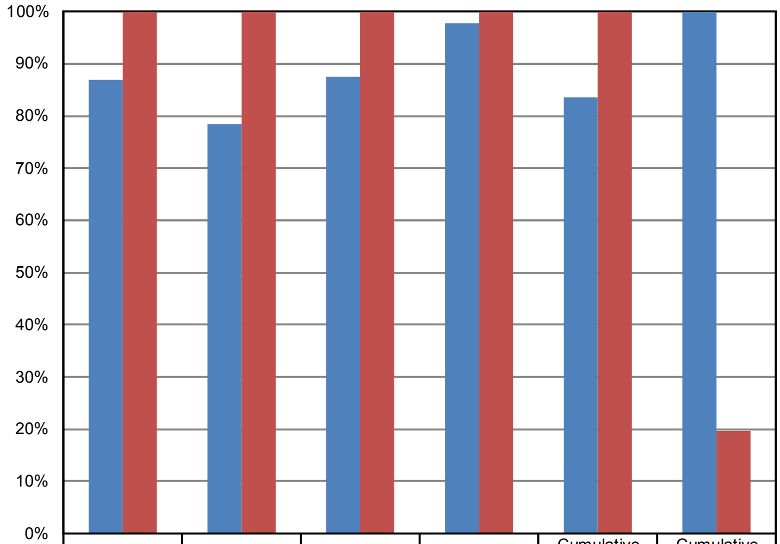
1. The Forté building, featuring cross laminated timber panels as the main structural material and energy efficient lighting and HVAC systems. The lighting systems are lower than maximum permissible BCA 2011 energy densities and the heating and cooling appliances exceed the October 2011 Minimum Energy Performance Standards (MEPS).

2. A building of similar design, however built using a conventional structure utilising predominantly reinforced concrete as the main structural material, deemed compliant to BCA 2011 minimum 6 star energy standards, with lighting with maximum permissible BCA 2011 energy densities, and heating and cooling appliances with efficiencies which meet the October 2011 Minimum Energy Performance Standards (MEPS). This building is referred to as “Reference building”.

The reference building is intended to represent the design and performance of potential new multi-level residential development, but should not be taken as representative for all of the current building stock or all new buildings.

Life Cycle Assessment (LCA) has been used as the core method for determining the potential environmental impacts of the products considered. LCA has been applied in accordance with ISO 14040:2006. Data on the building materials quantities and construction details were supplied by Lend Lease, background life cycle inventory data was gathered from Australian (AUPLCI) and European (Ecoinvent) databases. Data on cross laminated timber was provided by the manufacturer in an Environmental Product Declaration (EPD). Annual operational energy use for the Forté and the reference buildings were calculated using the dynamic building energy simulation software tool ApacheSim. The simulation results for residential spaces were validated against results from an Accurate assessment.

Figure E-1 shows the potential environmental impacts of the Forté building and the reference building. The potential environmental impacts of all considered impact categories, except renewable energy demand, are lower for the Forté building. If carbon sequestration in the CLT panels at the end of life is included, the Forté building has a 22% lower global warming potential. The majority of the life cycle impacts are occurring during the operation of the buildings, however building materials are also of importance, contributing to between 5% and 21% of impacts, depending on the environmental impact category and the building considered.



	Global Warming - ex sequestration	Global Warming - inc sequestration	Eutrophication	Water Use	Cumulative energy demand - non renewable	Cumulative energy demand - renewable
Forté Building	87%	78%	88%	98%	84%	100%
Reference Building	100%	100%	100%	100%	100%	20%

Figure E-1: Environmental impacts of the Forté building compared to the reference building.

The main conclusions of this study are:

1. The Forté building has lower environmental impact on all assessed categories, except renewable energy demand, compared to the reference building.
   a. If carbon sequestration is included the Forté building's impacts are 22% lower on global warming potential, if sequestration is not included in this indicator, Forté's impacts are 13% lower.
   b. Eutrophication potential is 12% lower for Forté when compared to the reference building.
   c. Water use is 2% lower.
   d. Non-renewable cumulative energy demand is 16% lower.
2. The reductions in environmental impacts are primarily driven by the use of more efficient HVAC and lighting systems in Forté, than for the reference building.
3. The operation of the building contributes to between 75% and 96% of environmental impact, depending on the impact category and the building considered. The main drivers of impacts in the use phase are space conditioning (heating and cooling), lighting and hot water supply. Domestic water use is the main driver of water use impacts.
4. The global warming potential of the building materials (cradle to gate) for the Forté building are 30% lower than the reference building. If the materials' construction, transport and end-of-life impacts are included, the global warming potential of Forté's building materials are 15% higher (if sequestration is excluded) or 52% lower (if sequestration is included).
5. Even though the CLT is imported (whereas the reference building's materials are mostly locally produced), the Forté building still has a lower impact for materials and transport combined when compared to the reference building (which utilises concrete).

The main limitations of this study are:

1. There was no building specific data available for hot water use. The energy use for heating water was estimated using current literature.
2. Limited data availability CLT. The data in the Environmental Product Declaration (EPD) for cross-laminated timber (CLT) does not provide data to allow assessments regarding the land use, land use change or fossil fuel depletion impact indicators. These indicators could therefore not be assessed in this study.
3. The comparative assertions regarding greenhouse impacts are sensitive to both the selection of the HVAC and lighting systems for the reference building, and the inclusion or exclusion of carbon sequestration credits.
4. There is no publically available evidence regarding the end of life fate of CLT, including potential degradation in landfill and recycling.

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1 Introduction

Lend Lease is constructing a new residential building using cross laminated timber (CLT). This material is a relatively new building material in Australia, which has found increased use in multi-story residential and commercial buildings, particularly in Europe. The Centre for Design (CfD), School of Architecture and Design, RMIT University was commissioned by Lend Lease through Forest and Wood Products Australia (FWPA), to investigate the environmental performance associated with the production of the materials, the operation and end-of-life of this novel building, using a life cycle approach.

The information on environmental performance gained through this study will primarily be used by Lend Lease to inform the public (for marketing purposes) and other stakeholders (for advocacy purposes), but may also be used for internal decision making and process improvement.

This study uses life cycle assessment to assess the potential environmental impacts across the entire life cycle which includes resource extraction, building material fabrication, building construction, use and end of life. The results of the study have been presented in two separate reports; the first report detailed the environmental impacts for materials used in the construction of the building, including all processes up to the construction site (cradle-to-site). This second and final report details the potential environmental impacts over the full life cycle (cradle-to-grave analysis). This full life cycle includes the materials, construction, operational, maintenance and end-of-life impacts.

This report describes the methodology that is utilised, the processes involved and the results of the environmental life cycle impact assessment.

1.1 Forté Building

The Forté building is currently being built in Victoria harbour, Docklands, Victoria and is due for completion by the end of 2012. The building's structure consists predominantly of cross laminated timber (CLT) panels, with an additional protective rain screen on the outside with plasterboard finishes in the apartments. The foundations and the ground floor utilise reinforced concrete. Floors from the second storey upwards utilise CLT. A 70mm thick layer of concrete and a 10mm rubber-like layer on the CLT floors provide additional thermal comfort and acoustic insulation. The building has no car park; however it features a bicycle cage and a car share space. Figure 1-1 provides an artist's impression and a map with the location of the building.

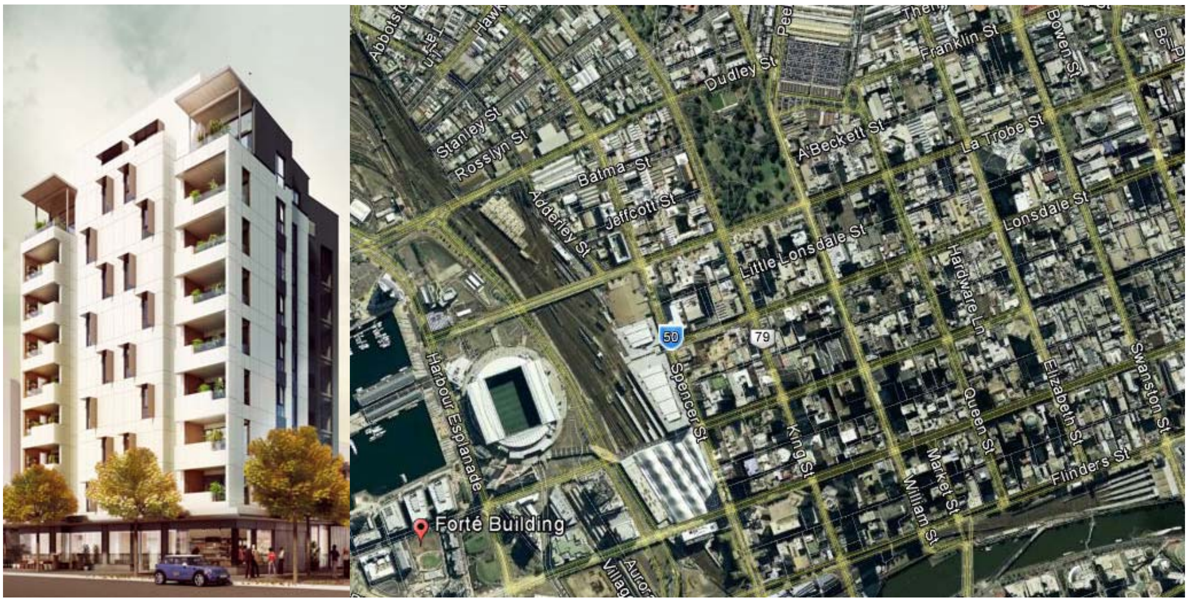

Figure 1-1: Artist's impression of Forté (left) and geographical location of Forté building (right)

1.2 About Cross Laminated Timber (CLT)

Cross laminated timber (CLT) is produced from softwood timber that is cross laminated, utilising three to seven layers, depending on thickness and structural requirements (see Figure 1-2). The layers are sawn and planed, and then glued together under pressure using a polyurethane adhesive. Panels can be fabricated to size as required by the builder, with maximum dimensions of 16.5 m (L) x 2.95 m (W/H) x 0.5 m (D).

Figure 1-2: Cross laminated panels; detail (left) and hoisted panels on the Forté building construction site (right).

The panels are sourced from KLH, an Austrian company that pioneered the manufacture of CLT, and is a world leader in the field. The panels are manufactured to specifications in KLH's plant in Austria from where it is trucked to a Mediterranean port and subsequently shipped to Melbourne on container ships via Singapore.

2 Goal of the study

2.1 Reason for carrying out the study

Lend Lease is currently building a multi-storey residential building that uses cross laminated timber panels as structural elements. Lend Lease wishes to better understand the potential environmental benefits (or drawbacks) of using CLT, along with other selected systems (e.g. heating, ventilation and cooling [HVAC] and lighting) in a multi-story residential building, relative to a construction design based on a conventional concrete construct, and standard HVAC and lighting equipment. The purpose of this study is to assess the environmental impacts of using the CLT material and other building systems in the Forté building, compared to a reference building. The scope of the study includes all building materials, construction, transport, building operation and the end-of-life of the building(s).

2.2 Involved parties

The study was commissioned by the Forest and Wood Products Australia (FWPA) in participation with Lend Lease Corporation Limited (Lend Lease). The study was undertaken by the Centre for Design, School of Architecture and Design, at RMIT University. The independent peer review for the Stage 1 and Stage 2 reports was undertaken by Start2See Pty. Ltd.

2.3 Intended audience and statement regarding comparative assertions

The results of this study are intended to be used as a basis for comparative assertions which are to be disclosed to the general public, Lend Lease internal stakeholders and business partners. It is therefore reviewed according to the ISO 14040:2006/14044:2006 (International Organization for Standardization, 2006c, International Organization for Standardization, 2006b) standards by an independent external critical reviewer. A peer review assures robustness of the study, and assures transparency and completeness. The peer-reviewer’s comments and response to these comments are reported in Appendix B. The reviewer’s final review statement will be presented in Appendix F.

3 Scope

3.1 Description of product systems under investigation

This report details and compares the full life cycle of the following systems:

3. The Forté building, featuring cross laminated timber panels as the main structural material and energy efficient lighting and HVAC systems. The lighting systems are lower than maximum permissible BCA 2011 energy densities and the heating and cooling appliances exceed the October 2011 Minimum Energy Performance Standards (MEPS).

4. A building of similar design, however built using a conventional structure utilising predominantly reinforced concrete as the main structural material, deemed compliant to BCA 2011 minimum 6 star energy standards, with lighting with maximum permissible BCA 2011 energy densities, and heating and cooling appliances with efficiencies which meet the October 2011 Minimum Energy Performance Standards (MEPS). This building is referred to as the “reference building”.

The reference building is intended to represent the design and performance of potential new multi-level residential development, but should not be taken as representative for all of the current building stock or all new buildings.

The scope of the study includes HVAC and lighting systems, but does not include fixture and fittings within the building envelope (e.g. door handles, switches, electrical appliances). The materials that provide structural integrity (i.e. CLT in the Forté building and reinforced concrete in the reference building) were studied in a previous study (the stage 1 report). In this Stage 2 report, the scope is extended to include the full life cycle of the building.

3.2 Functions of product systems and functional unit

The systems under investigation provide multiple functions; the structural elements provide integrity to the building, keeping it upright for a long (greater than 50 years) period of time. The building provides shelter from the elements and privacy for its inhabitants. Other functions of the building include indoor temperature control, outfitting etc. The building itself provides a secure space for commercial enterprise and space for living in comfort.

The functional unit of this study is:

> "The provision of comfortable living space for its inhabitants and space for commercial enterprise for the duration of 50 years, in a nine story building with 197 m^2 retail space and 23 apartments with an area of 1558 m^2 located on Bourke street, Docklands, Victoria"

This functional unit is either delivered by the Forté building, utilising a CLT construction and beyond compliance operational design features (HVAC and lighting); or by the reference system, utilising a predominantly reinforced concrete structure and standard operational design features, compliant to BCA 2011 minimum requirements and HVAC systems meeting minimum regulatory requirements. The reference flows, delivering the functional unit for both investigated systems, are listed in Section 5.1.

3.3 System boundary

The system boundary describes the processes which are included in the analysis, including material and energy flows to and from the environment associated with the manufacture and disposal life cycle stages. As outlined in Figure 3-1, the system boundary of this study includes the:

- Processes for extraction and production of the raw materials;
- Transport and conversion of the materials into products;
- Transport of materials to construction site;
- Construction of the building;
- Operation and use of the building; and
- Demolition of the building at end of life and subsequent waste management.

Infrastructure processes (including capital equipment), building maintenance, human labour and administration overheads were excluded from the system boundary. Given that the external and interior surfaces of both buildings are similar, maintenance is considered to be similar for both buildings. The exclusion would therefore not affect the directional nature of the comparisons. The management of waste produced during manufacture has been omitted for some materials, including concrete and steel, while other materials included waste management under elementary environmental flows (e.g. mass of dross and spent lining from aluminium production) or in the aggregated life cycle inventory (CLT materials). Construction waste has been omitted from the system boundary. Packaging is included in the background processes. No packaging is present in foreground processes (CLT is shipped in containers without additional packaging, while concrete is transported in trucks, both the containers and trucks are considered to be infrastructure). During the use phase, the use of heating, ventilation and cooling (HVAC), lighting and (hot) water use has been included. The use of electricity and natural gas for other appliances (e.g. ovens, televisions) has been excluded.

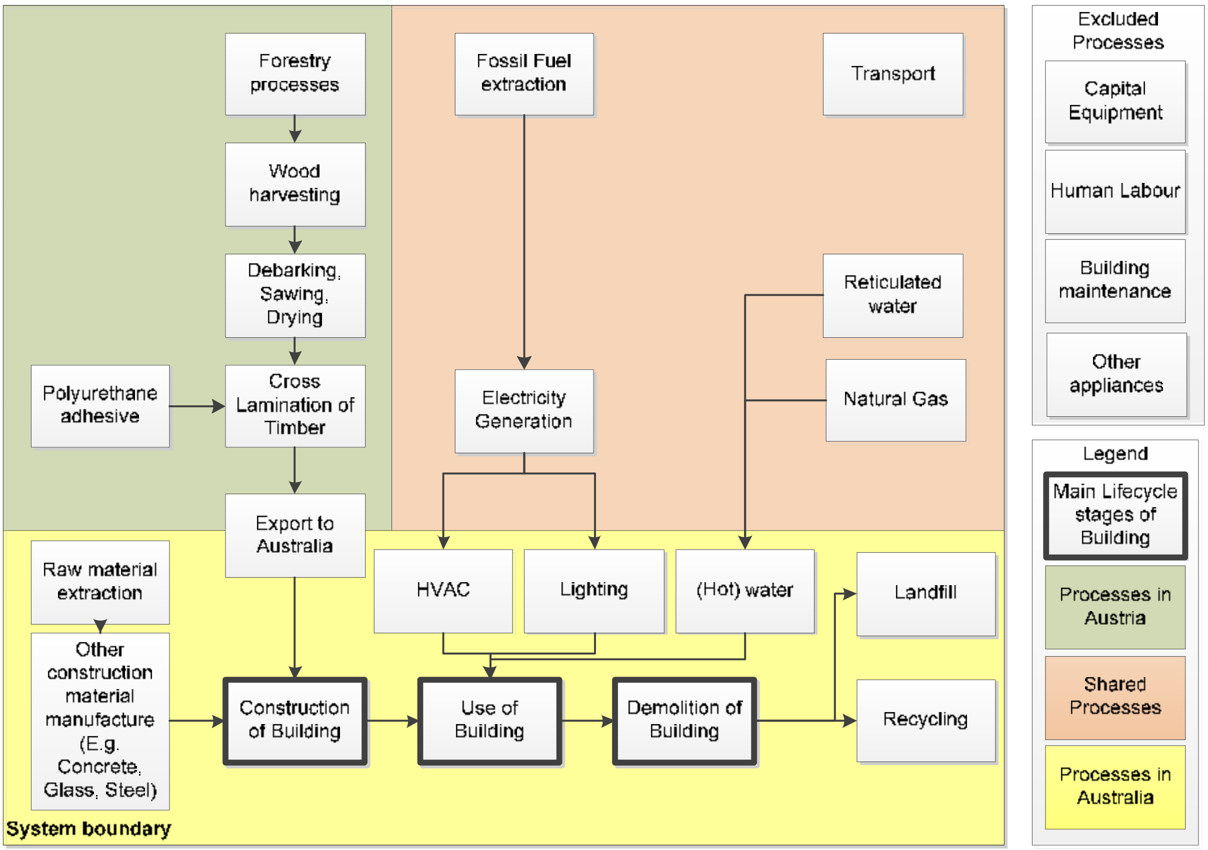

Figure 3-1: System boundary for the full life cycle of the Forté building and reference building. The reference building does not include CLT (green).

3.4 Data and data quality requirements

The following primary inventory data was required to undertake this study:

- Production of CLT panels in Austria
- International container transport

In addition, material quantities were required for both buildings, including:

- CLT (for Forté)
- Concrete (including reinforced)
- Plasterboard
- Windows and window frames
- Structural steel
- Insulation
- Rain screen cladding

Also, other data was required:

- Disposal processes were applicable to the building at the end of life
- Material properties on heat resistance, and thermal mass, required for thermal modelling
- Wall and floor designs
- Building plans
- Type and efficiency of heating and cooling appliances

An assessment of the data quality requirements for materials and processes is provided in Table 3-1. It is acknowledged that some primary and secondary data may fall outside these data requirements. Section 7.5 details the data quality assessment and summaries any areas of issue to be further investigated in sensitivity studies and in the second stage report.

Table 3-1: Data quality requirements (very poor – poor – average – good - very good)

Data description	Cross laminated timber manufacture	Trans-oceanic container transport	Concrete manufacture	Steel manufacture	Transport of concrete and steel	Plasterboard manufacture	Window + window frame manufacture	Rain screen cladding manufacture	Disposal of building materials	Material properties (Heat resistance and thermal mass)	Wall and floor designs	Building plans	Type and efficiency of heating and cooling appliances
Time related coverage	After 2005	After 2005	After 2005	After 2005	After 2005	After 2005	After 2005	After 2005	After 2005	2012	2012	2012	2012
Geographical coverage	Austria	Global	Australia	Australia	Victoria, Australia	Australia	Australia	Australia	Australia	Australia	Australia	Australia	Australia
Technology coverage	Specific technology	Technology mix	Technology mix	Technology mix	Technology mix	Technology mix	Technology mix	Technology mix	Technology mix	Specific product	Specific Design	Specific Design	Specific Design
Precision	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
Completeness	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%
Representativeness	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
Consistency	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
Reproducibility	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
Primary Sources of data	EPD	Data from operator / background data	Background data	Background data	Background data	Background data	Background data	Background data	Background data	Data from manufacturer	Data from builder	Data from builder	Data from manufacturer
Uncertainty	Average	Average	Average	Average	Average	Average	Average	Average	Average	Low	Low	Low	Low
Type of data required	Environmental flows.	Process and environmental flows	Process and environmental flows	Process and environmental flow	Process and environmental flow	Process and environmental flows	Process and environmental flows	Process and environmental flows	Process and environmental flows	U / R values thermal mass	Wall layers	Building plans	COP and other properties

3.5 Treatment of missing data

The treatment of missing data has been documented in the inventory for each unit process where missing data was identified.

3.6 Data collection procedures

In order to develop the life cycle inventory, inventories relating to the following foreground processes and/or life cycle stages were required:

- Process and environmental flows relating to:
  - The production of CLT panels in Austria
  - International container transport
  - Concrete production in Australia.
  - Plasterboard
  - Windows and window frames
  - Rain screen cladding
  - Disposal of the building at the end of life
- Material properties on heat resistance, and thermal mass.
- Wall and floor designs
- Building plans
- Type and efficiency of heating and cooling appliances

These foreground inventories were developed from various sources, including data directly from suppliers, literature, calculations and existing life cycle inventories. Table 3-2 details these foreground inventories, including the data source. Unless otherwise indicated, the data are reported in the form in which they were entered into the life cycle model.

Table 3-2: Foreground process and data sources.

Foreground process	Data source
Cross laminated timber manufacture	Environmental Product Declaration (KLH Massivholz GmbH, 2012)
Shipping distances for CLT	Ports supplied by Lend Lease, distances through (Portworld.com, 2011)
Container transport	(Carbon War Room, 2011, Portworld.com, 2011) (Shippingefficiency.org, 2012)
Concrete manufacture	Ecoinvent 2.2 (Kellenberger et al., 2007) adjusted to Australian conditions
Plasterboard	Ecoinvent 2.2 (Kellenberger et al., 2007) adjusted to Australian conditions
Windows and window frames	Ecoinvent 2.2 (Kellenberger et al., 2007) adjusted to Australian conditions
Rain screen cladding	Manufacturer data, Australian background data
Bill of quantities CLT and Reference buildings	Lend Lease
Concrete mix design	Concrete supplier, through Lend Lease
Concrete transport	Distances provided by Lend Lease, trucking model from background data
Steel manufacture	Quantities and type from Lend Lease, manufacturing inventory from background data
Steel transport	Distances provided by Lend Lease, trucking model from background data
Other building materials	Quantities provided by Lend Lease, inventories from background datasets.

3.7 Cut-off criteria

The cut-off criteria for the inclusion of inputs and outputs were based on mass and energy. Foreground energy and mass flows used in the impact assessment methods were captured, however some background flows associated with the background datasets may have been omitted.

It is estimated that elementary flows representing approximately 1% of the cumulative mass flows were omitted, including emissions associated with management of waste produced. Likewise, it is estimated that elementary flows representing approximately 1% of the cumulative energy flows were omitted. These cut-off criteria are considered not to influence the directional outcomes of this study.

The majority of energy data is to the second order (cradle to gate and transmission losses) although some background European data from Ecoinvent include the third order (capital equipment). This capital equipment has been excluded from the inventory.

3.8 Description of critical review process

The comparative assertions in this report may be disclosed to the public. As such, the report will be peer-reviewed by an external expert. This review is carried out by Start2See to the requirements of ISO 14040:2006/ISO 14044:2006. Reviewer comments and actions to address these are published in Appendix B.

3.9 Allocation

The study follows the allocation hierarchy as set out in the ISO standards. ISO 14044:2006 (International Organization for Standardization, 2006c), contains a hierarchal procedure for partitioning:

a) **Step 1:** Wherever possible, allocation should be avoided by:
   (1) (increasing detail by) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or
   (2) expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3.

b) **Step 2.** Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

c) **Step 3.** Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

In this study, the foreground systems which have been subject to the ISO 14044:2006 hierarchy are multi-output, multi-input and recycling processes. Multi-input processes were predominantly associated with background data. A summary of the treatment of key foreground data requiring allocation is provided in Table 3-3. Further details regarding the allocation procedures are provided in the life cycle inventory (Section 5).

Table 3-3: Treatment for processes requiring allocation

Process	Treatment and notes
Sea freight of CLT panels to Australia	Physical allocation (by shipping containers).
Truck freight	Physical allocation by mass
Diesel production (from crude oil refining)	Physical allocation by energy content (background databases adopted)
Fuel oil production (from crude oil refining)	Increased detail, then physical allocation by mass (ecoinvent background databases adopted)
Natural gas production	Physical allocation by energy content (background databases adopted)
Structural pine	Physical allocation by mass (for pine logs from forestry and structural pine). Used for avoided product in recycling sensitivity
Ground granulated blast furnace slag (in concrete)	Avoided allocation by system expansion.
Landfill of construction materials	Increased detail, then allocated by input mass (ecoinvent and AUPLCI background databases adopted)
Recycling of structural elements	Avoided allocation by system expansion.
Wastewater treatment	Physical allocation by mass/volume.

3.9.1 System expansion

ISO 14044:2006 states that allocation should be avoided, if possible, through system expansion. The rules for system expansion are not defined in ISO 14044:2006. There is still no agreed consensus on how to perform system expansion. Rather than applying system expansion on an ad-hoc basis, the following three rules, as outlined by Weidema (Weidema, 2003), were used to expand the system boundary. Using Weidema's rules ensures a consistent and impartial expansion of the system boundary. The system expansion rules are as follows (Weidema, 2003):

1. The co-producing process shall be ascribed fully (100%) to the determining co-product for this process (Product A in Figure 3-2).
2. Under the conditions that the dependent co-products are fully utilised, i.e. that they do not partly go to waste treatment, product A shall be credited for the processes that are displaced by the dependent co-products. The intermediate treatment (I in Figure 3-2) shall be ascribed to product A. If there are differences between a dependent co-product and the product it displaces, and if these differences cause any changes in the further life cycles in which the dependent co-product is used, these changes shall likewise be ascribed to product A.
3. When a dependent co-product is not utilised fully (i.e. when part of it must be regarded as a waste), the intermediate treatment shall be ascribed to the product in which the dependent co-product is used (product B in Figure 3-2), while product B is credited for the avoided waste treatment of the dependent co-product.

The associated processes are presented schematically in Figure 3-2. Intermediate processes (I) occur between the co-producing process and where displacement or substitution occurs (Weidema, 2001). In a competitive market, substitution can only occur if supply is not constrained. A stepped procedure for dealing with the system expansion rules is outlined in a decision-diagram in Figure 3-3. Further details on the application of this procedure are provided in relevant parts of Section 5.

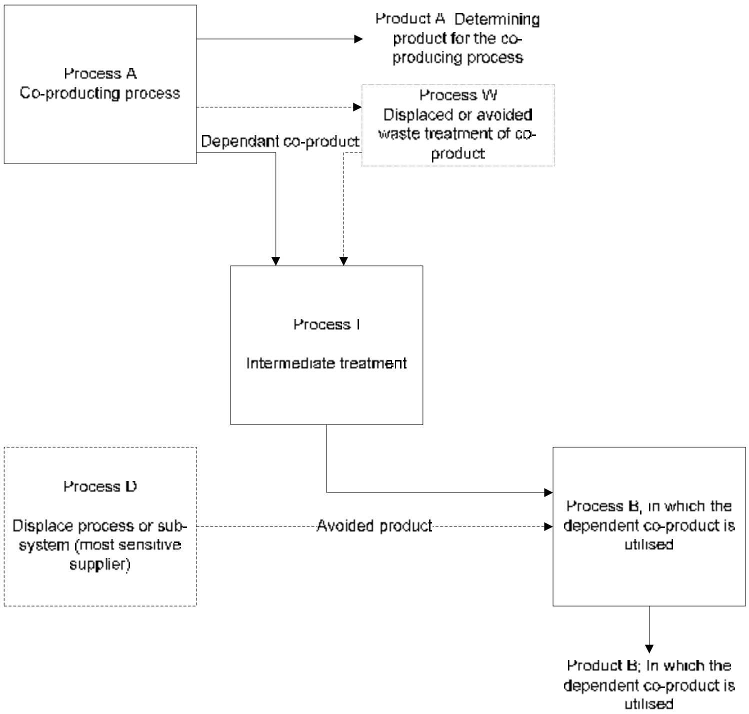

Figure 3-2. Model for system expansion (Weidema, 2003).

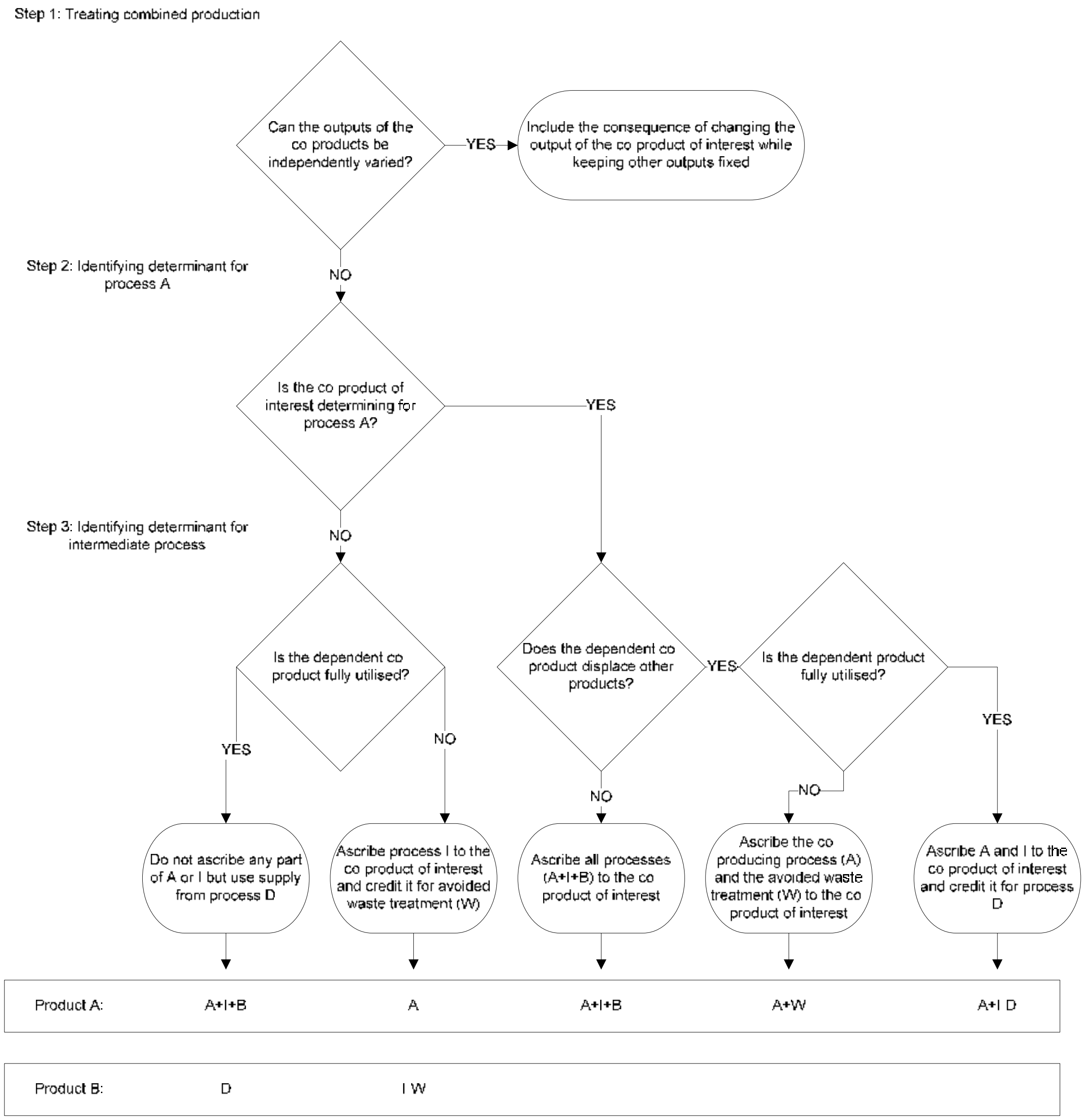

Figure 3-3. Decision tree for system expansion (Weidema, 2003).

3.10 Life Cycle Impact Assessment method

This study utilises the Australian Impact Method (Table 3-4) to interpret LCA inventory results. The method translates the environmental flows (emissions and raw material extraction) into defined environmental or inventory indicators.

The main environmental area of concern for Lend Lease related to this study, and the focus of the marketing outcomes for this study, is global warming potential. The ongoing debate on the inclusion or exclusion of carbon sequestration (credits) necessitated the need to include two alternate greenhouse impact assessment methods. To account for possible trade-offs between different environmental indicators, other environmental indicators were included, namely eutrophication potential and water use. The inclusion of other environmental indicators, including land use and fossil fuel depletion, could not be included due to the lack of inventory data in supporting Environmental Product Declarations (EPDs)

A list of the factors used in the assessment method are provided in Appendix A.

Table 3-4: Environmental Indicators

Impact Category	Unit	Description
Global warming potential – no sequestration	kg CO_2 eq	Cumulative indicator for greenhouse gas emissions, leading to climate change. This indicator is represented in CO_2 equivalents. Factors applied to convert emissions of greenhouse gas emissions into CO_2 equivalents emissions conform to IPCC 2007 factors for a 100-year time horizon (IPCC, 2007). The indicator does not account for biogenic carbon uptake, biogenic carbon dioxide emissions, or carbon sequestration.
Global warming potential – including sequestration	kg CO_2 eq	Cumulative indicator for greenhouse gas emissions, leading to climate change. This indicator is represented in CO_2 equivalents. Factors applied to convert emissions of greenhouse gas emissions into CO_2 equivalents emissions conform to IPCC 2007 factors for a 100-year time horizon (IPCC, 2007). The indicator accounts for biogenic carbon sequestration.
Eutrophication potential	kg PO_4^{3-} eq	Eutrophication is the release of nutrients (mainly phosphorous and nitrogen) into land and water systems, altering biotopes, and potentially increasing algal growth and potentially causing the loss of aquatic species. Factors applied to convert emissions into PO_4^{3-} equivalents are taken from the CML impact assessment method from 2000 (CML baseline 2000 all impact categories V2.04). CML is a research centre based in the Institute of Environmental Sciences of Leiden (the Netherlands). It has been developing impact assessment methods for LCA since 1992 and is a reference in the domain.
Water use	kL H_2O	Total of fresh water (from reservoirs) used by the processes considered. This indicator does not account for the regional impacts of water, such as scarcity.
Cumulative energy demand LHV – non renewable	MJ LHV	All non-renewable energy use including fossil, electrical and feedstock. The energy indicator has been designed on the basis of the first CML impact assessment method (CML 92 V2.04).
Cumulative energy demand LHV – renewable	MJ LHV	All renewable energy use including solar, wind, biomass and wood.

3.10.1 Treatment of biogenic flows and carbon sequestration

During tree growth, carbon dioxide (CO_2) from the atmosphere is taken up by the plant therefore reducing the overall CO_2 levels in the air. This carbon is stored in the wood, and when harvested, the products made from that timber. However, the carbon may be released back into the atmosphere when the product reaches the end of its life. For example, when the wood product is incinerated, the carbon will be released back into the atmosphere (resulting in no net removal of CO_2 from the air). However, when the wood product is reused, the carbon remains sequestered in the product. If the wood or wood product ends up in landfill it may decompose releasing a portion of its carbon back into the atmosphere as CO_2 and/or methane (CH_4). Because of the uncertainty regarding the end of life of the building at this stage of the project, modelling was undertaken and results are presented using a range; with both sequestration (best case) and no sequestration (worst case).

Two models are considered:

1. No storage (sequestration) of carbon in wood. This is a worst-case scenario, assuming that no carbon credits are given for the uptake of carbon dioxide during the growth of the tree or for long-term carbon storage at the end of life.

2. The carbon in wood is sequestered in landfill. The carbon dioxide that is taken up during the growth of the tree will be locked in the building and will not be released back into the atmosphere. Some carbon will be released in the form of methane and carbon dioxide at the end of life, but credits are given for the carbon being sequestered in landfill.

The modelling and treatment of biogenic carbon dioxide emissions were based on IPCC guidelines for the development of greenhouse gas inventories:

> ”Carbon dioxide from the combustion or decay of short-lived biogenic material removed from where it was grown is reported as zero in the Energy, IPPU and Waste Sectors (for example CO_2 emissions from biofuels and CO_2 emissions from biogenic material in Solid Waste Disposal Sites (SWDS).” (Section 1.2, IPCC, 2006a)

Based on these guidelines and to ensure carbon balance, biogenic carbon dioxide inputs and air emissions were assigned a Global Warming characterisation factor of zero. This includes those biogenic carbon dioxide emissions resulting from the stoichiometric combustion of biogenic methane.

The characterisation factor for biogenic methane was adjusted to account for sequestered biogenic carbon in the methane molecule. One methane molecule (molecular mass 16 g/mol) effectively sequesters one molecule of biogenic carbon dioxide (44 g/mol). So applying the standard 100-year time horizon global warming potential of both gases and their relative masses, the GWP of biogenic methane is reduced by 2.25 kg $CO_{2\text{-eq}}$/kg relative to fossil methane.

The treatment of non-degraded biogenic carbon in landfill is modelled as the sequestration of carbon. That is, carbon from the short-term carbon cycle (less than or equal to 100 years) is assumed to be stored in a long-term carbon storage (greater than 100 years, see Figure 3-4). Biogenic carbon sequestration was calculated based on carbon-dioxide equivalents. Global warming potential results are reported including and excluding this sequestration in landfill.

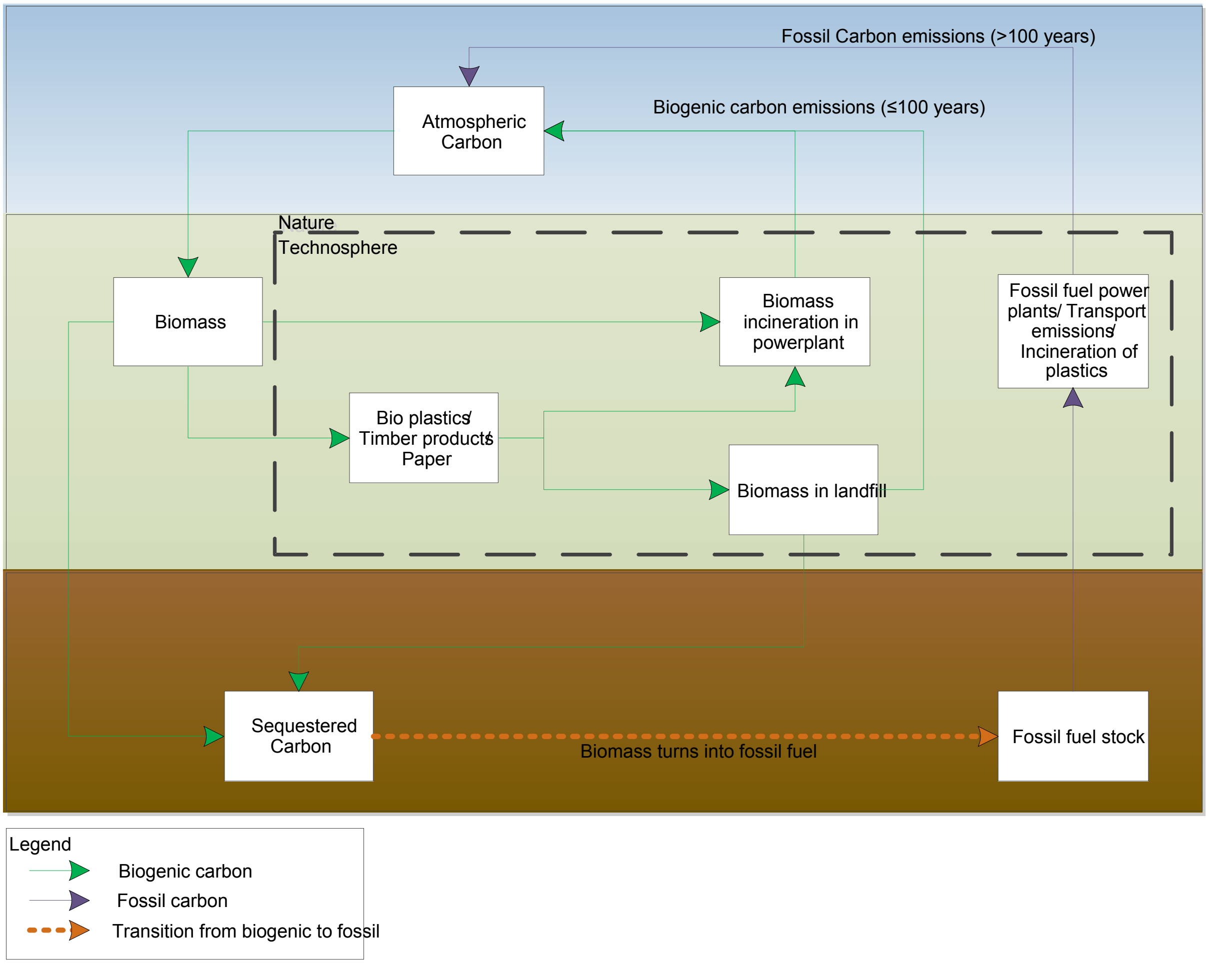

Figure 3-4: Schematic differentiating different types of carbon flows.

3.11 Limitations

Impacts reported represent potential environmental impacts across the life cycle and do not reflect specific site related environmental impacts. Operational impacts are based on modelling and may not reflect actual environmental impacts. This study uses background data that is tailored for Australian conditions; therefore, one should be careful when comparing the results of this study with studies that have other geographical scopes. Current technology is used. Data used in this study is representative for cross laminated timber manufacturing in Austria. More study specific limitations are documented throughout the report and are listed in Section 1.

4 Methodology

Life Cycle Assessment (LCA) has been used as the core method for determining the potential environmental impacts of the products considered. LCA has been applied in accordance with ISO 14040:2006 and ISO 14044:2006. Refer to Section 10 for a description of the LCA process. The remaining sections of this report are aligned with this process. To determine the energy and water use during the occupational phase of the building, some additional tools and specialist software were used.

4.1 Operational energy and water use modelling

Annual operational energy use (natural gas and electricity) for the Forté (CLT) building and the reference building, for both the commercial and residential spaces, were calculated using the dynamic building energy simulation software tool, ApacheSim. The simulation results for the residential spaces were validated against an Accurate assessment and were found to be consistent.

ApacheSim assesses the building as a complete system, and accounts for the location and orientation, the characteristics of the built form, the type and efficiencies of the heating, cooling and hot water systems, the fuel types used, as well as the energy demand and heat gains from occupants and lighting elements.

Building construction materials are applied to the building elements and the building's heating and cooling systems are defined based on information supplied by Lend Lease. The energy modelling software takes into consideration the heat transfers through the building envelope, occupancy and usage patterns, and internal heat gains from occupants, lights and appliances as well as the energy used by lighting and appliances. The recommended illumination values from the BCA (2012) and the occupancy profiles presented in the Heating and Cooling Loads Data Collection and Analysis – Residential End Use Monitoring Program report (2012) were used for the modelling of the occupancy, lighting and equipment profiles. An additional ApacheSim module, SunCast, was used to model solar shading by neighbouring buildings and local shades. The simulations are driven by real weather data for the nearest available climatic weather station for Melbourne.

4.1.1 Building water use

ApacheSim cannot readily assess the water use for the use phase of the buildings. Therefore generic numbers are used to estimate the water use for this phase of the life cycle, using current literature sources.

5 Life cycle inventory

This section details the information and assumptions used to develop the life cycle inventory for the products considered in this study. Unless otherwise indicated, process data are reported in the scale by which they were originally reported.

5.1 Delivery of Functional unit

The total amount of CLT panels and concrete that is needed in the construction of the Forté building was provided by Lend Lease. Sources of data are the shipping documents for the CLT panels, and/or the detailed bill of quantities for the concrete alternative building. Material requirements are listed in Section 5.1.1 for the Forté building and Section 5.1.2 for the reference building. For readability, the quantities listed in this section are rounded to a maximum of four significant numbers.

5.1.1 Forté Building

The following tables (Table 5-1, Table 5-2,Table 5-3 and Table 5-4), provide the reference flows that deliver the functional unit (i.e. the materials, construction, use and disposal of the building) for the Forté building. The materials and processes will be further discussed in the Section 5.2. Material flows associated with maintenance are not included in the model.

Table 5-1: Material requirements for Forté building

Material	Quantity	Unit
10mm thick Uniroll	1503	m^2
200mm hollow block wall	273	m^2
64mm stud wall	361	m^2
Alubond	1478	m^2
Bar reinforcement	83.24	tonne
CLT, 090 mm thickness, 3 layer	47	m^2
CLT, 094 mm thickness, 3 layer	48	m^2
CLT, 095 mm thickness, 3 layer	343	m^2
CLT, 125 mm thickness, 5 layer	379	m^2
CLT, 128 mm thickness, 5 layer	3175	m^2
CLT, 140 mm thickness, 5 layer	597	m^2
CLT, 145 mm thickness, 5 layer	2575	m^2
CLT, 158 mm thickness, 5 layer	90	m^2
Concrete, 15MPa, including in 70 mm screed and flooring	109	m^3
Concrete, 40MPa	552.4	m^3
Concrete, 50MPa	24	m^3
Glazing, double	687	m^2
Glulam	1.68	m^3
Gravel	192	tonne
Hebel autoclaved concrete panels	252	m^2
LDPE film	395	kg
Glass wool insulation	150	m^3
Plasterboard 13mm	9380	m^2
Plasterboard 16mm	3910	m^2
Sand, at Mine	36.08	tonne
Structural steel	5.02	tonne
Window frame, aluminium	120.6	m^2

Table 5-2: Transport and construction requirements for Forté building. TEU is a commonly used description of volume in sea freight (equivalent to the volume a twenty foot container can hold)

Component	Quantity	Unit	Comment
Excavator	35.6	hr	Excavator removes 5 m^3 per hour on average
Gravel	282.2	tonne	200 mm thick layer as road base during piling works
Rigid truck	1.724E4	tonne.km	transport of steel beams and reinforcement, plasterboard, window frames, glazing, alubond, glulam, uniroll, and insulation
Concrete truck	1.74E4	m^3km	Transport of concrete
Grasmere Maersk	3.498E5	TEU*km	Transport of CLT panels
Maersk Karachi	6.219E5	TEU*km	Transport of CLT panels
Transport, lorry 7.5-16t, EURO5	1.541E5	tonne.km	Transport of CLT panels by road

Table 5-3: Use phase requirements for Forté building for 1 year of operation

Component	Quantity	Unit	Comment
Electricity, low voltage, Victoria	67.18	MWh	For heating, cooling and lighting
Heat from natural gas	81.95	MWh	For domestic hot water
Water, reticulated	4403	m^3	Drinking water for residential and retail
Wastewater treatment	4403	m^3	-

Table 5-4: End of life inventory for Forté building

Component	Quantity	Unit	Comment
Rigid truck freight, customisable/AU U	71946.7	tonne.km	Assumed 30 km to disposal
Disposal, concrete, 5% water, to inert material landfill/CH U	592185.6	kg	Landfill of concrete
Recycling concrete/AU U	1052774.4	kg	Recycling of concrete
Disposal, concrete, 5% water, to inert material landfill/CH U	3402.0	kg	Landfill of Hebel panels
Recycling concrete/AU U	6048.0	kg	Recycling of Hebel panels
Recycling steel, reinforced applications/AU U	30.0	tonne	Landfill of reinforcing steel
Disposal, steel, 0% water, to inert material landfill/CH U	53.3	tonne	Recycling of reinforcing steek
Recycling steel, structural applications/AU U	0.9	tonne	Landfill of structural steel
Landfill steel products/AU U	4.1	tonne	Recycling of structural steel
Disposal, aluminium, 0% water, to sanitary landfill/CH U	39.2	kg	Landfill of aluminium in alubond
Recycling aluminium LL/AU U	3877.5	kg	Recycling of aluminium in alubond
Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U	6011.4	kg	Landfill of LDPE in alubond + LDPE film
Disposal, glass, 0% water, to inert material landfill/CH U	15179.9	kg	Landfill of glazing
Recycling window glass, 0% cullet/AU U	153.3	kg	Recycling of glazing
Disposal, gypsum, 19.4% water, to sanitary landfill/CH U	154000.0	kg	Landfill of plasterboard
Disposal, aluminium, 0% water, to sanitary landfill/CH U	861.8	kg	Landfill of aluminium – for window frames
Recycling aluminium LL/AU U	3926.0	kg	Recycling of aluminium – for window frames
Landfill, CLT	463861.1	kg	CLT panels
Landfill, Glulam	924	kg	Glulam
Disposal, mineral wool, 0% water, to inert material landfill/CH U	2960.0	kg	Landfill of rock wool
Disposal, polyurethane, 0.2% water, to inert material landfill/CH U	3757.5	kg	Landfill of uniroll

5.1.2 Reference building

The following tables (Table 5-5, Table 5-6, Table 5-7 and Table 5-8), provide the reference flows that deliver the functional unit (i.e. the materials, construction, use and disposal of the building) for the reference building. The materials and processes will be further discussed in the section 5.4. Material and energy flows for maintenance have not been included in the model. The reference building has a similar design, however shows differences in the materials utilised, the HVAC equipment and lighting installed. Whereas the Forté building is based on data provided by Lend Lease, the reference building is fictitious. The material quantities and HVAC and lighting equipment were modelled using current building code minimum requirements (for energy use). The building's features were scaled to comply with a 6-star energy rating and does not go beyond this compliance.

Table 5-5: Material requirements for reference building

Materials	Quantity	Unit
200 mm hollow block wall	273	m^2
64 mm stud wall	361	m^2
Bar reinforcement	201	tonne
Concrete, 15MPa,	163	m^3
Concrete, 32MPa	119	m^3
Concrete, 40MPa	1441	m^3
Concrete, 50MPa	24	m^3
Cork tiles, 10mm thick	2282	m^2
Uniroll	850	kg
Internal insulation, rock wool	150	m^3
Glazing, double	687	m^2
Glulam	1.68	m^3
Gravel	191.8	tonne
Hebel panels	252	m^2
LLDPE	394.7	kg
Plasterboard	13969	m^2
Sand, at Mine	36.08	tonne
Structural steel beams	5.02	tonne
Steel sheet 3 mm thick, density of 7800 kg/m^3	331	m^2
Window frame, aluminium	120.6	m^2

Table 5-6: Transport and construction requirements for reference building

Component	Quantity	Unit	Comment
Excavator	35.6	hr	Excavator removes 5 m^3 per hour on average
Gravel	282.2	tonne	200 mm thick layer as road base during piling works
Rigid truck	2.220E4	tonne.km	transport of steel beams and reinforcement, plasterboard, window frames, glazing, glulam, and insulation
Concrete truck	5.241E4	m^3.km	Transport of concrete

Table 5-7: Use Phase requirements for reference building for 1 year

Component	Quantity	Unit	Comment
Electricity, low voltage, Victoria	84.6	MWh	For heating, cooling and lighting
Heat from natural gas	81.94	MWh	For domestic hot water
Water, reticulated	4403	m^3	Drinking water for residential and retail
Wastewater treatment	4403	m^3	

Table 5-8: End of life requirements for reference building

Component	Quantity	Unit	Comment
Rigid truck freight, customisable/AU U	137385	tonne.km	Transport to disposal
Disposal, concrete, 5% water, to inert material landfill/CH U	1509580.8	kg	Recycling concrete
Recycling concrete/AU U	2683699.2	kg	Landfill concrete
Disposal, steel, 0% water, to inert material landfill/CH U	72396.0	kg	Landfill of reinforced steel
Recycling steel, reinforced applications/AU U	128704.0	kg	Recycling of reinforced steel
Recycling steel, structural applications/AU U	4116.4	kg	Recycling of structural steel
Disposal, steel, 0% water, to inert material landfill/CH U	903.6	kg	Landfill of structural steel
Disposal, steel, 0% water, to inert material landfill/CH U	1394.2	kg	Landfill of steel sheeting
Recycling steel, sheet steel/AU U	6351.2	kg	Recycling of steel sheeting
Disposal, glass, 0% water, to inert material landfill/CH U	15179.9	kg	Landfill of glazing
Recycling window glass, 0% cullet/AU U	153.3	kg	Recycling of glazing
Disposal, gypsum, 19.4% water, to sanitary landfill/CH U	143800.0	kg	Landfill of plasterboard
Recycling aluminium LL/AU U	861.8	kg	Recycling of window frames
Disposal, aluminium, 0% water, to sanitary landfill/CH U	3926.0	kg	Landfill of window frames
Disposal, polyurethane, 0.2% water, to sanitary landfill/CH U	850.0	kg	Landfill of uniroll
Disposal, mineral wool, 0% water, to inert material landfill/CH U	2960.0	kg	Landfill of rock wool
Disposal, concrete, 5% water, to inert material landfill/CH U	3402.0	kg	Landfill of Hebel
Landfill of glulam	840.0	kg	Landfill of Glulam
Landfill of plastics/AU U	394.7	kg	Landfill of LLDPE
Landfill of wood	19.0	kg	Landfill of cork tiles

The life cycle inventories are discussed in the following sections.

5.2 Common systems

A number of processes are common to the reference and Forté buildings

5.2.1 Electricity and natural gas

Table 5-9: Electricity production, Victoria, low voltage (at consumer)

Output		
Electricity, low voltage, Eastern Australia/AU U	1	kWh
Electricity/heat		
Electricity, hydropower/AU U	0.0236	kWh
Electricity, Natural Gas (Steam) , Sent Out/AU U	0.0318	kWh
Electricity, Natural Gas (Turbine), Sent Out/AU U	0.0172	kWh
Electricity brown coal VIC, sent out/AU U	0.9337	kWh
Electricity, biomass/AU U	1.85E-5	kWh
Electrictiy landfill gas, sent out/AU U	0.0059	kWh
Electrictiy wastewater gas, sent out/AU U	0.0029	kWh
Electricity, solar/AU U	0.0476	kWh
Electricity, hydropower/AU U	0.0002	kWh
Electricity, wind power/AU U	0.0237	kWh
Non material emissions		
Energy losses in electricity transmission and distribution	0.0867	kWh

The production and use of natural gas was based on data from the Australasian Unit Process Life Cycle Inventory (AUPLCI). Allocation of gas processing outputs (natural gas, ethane, liquid petroleum gas) could not be avoided and impacts were allocated on an energy basis.

5.2.2 Diesel production and supply

The supply of diesel fuel was modelled using an existing unit process Australasian Unit Process Life Cycle Inventory. Allocation of crude oil refining outputs (including diesel fuel, kerosene etc.) could not be avoided and impacts of crude oil refining were allocated on an energy basis.

5.2.3 Road freight transport

Road freight impacts were allocated on a mass basis. Road freight distances were used in conjunction with Australian Life Cycle Inventory unit processes for national average transport for articulated/rigid trucks for tonne-kilometre based freight. The Australian Life Cycle Inventory transports unit process used are based on data from Apelbaum Consulting (Apelbaum 2001). Emissions are based on fuel use with factors were adopted from (NGGIC 1997). Estimated road transport distances were based on the directions function in Google maps.

5.2.4 Transport of building materials to disposal site

As the building will not be demolished for at least 50 years, it is uncertain as to where disposal sites will be located. It is assumed that there will be a suitable disposal site within 30 km. The building waste will be transported to the landfill site, using a rigid truck (based on AUPLCI model).

5.2.5 Concrete Transport

The Australasian Unit Process LCI (AUPLCI) process “Concrete truck /AU U” is used to model the transport from concrete plant to construction site on a volumetric basis. The distance is assumed to be 30 km, based on the distance from the concrete supplier to the construction site.

5.2.6 Road freight of steel to site

The steel is transported from the regional store in Altona North (Onesteel manufacturing site and depot; this information is supplied by Lend Lease), to the construction site in Victoria Harbour, Docklands. The transport distance is 15 km. The Australasian Unit Process LCI (AUPLCI) process "Rigid truck, per unit freight moved/AU U" is used to model the transport. Transport impacts were allocated based on the mass of the freight moved.

5.2.7 Concrete

The Australasian Unit Process Life Cycle Inventory (AUPLCI) dataset for concrete manufacture is used as a basis for the concrete inventories. The concrete mixes are modified to suit the mix designs provided by Lend Lease. Table 5-10 summarises the modified processes that are utilised in this study.

Table 5-10: Concrete manufacturing

Products	Unit	Concrete, 15 MPa	Concrete, 32 MPa	Concrete, 40 MPa	Concrete, 50 MPa
Concrete	m^3	1	1	1	1
Materials/fuels					
Cement, Portland, at plant/AU U	kg	98	155	195	262
Blast furnace slag, no credit to steel production, at steel plant/AU U	kg	98	155	195	262
Gravel, at mine/AU U	kg	980	1050	1080	1100
Sand, river, at mine/AU U	kg	972	860	790	650
Rigid truck, per unit freight moved/AU U	tkm	195	191	187	175
Water, drinking, Australia, reticulated/AU U	l	170	170	175	180
Articulated Truck, average, freight task/AU U	tkm	19.6	31	39	52
Electricity/heat					
Electricity, Low Voltage, Victoria /AU U	MJ	0.0025	0.0025	0.0025	0.0025
Energy, from diesel/AU U	MJ	0.008	0.008	0.008	0.008
Emissions to air					
Particulates, unspecified	g	0.00125	0.00125	0.00125	0.00125

Gravel is used as a proxy for coarse aggregate (20 and 14 mm aggregate). A large portion of the concrete utilised in the building is high-strength concrete (>= 40 MPa), Table 5-1 (and Table 5-5 for the reference building).

5.2.7.1 Application of system expansion

Granulated blast furnace slag (GBFS) is a co-product of pig iron production. Following granulation at the blast furnace, the slag is ground to produce ground-granulated blast furnace slag. The pig iron is the determinate product and the total production of blast furnace slag (air-cooled and granulated) cannot be independently varied. The supply of ground-granulated blast furnace slag (GGBFS) in Australia is currently constrained by the volume of material being produced at the blast furnaces; that this material is being imported is a reflection of this constraint. However, there is capacity to better utilise the blast furnace slag produced in Australia, as much of it is currently being used in low-value applications, such as road-base. By applying Bo Weidema's system expansion methodology, the GGBFS (Product B) is assigned the intermediate processing impacts (grinding of GBFS into GGBFS) and credited with the avoidance of the waste treatment (landfill). Inventory data for the grinding of GGBFS was adopted from (Heidrich et al., 2005). In this article, the emissions due to milling and drying of 1 tonne of slag were 0.064 tonne (electricity) and 0.049 tonne (natural gas), respectively. These emissions were calculated based on a weighting of Australia's 2004 emission factors (AGO, 2004). Back-calculating these values using Victoria's emissions gave an energy input of 45.98 kWh of electricity, and 772.9 MJ of natural gas, per tonne of GGBFS produced. Landfill avoidance impacts were assigned based on landfill of inert material in Australia.

5.2.8 Reinforcement steel manufacture

The Ecoinvent process "Reinforcing steel, at plant/RER U" was adjusted to account for Australian condition by changing the electricity and natural gas grids. Also the process feeding into this process were adjusted to Australian conditions (Steel, converter, unalloyed, at plant /RER U, Steel electric, un- and low-alloyed, at plant/RER U and Hot rolling, steel/RER U). The top level process is reported in Table 5-11.

Table 5-11: Reinforcing steel, at plant /AU U

Products	Quantity	Unit
Reinforcing steel, at plant/AU U	1	kg
Materials/fuels		
Hot rolling, steel/AU proxy	1	kg
Steel, converter, unalloyed, at plant/AU proxy	0.63	kg
Steel, electric, un- and low-alloyed, at plant/AU proxy	0.37	kg

5.2.9 Plasterboard

The process Gypsum plaster board, at plant/CH U from the Ecoinvent database (Kellenberger et al., 2007) is used to model the plasterboard. The inventory is regionalised for Australia by substituting the European electricity grid with "Electricity, average, low voltage /AU U" and substituting a European Energy from fuel oil with an Australian Equivalent (refer Table 5-12).

Table 5-12: Inventory for plasterboard

Products	Quantity	Unit
Gypsum plaster board, at plant/CH U - Lend Lease	1	kg
Resources		
Water, unspecified natural origin/m3	0.000182	m^3
Materials/fuels		
Alkylbenzene sulfonate, linear, petrochemical, at plant/RER U	0.00000968	kg
Electricity, Low Voltage, Australian average/AU U	0.0937	kWh
Glass fibre, at plant/RER U	0.000161	kg
Energy, from fuel oil/AU U	1.36	MJ
Potato starch, at plant/DE U	0.0029	kg
Silicone product, at plant/RER U	0.000129	kg
Stucco, at plant/CH U	0.811	kg
Tap water, at user/RER U	0.364	kg
Transport, lorry 20-28t, fleet average/CH U	0.3	tonne.km
Whitelined chipboard, WLC, at plant/RER U	0.0484	kg
Wooden board manufacturing plant, organic bonded boards/RER/I U	1.67E-11	p
Emissions to air		
Heat, waste, low. pop.	0.337	MJ

5.2.9.1 Glass Wool Insulation

Glass wool is used as insulation in the stud walls and Hebel systems in Forté and the reference building. An Ecoinvent process was used, details listed in Table 5-13. A density of 14 kg/m^3 was used in the model.

Table 5-13: Inventory for glass wool.

Products		
Glass wool mat, at plant/CH U	1	kg
Materials/fuels		
Acrylic dispersion, 65% in H2O, at plant/RER U	5.7E-06	kg
Acrylic varnish, 87.5% in H2O, at plant/RER U	0.0035	kg
Ammonia, liquid, at regional storehouse/CH U	0.00247	kg
Ammonium sulphate, as N, at regional storehouse/RER U	0.000803	kg
Calcium nitrate, as N, at regional storehouse/RER U	0.000576	kg
Chemicals organic, at plant/GLO U	5.74E-05	kg
Corrugated board, mixed fibre, single wall, at plant/RER U	0.0114	kg
Diesel, burned in building machine/GLO U	0.054	MJ
Dolomite, at plant/RER U	0.00293	kg
Electricity, medium voltage, at grid/CH U	2.32	kWh
Feldspar, at plant/RER S	0.136	kg
Fluorspar, 97%, at plant/GLO U	0.022	kg
Formaldehyde, production mix, at plant/RER U	0.0921	kg
Glass cullets, sorted, at sorting plant/RER U	0.797	kg
Limestone, milled, packed, at plant/CH U	0.00964	kg
Lubricating oil, at plant/RER U	0.0111	kg
Manganese, at regional storage/RER U	0.00262	kg
Molybdenum, at regional storage/RER U	1.25E-05	kg
Natural gas, burned in industrial furnace low-NOx >100kW/RER U	7.33	MJ
Operation, barge/RER U	0.0529	tkm
Packaging film, LDPE, at plant/RER U	0.0132	kg
Phenol, at plant/RER U	0.0294	kg
Refractory, fireclay, packed, at plant/DE U	0.00229	kg
Rock wool plant/CH/I U	4.43E-10	p
Rosin size, in paper production, at plant/RER U	0.000344	kg
Silica sand, at plant/DE U	0.11	kg
Silicone product, at plant/RER U	0.0297	kg
Soda, powder, at plant/RER U	0.0836	kg
Sodium borates, at plant/US U	0.0576	kg
Sodium hydroxide, 50% in H2O, production mix, at plant/RER U	0.0035	kg
Solvents, organic, unspecified, at plant/GLO U	1.15E-05	kg
Sulphuric acid, liquid, at plant/RER U	0.00206	kg
Tap water, at user/CH U	5.74	kg
Transport, freight, rail/RER U	0.382	tkm
Transport, lorry >16t, fleet average/RER U	0.0553	tkm
Urea, as N, at regional storehouse/RER U	0.0386	kg
Electricity/heat		
Transport, municipal waste collection, lorry 21t/CH U	0.000783	tkm
Emissions to air		
Ammonia	0.00146	kg
Fluorine	0.00009	kg
Formaldehyde	0.00046	kg
Heat, waste	8.35	MJ
Phenols, unspecified	0.00026	kg

5.2.10 Windows

The windows and window frames are modelled using Ecoinvent inventories (Kellenberger et al., 2007), that were adjusted by changing the electricity grids from Europe to Australia. For the aluminium window frames, the inventory for aluminium from Europe was substituted with the Australian equivalent (see Table 5-14).

Table 5-14: Aluminium window frames

Products	Quantity	Unit
Window frame, aluminium, U=1.6 W/m2K, at plant/RER U MOD AU	1	m^2
Materials/fuels		
Synthetic rubber, at plant/RER U	4.87	kg
Reinforcing steel, at plant/RER U	0.516	kg
Chromium steel 18/8, at plant/RER U	0.457	kg
Powder coating, aluminium sheet/RER U	9.8	m^2
Section bar extrusion, aluminium/RER U	38	kg
Section bar rolling, steel/RER U	0.975	kg
Extrusion, plastic film/RER U	0.246	kg
Polyethylene, HDPE, granulate, at plant/RER U	0.246	kg
Electricity, High Voltage, Australian Average/AU U	1.27	kWh
Isopropanol, at plant/RER U	0.0208	kg
Transport, lorry >16t, fleet average/RER U	4.57	tonne.km
Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	5.27	kg
Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER U	0.4	kg
Nylon 6, at plant/RER U	0.0146	kg
Aluminium, at plant/AU U	39.7	kg
Adhesive for metals, at plant/DE U	0.29	kg
Metal working factory/RER/I U	2.32E-08	p
Emissions to air		
Heat, waste	4.57	MJ
Waste to treatment		
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	0.102	kg
Disposal, building, polyethylene/polypropylene products, to final disposal/CH U	0.246	kg

For the window glazing, the glass, argon, aluminium and trucking inventories were replaced by Australian data (refer Table 5-15).

Table 5-15: Window glazing

Products	Quantity	Unit
Glazing, double (2-IV), U<1.1 W/m2K, at plant/RER U MOD AU	1	m^2
Materials/fuels		
Argon, liquid, at plant/AU U	0.0244	kg
Water, completely softened, at plant/RER U	0.996	kg
Glass, flat, at plant/AU U	9.68	kg
Glass, flat, at plant/AU U	9.68	kg
Sheet rolling, aluminium/RER U	0.303	kg
Polybutadiene, at plant/RER U	0.0093	kg
Zeolite, powder, at plant/RER S	1.31	kg
Articulated Truck, average, freight task/AU U	0.627	tonne.km
Electricity, Low Voltage, Australian average/AU U	3.21	kWh
Aluminium, at plant/AU U	0.303	kg
Polysulphide, sealing compound, at plant/RER U	0.438	kg
Emissions to air		
Heat, waste	11.5	MJ
Waste to treatment		
Disposal, glass, 0% water, to inert material landfill/CH U	1.36	kg
Treatment, sewage, unpolluted, to wastewater treatment, class 3/CH U	0.000996	m^3

5.2.11 Excavators

Excavators are used during the initial stages of construction to remove earth and flatten the ground surface. Fuel use for excavation was based on an estimate of 36 litres per hour (calculated from average of low and high consumptions of a John Deere excavator, http://www.deere.com/en_US/docs/construction/non_current_products/excavators/330LC+370.pdf).

Other construction equipment has not been included in the model, due to a lack of available data. This lack of data will be addressed in a sensitivity analysis. Inventory values (in hours) for excavation are provided in Table 5-2 and Table 5-6 for Forté and the reference building, respectively.

Table 5-16: Operation of an excavator for 1 hr.

Products	Quantity	Unit
Excavator/AU U	1	hr
Materials/fuels		
Diesel, used in industrial machinery, per litre fuel/AU U	36	l

5.2.12 Water use and disposal in buildings

The water use is estimated using literature sources from the Victorian Government Department of Sustainability and Environment and City West Water, combined with building specific data from Lend Lease. Table 5-17 further details the assumptions that were made to estimate the water use in the operational phase.

Table 5-17: Estimation of water use in Forté building.

Description	Value	Source
Average Occupancy residential space	2	estimate, based on apartment size
Number of apartments	23	Lend Lease
Estimated total number of inhabitants	23*2=46	Estimated based on average of inhabitants per aparatment
Average daily water use per person	152 L	(Victorian Government Department of Sustainability and Environment, 2011)
Percentage hot water	33%	(George Wilkenfeld & Associates Pty Ltd, 2008) For gas heaters.
Water heater efficiency	73%	
Yearly water use residential space	46*152*365=2552080 L = 2552 m^3	
Energy use for hot water supply	2552*.33*(1/.73)*4.2*60= 295000 MJ	Cp of water is 4.2 kJ/kg*K or = 4.2 MJ/m^3*K, assuming an increase in water temperature of 60 degrees C.
Retail space gross area	197	Lend Lease
Retail space occupation	Cafés and restaurants = 9.4 kL/m^2/yr	(City West Water, 2007)
Yearly water use retail space	9400*197 = 1851800 L = 1852 m^3	Calculated
Waste water disposed	1852+2552 = 4404 m^3	Same as total water use

The AUPLCI background dataset for drinking water supply for Melbourne ("Water, drinking, Melbourne, reticulated/AU U" was used to model the upstream processes, Table 5-18.

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Table 5-18: Supply of drinking water, Melbourne

Products	Quantity	Unit
Water, drinking, Melbourne, reticulated/AU U	1	m^3
Resources		
Water, unspecified natural origin/m^3	1	m^3
Materials/fuels		
Chlorine, at plant/AU U	1.1	g
Hydrofluosilicic acid, at plant/GLO U	2.596	g
Lime, calcined, at regional store/AU U	4.14	g
Aluminium sulphate, at plant/AU U	3.5	g
Ammonia, at plant/AU U	0.016	g
Electricity/heat		
Energy, from natural gas/AU U	0.0605	MJ
LCV engine operation, petrol/AU U	0.0302	MJ
Energy, from LPG/AU U	0.0076	MJ
Energy, from diesel/AU U	0.0151	MJ
Electricity, wind power/AU U	0.0151	MJ
Electricity, low voltage, Eastern Australia/AU U	0.3931	MJ

The heat for the hot water system is supplied by natural gas (see Table 5-17). The AUPLCI unit process, “Energy, from natural gas/AU U” inventory was used to model heat for the gas water heater.

It was assumed that all reticulated water was disposed of as wastewater. The inventory for the disposal of water was taken from the AUPLCI unit process “Wastewater treatment, Melbourne/AU U”. Wastewater is a pool of multiple wastewater inputs, including from industrial sewage and residential sewage. The treatment and emissions arising from wastewater treatment are based on the collective pool of wastewater. In this respect, wastewater treatment is a multi-input process which requires allocation. Sub-division or system expansion is not possible to avoid allocation. As such, the allocation of wastewater impacts these wastewater streams have been allocated on a volume basis,

5.2.13 Landfill of construction material

The inventory processes for inert material landfill were adopted from the Ecoinvent database (Doka, 2009). The ecoinvent database comprises of two landfill datasets. The first of these are process-specific processes, which allocate impacts based on the mass of the material entering landfill. Included processes are land use change and energy use in moving the material in land fill site (utilisation of bulldozers etc.). The process-specific inventory is summarised in Table 5-19. The landfill of concrete, glass, mineral wool, polyurethane, and steel used this inventory.

Table 5-19: Inventory for landfill of inert material.

Waste treatment		
Process-specific burdens, inert material landfill/CH U	1	kg
Resources		
Transformation, from pasture and meadow	4.44E-05	m^2
Occupation, construction site	4.44E-05	m^2a
Transformation, to dump site, inert material landfill	4.44E-05	m^2
Occupation, dump site	0.000444	m^2a
Transformation, from dump site, inert material landfill	4.44E-05	m^2
Transformation, to shrub land, sclerophyllous	4.44E-05	m^2
Occupation, shrub land, sclerophyllous	0.000222	m^2a
Transformation, from shrub land, sclerophyllous	4.44E-05	m^2
Transformation, to forest	4.44E-05	m^2
Materials/fuels		
Diesel, burned in building machine/GLO U	0.027	MJ
Electricity, low voltage, at grid/CH U	1.33E-05	kWh
Light fuel oil, burned in boiler 10kW, non-modulating/CH U	0.00143	MJ
Emissions to air		
Heat, waste, high population	0.000048	MJ

The second type of landfill process in ecoinvent are waste-specific processes. In these processes, landfill impacts are allocated based on the chemical composition of the incoming waste. The landfill of aluminium and gypsum utilised waste-specific processes from ecoinvent.

5.2.14 Recycling of construction material

From the all the construction materials that are available after the demolishment of the building, a number of materials are likely to be recycled. Table 5-20 lists the average recycling rates for a number of construction and demolition waste streams in Victoria. The recycling processes were taken from AUPLCI.

Table 5-20: Recycling rates for construction and demolition (C&D) waste recycling in Victoria

Material	Disposal (tonne)	Recycling (tonne)	Recycling rate	Reference and notes
Masonry (including concrete)	1003806	1762228	64%	(Hyder Consulting Pty Ltd, 2011) Recycling rates for 2008/09
Metals (steel and aluminium)	26662	118906	82%	
Organics	152328	22632	13%	
Paper and Cardboard	12177	0	0%	
Plastics	13312	2380	15%	
Other (including glass)	12184	84	1%	
Hazardous	497468	0	0%	
Wood products	-	-	40%	(Taylor and Warnken, 2008) Recycling rate based on 2007 values determined by Sustainability Victoria. Rates in alignment with other reported study by Crowther (2000)

Lend Lease indicated that the aluminium façade has been designed and labelled in such a way to ensure that it can readily detach from the other building components, thereby making the probability of recycling high. Given this, and a potential fall-out during recovery, a recycling rate of 99% was assumed for this material. No disaggregated recycling rate data for other aluminium components (window frames) are available. In the absence of this information, the metal recycling rate of 82% was assumed. For the recycling of steel reinforcement (in concrete), the recycling rate is limited by the recovery of concrete. As such, for recycling of steel, the recycling rate was assumed to be the same as for concrete (64%).

5.2.14.1 Application of system expansion

The system expansion procedure, proposed by Weidema, was applied to the recycling of construction materials (Weidema, 2003). In this approach, individual recycled products (e.g. recycled concrete, recycled steel) are all co-products of the recycling construction process. These products are the determining products for recycling of construction material. The answer to the question of whether or not the recycled products will displace other (e.g. virgin products) is uncertain and depends on market dynamics, particularly as the recycling process will not occur for some time. However, given increased collection and demand for recycled construction materials (e.g. to gain certification credits), it is considered likely that a) the use of these co-products will displace virgin products and b) that the co-products will be fully utilised. Using this approach, the recycled products are burdened with all recycling impacts, and credited with the avoidance of virgin material production. Details of which virgin production process has been credited for the various recycling inventories are reported in Table 5-21.

Table 5-21: Credits applied for recycling processes

Recycled material	Credited process (avoided product)
Concrete	Gravel
Reinforced steel	Pig iron
Structural steel	Pig iron
Aluminium	Aluminium
Window glass	Flat window glass
CLT	Structural pine

5.3 Forté building

5.3.1 Forté – Materials

Although the construction of the Forté building consists predominantly of CLT, a number of other materials are used in the construction of the building. Steel reinforced concrete is used for the foundations and the ground floor, the windows consist of glass in aluminium frames and an external cladding is utilised to protect the building from the elements. The apartment finishes include plasterboard for the walls and ceiling and concrete screed and a rubberlike layer for the flooring. All these materials and the modelling approaches will be discussed in the following sections of the report.

5.3.1.1 Forté – Cross laminated timber

Cross laminated timber (CLT) is manufactured in Austria by KLH. KLH has released an environmental product declaration (EPD) for its product (KLH Massivholz GmbH, 2012) . This EPD is in accordance to ISO 14025:2006 (International Organization for Standardization, 2006a), and based on the product category rules (PCR): Solid wood products, 06-2011. The EPD has been independently verified by an external party. The life cycle data in the EPD is based on an LCA study undertaken by PE International. The inventory used in this study was based on emission factors reported in the EPD.

The EPD reports the environmental impacts for two typical CLT panels; a three layer, thickness 57mm panel and a five layer, thickness 320 mm panel. The EPD covers the production stages (including raw material supply, transport to manufacturer and production) and the disposal stage (reuse, recovery or recycling potential). For this study only the data for production stages is used.

The panels used for the construction of the Forté building vary in thicknesses and number of layers.

To adequately determine the environmental impact for each of these panels, the life cycle impacts from the EPD are interpolated, using the thickness and number of bonds (number of layers minus one) as variables:

$$n_i * I_{c_L} + t_i * I_{c_T} = I_{ci}$$

Where:

n_i = *number of bonds between layers of panel i*

I_{c_L} = *impact on category c driven by number of bonds*

t_i = *thickness of panel i*

I_{c_T} = *Impact on category c driven by thickness*

I_{ci} = *Total impact on category c for panel i*

Since the total impact is known as well as the thickness and number of layers (and therefore the number of bonds) for two panels, I_{c_T}, I_{c_L} can be determined. This can then subsequently be used to interpolate the impacts for the panels used in this study. This approach can also be used to determine the total non-renewable energy demand, renewable energy demand and water use. Table 5-22 summarises key data from the EPD per square meter of panel. Table 5-23 lists the impact components related to panel thickness and number of bonds (e.g. a 3 layer panel has two bonds between panels).

Table 5-22: Key information from EPD

Property	Unit	Panel 1 /m^2	Panel 2 /m^2
Mass	kg	27.4	154
Thickness	mm	57	320
Number of layers	(-)	3	5
Greenhouse gases emitted	kg CO_{2eq}	4.6	20.4
Greenhouse gases sequestered	kg CO_{2eq}	50.6	284.4
Nett Carbon footprint	kg CO_{2eq}	-46	-264
Eutrophication Potential	kg PO_4^{3-} eq	0.004	0.024
Cumulative Energy Demand – non renewable	MJ	97	471
Cumulative Energy Demand – renewable	MJ	630	3539
Water use	m^3	0.072	0.392

In Table 5-23, most impact categories show only a small sensitivity towards number of layers and impacts are mainly driven by the thickness (and therefore volume of wood used in panel manufacture). Exceptions are the greenhouse gasses emitted and cumulative energy demand, where the number of layers is a significant driver.

Table 5-23: Impact split by thickness related impacts and number of bonds related impact

Impact category	Unit	I_thickness related (unit /m)	I_layer related (unit /bond)
Greenhouse gasses emitted	kg CO_{2eq}	54.1	0.781
Greenhouse gasses sequestered	kg CO_{2eq}	889	-0.0154
Net Carbon footprint	kg CO_{2eq}	-835	0.796
Eutrophication Potential	kg PO_4^{3-} eq	0.0777	-0.000210
Cumulative Energy Demand – non renewable	MJ	1350	10.18
Cumulative Energy Demand – renewable	MJ	11063	-0.29854
Water use	m^3	1.20	0.00168

Eight different types of CLT panel are used in the construction of the Forté building (refer Table 5-24). These models are verified in Section 7.4.2 by comparing them to a similar Ecoinvent process. The quantities used in the Forté building are listed in 5.1.

Table 5-24: Size of CLT panels used in Forté building.

Number of layers	Thickness (mm)
3	90
3	94
3	95
5	125
5	128
5	140
5	145
5	158

5.3.1.2 Forté – Rain Screen

The building is protected from the elements by the application of a rain screen. The cladding used is produced by Alubond. The panels consist of a 4 mm thick LDPE core with two aluminium sheets of 0.5 mm thickness on either side of this core (Alubond, 2011). A polyvinylidene fluoride (PVDF) coating is applied to the outward facing side. Polyvinylflouride from the USLCI database is used as a proxy as no data is available on PVDF. Alubond has manufacturing facilities in the USA, India and Europe. For this study it was assumed that the panels were manufactured in Europe. The inventory is shown in Table 5-25.

Table 5-25: Inventory for Alubond

Products	Quantity	Unit
Alubond	1	m2
Materials/fuels		
Aluminium, primary, at plant/RER U	2.65	kg
Polyethylene, LDPE, granulate, at plant/RER U	3.74	kg
Polyvinylfluoride film, at plant/US U	0.178	kg
Hot rolling aluminium sheet/AU U	2.65	kg

5.3.1.3 Uniroll

Uniroll is applied to all CLT flooring in a 10mm thick layer. Uniroll is manufactured using recycled foam rubber and cork. The exact consistency is not clear from publically available data. As a proxy flexible polyurethane foam from the Ecoinvent database was used as a basis for the material inputs. The Uniroll products are likely to be formed using a calendaring process. The average energy use (MJ/kg) for the forming recycled rubber products is approximately three times that for virgin materials (Department of Alternative Energy Development and Efficiency). This factor was applied to the energy requirements for calendaring (0.505 kWh/kg, from ecoinvent), and added to the inventory. The inventory for this is shown in Table 5-26.

Table 5-26: Inventory for Uniroll

Products	Quantity	Unit
Uniroll, at plant/A U	1	kg
Resources		
Water, unspecified natural origin/m3	0.021	m^3
Materials/fuels		
Toluene diisocyanate, at plant/RER U	0.285	kg
Polyols, at plant/RER U	0.713	kg
Electricity, low voltage, Australian average/AU U (material)	0.417	kWh
Electricity, low voltage, Australian average/AU U (calendaring)	1.515	kWh
Transport, lorry >16t, fleet average/RER U	0.2	tkm
Chemical plant, organics/RER/I U	4E-10	p
Emissions to air		
Heat, waste	1.5	MJ
Carbon dioxide, fossil	0.051	kg
Waste to treatment		
Disposal, polyurethane, 0.2% water, to municipal incineration/CH U	0.02	kg

5.3.2 Forté – Transport of materials to construction site

Table 5-27 details the transport steps required to replace the building materials to the construction site. For a number of materials the actual transport distance is not known and assumptions had to be made. These assumptions will be tested in a sensitivity study.

Table 5-27: Transport modes and distances for material transport to construction site Port locations provided by Lend Lease distances through portworld.com (Portworld.com, 2011).

Material	Mode	Distance	Comment
10mm thick uni-roll	rigid truck	900 km	from Sydney area, estimate
200mm hollow block wall	rigid truck	50 km	estimate
Alubond	rigid truck ship	30 km 21852 km	estimate
Bar reinforcement	rigid truck	50 km	estimate
CLT	rigid truck container ship rigid truck	352 km 12,438 + 6995 = 19,433 km 10 km	Katsch an der Mur, Austria to Koper, Slovenia Koper to Melbourne via Singapore Port of Melbourne to site
Concrete	concrete truck	30 km	Lend Lease
Glazing, double	rigid truck	50 km	estimate
Glulam	rigid truck	50 km	estimate
Gravel	rigid truck	50 km	estimate
LLDPE	rigid truck	50 km	estimate
Plasterboard	rigid truck	50 km	estimate
Sand, at Mine	rigid truck	50 km	estimate
Steel beams	rigid truck	50 km	estimate
Window frame, aluminium	rigid truck	50 km	estimate

5.3.2.1 Transoceanic container freight

The impacts of container freight ships were allocated on a container-basis. There were 25 containers across two shipments – there are four ships as they containers were transhipped in Singapore (information supplied by Lend Lease):

- SAFMARINE KOMATI 1203
- Grasmere Maersk Voyage 212s
- Maersk Karachi V1205
- Maersk Diadema V214S

Shipping distance was calculated using portworld.com (Portworld.com, 2011), using a transport route as outlined in Table 5-27.

Emissions data was available for two specific container vessels: the Maersk Karachi and Grasmere Maersk Voyage. This data was taken from the shippingefficiency.org database (Shippingefficiency.org, 2012). The Maersk Karachi has a shipping route from the Mediterranean to Asia, while the Grasmere Maersk Voyage has a shipping route from Asia to Oceania. The dataset provides a "CO_2 efficiency" in gCO_2 equivalent per twenty foot equivalent unit per km, or gCO_{2eq}/ TEU*km. TEU is a commonly used description of volume in sea freight (equivalent to the volume a twenty foot container can hold). The fuel consumption per TEU*km was determined from the emission factors provided in the methodology document (Carbon War Room, 2011) and the specific CO_2 efficiency for the ships. It is assumed that the ships are primarily fuelled by heavy fuel oil. The Ecoinvent process for combustion of heavy fuel oil was used to determine the emissions associated the transport of 1 TEU per km. Table 5-28 and Table 5-29 show the inventories for the two ships. The fuel oil production (from crude oil) inventory in ecoinvent uses a mixture of allocation techniques; increasing detail (to avoid allocation), as well as mass-allocation of the co-products.

Table 5-28: Shipping 1 TEU*km in the Maersk Karachi.

Products	Amount	Unit	Comment
Maersk Karachi	1	TEU*km	Main shipping route Asia-Mediterranean
Materials/fuels			
Heat, heavy fuel oil, at industrial furnace 1MW/RER U	44.07*(67.57/3.1144)=956.1	kJ	Energy density of fuel oil * (CO2 emission from database / Emission factor of heavy fuel oil)

Table 5-29: Shipping 1TEU*km in the Grasmere Maersk.

Products	Amount	Unit	Comment
Shipping, Grasmere Maersk	1	TEU*km	Main shipping route Asia-Oceania
Materials/fuels			
Heat, heavy fuel oil, at industrial furnace 1MW/RER U	44.07*(77.73/3.1144)=1100	kJ	Energy density of fuel oil * (CO_2 emission from database / Emission factor of heavy fuel oil)

As some of the transported CLT panels do not fit into a twenty foot (6.1 meter) container, it is assumed that all cargo is transported in 40 foot shipping containers (or 2 TEU). As no data was available for the Safmarine Komati and Maersk Diadema, these two shipping models were used to model all the transport. The models are verified in Section 7.4.5. The shipping distances are 12438 km for the Maersk Karachi (Koper to Singapore) and 6995 km Grasmere Maersk (Singapore to Melbourne). Total volume shipped is 50 TEU (25 containers of 2 TEU).

5.3.3 Forté – Operation of the building

5.3.3.1 Forté – Heating and cooling

As described in Section 4.1, the energy demand for heating, cooling and lighting was determined through thermal modelling of the Forté and reference building using ApacheSim and Accurate. The following key parameters were used as inputs in the analysis (Table 5-30). The coefficient of performance (COP) and energy efficiency ratio (EER) for the Forté building are the actual values of the installed equipment, as are the heat transfer coefficient (U-value) and solar heat gain coefficient (SHGC) values for the windows. These figures were provided by Lend Lease.

Table 5-30: Key parameters used in the operational modelling of Forté.

Assumptions		Forté Building	Comment
Retail space			
Heating set-point		19°C	Estimate
Cooling set-point		23°C	Estimate
Seasonal coefficient of performance (COP)		3.72 (Heating)	Provided by Lend Lease
Seasonal energy efficiency ratio (EER)		3.08 (Cooling)	Provided by Lend Lease
Internal heat gains		90 W/person	Person heat gains default value from Apache modelling software.
Lighting		22 W/m^2	Provided by Lend Lease
Retail glazing heat transfer coefficient (U-value)		3.4 $W/K.m^2$	Provided by Lend Lease
Retail glazing solar heat gain coefficient (SHGC)		0.47	Provided by Lend Lease
Residential space			
Heating set-point		19°C	Estimate
Cooling set-point		24°C	Estimate
Seasonal COP	Ground floor	3.83 (heating)	Rated performance of Toshiba RAS-13SKV2-A1 3.4 KW (common room), Toshiba RAS-18SKV-A 4.89 kW (for Levels 1-7), Toshiba RAS-24SKV2A 8.1 kW reverse cycle split systems. Provided by Lend Lease. Maximum COP and EER are higher. Rating in accordance with MEPS 3823.2-2011 E&OE
	Level 1 – 7	3.72 (Heating)	
	Level 8	3.32 (Heating)	
Seasonal EER	Ground floor	3.43 (Cooling)	
	Level 1 – 7	3.52 (Cooling)	
	Level 8	3.05 (Cooling)	
Internal heat gains		90 W/person	Person heat gains default value from Apache modelling software.
Lighting power density	Living areas	3.2 W/m^2	Provided by Lend Lease
	Sleeping areas	3.2 W/m^2	
	Foyers, hallways, corridors (incl. fire stairs)	3.4 W/m^2	
	Amenities	3.2 W/m^2	
	Back of house	2.6 W/m^2	
	External lighting	10.6 W/m^2	
Double glazing U-value		4.43 $W/K.m^2$	Provided by Lend Lease
Double glazing SHGC		0.53	Provided by Lend Lease

ApacheSim was used to model the energy requirements for heating and cooling, using the building plans provided by Lend Lease, the parameters from Table 5-30, and other inputs such as building location and shading from adjacent buildings. The energy requirements per apartment and for the retail space are listed in Table 5-31.

Table 5-31: Energy requirements for the Forté building

Forté Apartment/Level number	Heating energy - MWh	Cooling energy, MWh	Total, MWh
Retail	3.46	3.00	6.46
Apt 11	0.67	0.68	1.36
Apt 12	0.67	0.68	1.35
Apt 13	0.69	0.46	1.15
Apt 21	0.59	0.68	1.27
Apt 22	0.58	0.66	1.24
Apt 23	0.60	0.45	1.05
Apt 31	0.57	0.68	1.25
Apt 32	0.55	0.67	1.23
Apt 33	0.59	0.46	1.05
Apt 41	0.56	0.69	1.25
Apt 42	0.55	0.67	1.22
Apt 43	0.58	0.46	1.04
Apt 51	0.55	0.69	1.24
Apt 52	0.65	0.68	1.33
Apt 53	0.58	0.46	1.04
Apt 61	0.53	0.69	1.22
Apt 62	0.51	0.68	1.19
Apt 63	0.58	0.46	1.04
Apt 71	0.52	0.69	1.21
Apt 72	0.49	0.68	1.18
Apt 73	0.63	0.46	1.09
Apt 81	1.26	1.07	2.33
Apt 82	1.24	1.05	2.29
Total	**18.21**	**17.88**	**36.09**

The energy source that was used in the heating and cooling process was electricity. The Victorian grid model was used in the analysis (see Table 5-9). The model includes line and transformation losses in high and low voltage grids (5% combined loss, dissipated as heat).

5.3.3.2 Forté – Lighting

Lend Lease provided lighting densities for different areas within the buildings (refer Table 5-3). These values were used in ApacheSim to prescribe the power densities for each room. ApacheSim uses the room areas, together with an inbuilt occupancy pattern to establish the energy use (power density multiplied by the average time that the lights are switched on). The total energy use for lighting was calculated as 31.09 MWh per year.

5.3.4 Forté – Demolition and disposal of building materials

At the end of life, the construction materials will be disposed of in landfill or recycled (i.e. the window frames, concrete and steel have a large recycling rate). The majority of the construction materials are considered to be inert, they will not degrade when placed in a landfill site. Therefore the only impacts associated with these materials are related to the transport (see 5.2.3), and the management of the landfill site (5.3.4.1). However the CLT and glulam beams may degrade when placed in landfill. During the degradation process, methane and carbon dioxide will be released. This is also discussed in Section 5.3.4.1. Lend Lease is looking at alternative disposal options, such as recycling or re-use of the panels. Given the modular design of the CLT panels (which facilitates separation from other building material elements, such as plasterboard), together with the volume of CLT used in Forté, it could be argues that there is a high likelihood that the CLT panels will be recovered for beneficial uses during demolition. The exact nature of what the recovered CLT panels could be used for is not known. Potential recovery options include reuse, direct recycling into engineered wood products, indirect recycling into new products such as playground fibre, and energy generation (such as co-firing with coal) (Taylor and Warnken, 2008).

5.3.4.1 Landfill of CLT and Glulam

Table 5-32 provides a review of degradation on a number of recent studies and models. Wang et. al. (2011), calculate a carbon loss of 7.9% for a mixture of woods under laboratory conditions over a time period of up to 3.69 years. Measurements performed wood that was excavated after 16-20 years in landfill, by Ximenes (2012), suggest that wood products in landfill store between 86.4% and 100% of carbon, depending on the type of wood product. The average storage was 93.9% storage, or 6.1% degradation.

The IPCC Tier 2 first order decay (FOD) model is based on calculating the mass of degradable organic carbon, $DDOC_m$, that remains after time period, *i,* for a material with a known initial degradable organic content, $DDOC_{m0}$ ($DOCxDOC_f$), using the following Arrhenius equation:

$$DDOC_m = DDOC_{m0} e^{\left(\frac{-k}{i}\right)}$$

The reaction rate constant, *k*, is dependent on the type of waste and the local landfill conditions. For Melbourne, a wet-temperate climate, the *k* value for wood is 0.02 (IPCC, 2006b). When the FOD model is applied with the time *i* set to 18 years, the stored carbon is 85%, corresponding to a carbon loss of 15%, which is over double of the maximum reported by Ximenes. If the DOC_f is adjusted to 0.25, then the stored carbon at 18 years is 92.5% with a loss of 7.5%.

The actual behaviour in landfill remains uncertain. A sensitivity study will be undertaken to determine the effect of different DOC_f values (at 100 years) on the outcomes of the study.

Table 5-32: Degradation amounts for wood products from different studies

Literature source	Material	Method	Removed carbon (weight % of original C)	Time at carbon removal measurement
IPCC, Tier 1	Wood	Calculation, DOCxDOCf, default DOC of 0.5, DOCf of 0.25	12.5	Not applicable
(U.S. Environmental Protection Agency, 2006, Eleazer et al., 1997)	Woody branches	Combination of experimental evidence and theory	23	80 days
(Ximenes, 2012)	MDF	Excavations	13.6 11 7.4	16-18 years 19-20 years 18 years
	Particleboard	Excavations	6.2 5.8 7	16-18 years 19-20 years 18 years
	Plywood	Excavations	9.4 0.5	16-18 years 18 years
	Veneer	Excavations	0 0	19-20 years 18 years
	Particleboard	Laboratory	1.75	-
	MDF	Laboratory	0	-
	High pressure laminates	Laboratory	0	-
(Wang et al., 2011)	Plywood	Laboratory	1.4	Up to 1347 days (3.69 years)
	Particleboard	Laboratory	1.3	
	OSB	Laboratory	0-19.9	
	MDF	Laboratory	1.1	

Degradation calculations were based on the Tier 1 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006b). A flow chart outlining the structure of these calculations is provided in Figure 5-1.

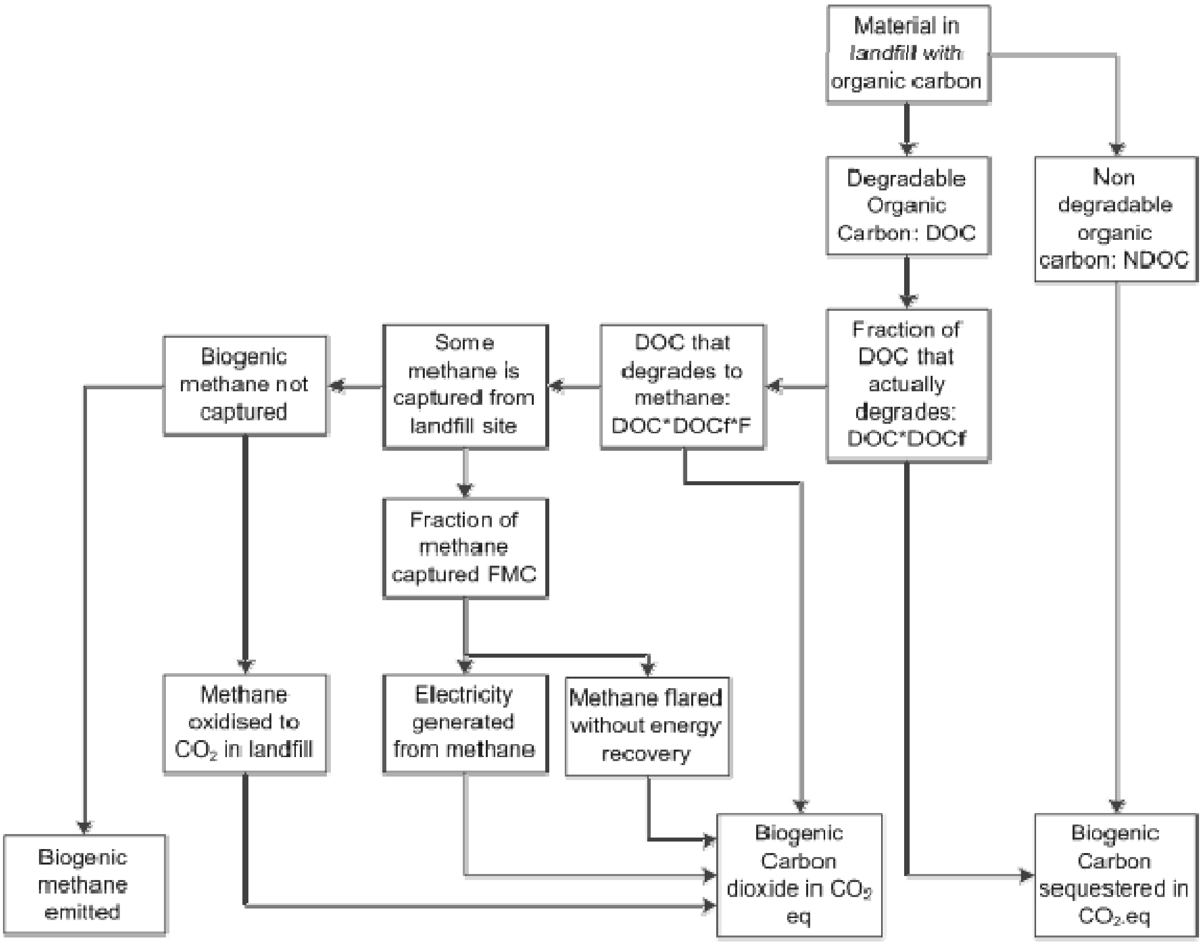


Figure 5-1: Degradation routes for carbon in landfill, based on IPCC methodology (IPCC, 2006b).

The degradation model relies on the following factors:

- *Ci*, the initial carbon content, based on the calculated weight percentage of carbon derived from natural (biogenic) sources and the mass of wood. Using this methodology, the initial carbon content (by weight) for CLT is 50.51%.
- *DOC* is the fraction of the organic carbon which is degradable, used default value of 0.5 (IPCC, 2006b)
- DOC_f is the fraction of the degradable organic carbon that actually degrades
- N_{DOC} is the non-degradable organic carbon, calculated by 1-*DOC*
- *F* is the fraction of *DOC* degrading into methane, used default value 0.5 (IPCC, 2006b).
- *FMC* is the fraction of methane captured, best estimate projection of 0.36 in Victoria in 2020 (Griffith and Pickin, 2007). Actual value at end of life could be higher.
- M_{ox} is the fraction of methane that oxidise (and subsequently released as biogenic CO_2). Used default value of 0.1 (IPCC, 2006b), representing covered, well-managed landfills.

The choice of DOC_f value is the most important value choice for the landfill modelling of wood and there is no consensus on an appropriate factor. The degradation of wood in landfill is dependent on many factors including time in landfill, moisture content, wood type, particle size, temperature, interaction with other materials (e.g. food waste), and is generally not well understood.

Carbon dioxide generated in the landfill or from the flaring or combustion of methane from landfill was treated as a zero-flow, as per IPCC guidelines. Non-degraded biogenic carbon was treated as carbon sequestration. The mass of the solid waste remaining in the landfill was calculated based on the material remaining after degradation. The following equations were used to compile the inventory for landfill of wood:

- Biogenic carbon emitted to soil (sequestered) = $N_{DOC} + DOC \times (1\text{-}DOC_f)$
- Biogenic carbon emitted to air = $DOC \times DOC_f \times [(1 - F) + F \times (FMC + ((1 - FMC) \times M_{ox}))]$
- Biogenic methane emitted to air = $DOC \times DOC_f \times [F \times (1 – FMC) \times (1 – M_{ox})]$

Emission values were converted to molecular-equivalency by scaling the carbon emissions based on the molar mass of carbon within the associated emission molecule (e.g. mass of carbon in methane). A summary of the factors used for the landfill model are provided in Table 5-33. The inventory for wood degradation, based on the above calculations is presented in Table 5-34.

Table 5-33: Default landfill parameters for determining wood landfill elementary flows

Parameter	Value
C_i	0.5052
k	0.02
DOC	0.5
N_{DOC}	0.5
DOC_f	0.25
F	0.5
Mox	0.1
FMC	0.36

Table 5-34: Inventory for wood degradation in landfill

Waste treatment		
Degradation of wood in landfill	1	kg
Emissions to air		
Carbon dioxide, biogenic	0.252	kg
Methane, biogenic	0.048	kg
Emissions to soil		
Carbon dioxide, biogenic	1.39	kg
Final waste flows		
Waste, final, inert	0.875	kg
Methane captured from landfill (Victoria)/AU U	0.027	kg

The inventory for methane capture was based on the existing unit process for methane capture from the Australasian Unit Process Life Cycle Inventory. Landfill methane capture utilisation rates were based on a report by Hyder Consulting (Griffith and Pickin, 2007); of the methane that was captured in Victoria, 20.7% was assumed to be flared, with the remaining 79.3% being captured for electricity generation. A generation efficiency of 31% was assumed (Griffith and Pickin, 2007), with credits being applied for the avoidance of high voltage electricity from the Victorian grid.

5.3.5 Recycling of CLT

As reported in Section 5.3.4, the CLT panels are considered likely to be recovered for recycling during demolition, but the nature of what the reprocessing path, including the next life cycle of the CLT material, is uncertain. Given this uncertainty, the inclusion of recycling will only be considered in a sensitivity study, with the credits applied for the avoidance of sawn pine timber (Structural pine, u=12%, at mill/AU U from AUPLCI). Reprocessing was based on the sawing operations for hard timber, adapted from the AUPLCI database. Sawing of hard timber was considered more appropriate than for sawn soft timber, due to potentially higher energy inputs associated with sawing through panels with resin. An estimated fall out rate of 10% (by weight) was included in the inventory to account for potential material loss during reprocessing. Sequestration credits for the remaining material were carried through to the next life cycle, with the 10% waste being treated in landfill. The structural pine inventory is linked to other unit process from forestry and processing operations. A number of these processes are multi-output processes requiring allocation. The default mass-allocation (pre-defined in the AUPLCI background dataset) was used in these instances.

5.4 Reference building

The reference building utilises similar materials and processes as for Forté. This section of the inventory details the additional processes, and processes which are different, to that used for Forté.

5.4.1 Reference building - External wall insulation, polyurethane

Rigid polyurethane foam is used as insulation in the roof structure and external walls of the reference building. The inventory has been taken from Ecoinvent, and regionalised by changing the electricity grid to Australia. Table 5-35 provides the inventory. The foam has a density of 30kg/m^3.

Table 5-35: Inventory for polyurethane rigid foam.

Products	Quantity	Unit
Polyurethane, rigid foam, at plant/RER U LL	1	kg
Materials/fuels		
Pentane, at plant/RER U	0.054	kg
Methylene diphenyl diisocyanate, at plant/RER U	0.616	kg
Polyols, at plant/RER U	0.386	kg
Electricity, low voltage, Eastern Australia/AU U	0.417	kWh
Transport, lorry >16t, fleet average/RER U	0.211	tonne.km
Chemical plant, organics/RER/I U	4E-10	p
Emissions to air		
Heat, waste	1.5	MJ
Pentane	0.054	kg
Waste to treatment		
Disposal, polyurethane, 0.2% water, to municipal incineration/CH U	0.02	kg

5.4.2 Reference building – Transport of materials to construction site

Table 5-36 details the transport steps required to replace the building materials to the construction site. For a number of materials the actual transport distance is not known and assumptions had to be made. The baseline assumption of 50 km will be tested in a sensitivity study.

Table 5-36: Transport distances for materials for the reference building.

Materials	Mode	Distance	Comment
200mm hollow block wall	rigid truck	50 km	estimate
Bar reinforcement	rigid truck	50 km	estimate
Concrete	concrete truck	30 km	Lend Lease
Cork tiles	rigid truck	50 km	estimate
External wall insulation	rigid truck	50 km	estimate
Glazing, double	rigid truck	50 km	estimate
Glulam	rigid truck	50 km	estimate
Gravel	rigid truck	50 km	estimate
Hebel panels	rigid truck	50 km	estimate
LLDPE	rigid truck	50 km	estimate
Plasterboard	rigid truck	50 km	estimate
Sand, at Mine	rigid truck	50 km	estimate
Steel beams	rigid truck	50 km	estimate
Steel sheet	rigid truck	50 km	estimate
Window frame, aluminium	rigid truck	50 km	estimate

5.4.3 Reference building – Operation of the building

5.4.3.1 Reference building - Heating and cooling

Table 5-37 lists key assumptions that were made to model the reference building. As can be seen in the table, some assumptions were identical to the Forté building. The other parameters were chosen to match the minimum requirements for BCA 2011.

Table 5-37: Key assumptions and parameters used to model heating and cooling loads

Assumptions		Reference Building	Comments
Retail space			
Heating set point		19˚C	Assumption identical to Forté building
Cooling set point		23˚C	Assumption identical to Forté building
Seasonal COP/EER		3.66	Minimum MEPS requirements
Internal heat gains		90 W/person	Assumption identical to Forté building
Lighting		22 W/m^2	Assumption identical to Forté building
Retail glazing U-value		5.16 W/K.m^2	U-values values are taken from Apache's database
Retail glazing SHGC		0.74	SHGC values are taken from Apache's database
Residential space			
Heating set point		19°C	Assumption identical to Forté building
Cooling set point		24°C	Assumption identical to Forté building
Seasonal COP/EER	Ground floor	3.66	Current minimum MEPS requirement for non-ducted split systems with capacity below 4kW.
	Level 1-7	3.22	Current minimum MEPS requirement for non-ducted split systems with capacity between 4 kW and 10 kW.
	Level 8	3.22	
Internal heat gains		90 W/person	Assumption identical to Forté building
Lighting power density	Within building	5 W/m^2	Maximum power lamp densities according to BCA 2012 Section J.
	Balconies	4 W/m^2	
Double glazing U-value		3.58 W/K.m^2	U-values values are taken from Apache's database for Clear/12 Air gap/Clear
Double glazing SHGC		0.68	SHGC values are taken from Apache's database

ApacheSim was used to model the energy requirements for heating and cooling, using the building plans provided by Lend Lease, the parameters from Table 5-37, and other inputs such as building location and shading from adjacent buildings. The energy requirements per apartment and for the retail space are listed in Table 5-38.

Table 5-38: Energy requirements for the reference building

Forté Apartment/Level number	Heating energy MWh	Cooling energy MWh	Total MWh
Retail	3.95	3.28	7.24
Apt 11	0.60	0.90	1.49
Apt 12	0.60	0.89	1.48
Apt 13	0.60	0.60	1.20
Apt 21	0.51	0.92	1.43
Apt 22	0.50	0.91	1.41
Apt 23	0.52	0.62	1.14
Apt 31	0.48	0.94	1.42
Apt 32	0.47	0.91	1.38
Apt 33	0.49	0.63	1.12
Apt 41	0.47	0.95	1.42
Apt 42	0.45	0.92	1.38
Apt 43	0.49	0.64	1.12
Apt 51	0.44	0.95	1.39
Apt 52	0.43	0.93	1.36
Apt 53	0.48	0.64	1.12
Apt 61	0.43	0.95	1.38
Apt 62	0.41	0.94	1.35
Apt 63	0.49	0.64	1.13
Apt 71	0.43	0.95	1.38
Apt 72	0.42	0.94	1.36
Apt 73	0.63	0.62	1.25
Apt 81	0.98	1.23	2.21
Apt 82	1.00	1.22	2.21
Total	**16.27**	**23.10**	**39.37**

5.4.3.2 Reference building – Water Use

The same background databases and assumptions are used in the reference building as what was used in the Forté building.

5.4.3.3 Reference building – Lighting

The energy requirements for the lighting were modelled using the maximum lamp power densities that are listed in BCA 2012 Section J. The code prescribes that for a sole occupancy unit of a Class 2 building the lamp power density may be no more than 5 W/m^2 within the building and no more than $4W/m^2$ for verandas and balconies. It also lists maximum illumination power densities for other types of spaces such as common areas and corridors, plant rooms and retail space. These values were used in ApacheSim to prescribe the power densities. ApacheSim uses an inbuilt occupancy pattern to establish the energy use (power density multiplied by the average time that the lights are switched on). The total energy use for lighting was calculated as 45.22 MWh per year.

5.5 Uncertainty analysis

All inventory data carries some uncertainty, due to precision, accuracy and the applicability of the data to the goal and scope of this study. Such uncertainty is quantified by assigning an error range on the data points. The type of these error ranges can vary. For example, a minimum, mean and maximum or a lognormal distribution can provide an error range. The breadth and depth of LCA studies means that it can be difficult to quantify all error ranges. To accommodate this, estimates of input data uncertainty are included in the inventory using an uncertainty pedigree matrix. The pedigree matrix translates qualitative data quality indicators relating to reliability, completeness, temporal correlation, geographical correlations, sample size and technological correlation, into a semi-quantitative lognormal distribution (Weidema and Wesnas, 1996). The data quality indicators are taken from the data quality assessment.

These uncertainties, and those incorporated in the background inventory datasets, were used to run a Monte Carlo simulation.

5.5.1 Pedigree matrices

To enable an uncertainty analysis of the foreground and background data, the pedigree matrices for all foreground processes were filled out. The sections below detail the selected levels of certainty for the different uncertainty categories.

Category	Uncertainty level				
	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data based on assumptions	Non-verified data based on assumptions	Qualified estimate	Non-qualified estimate
Completeness	Representative data from all sites	Representative data from >50 sites relevant	Representative data from only some sites (<50%)	Representative data from only one site relevant	Representativeness unknown
Temporal correlation	Less than 3 years from our reference year	Less than 6 years from our reference year	Less than 10 years from our reference year	Less than 15 years from our reference year	Age of data unknown
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study	Data from similar area	Data from unknown area
Further technological correlation	Data from enterprise, processes and materials under study	-	Data for related processes for laboratory scale for different technology	Data for related processes but different technology	Data related processes or materials but for laboratory scale of different technology
Sample Size	>100, continuous measurement	>20	>10, aggregate figure in env. report	>=3	unknown

5.5.1.1 Pedigree matrix for KLH EPD data

The pedigree matrix is set (2,1,1,1,4,1) for all parameters excluding the parameters relating to the dimensions of the final product. These are set to (1,1,1,1,1,1).

5.5.1.2 Pedigree matrix for container freight data

The pedigree matrix for fuel inputs is set to (3,1,1,1,1,1). The carbon dioxide emissions are set to (2,1,1,1,1,1).

6 Life Cycle Impact Assessment Results

6.1 Characterised results

The main results are summarised in Table 6-1 and Figure 6-1. The results will be further discussed in the following sections.

Table 6-1: Characterisation results. Results are reported per functional unit.

Impact Category	Forté Building	Reference Building
Global Warming - ex sequestration - tonne CO_2 eq	6618	7616
Global Warming - inc sequestration - tonne CO_2 eq	5970	7615
Eutrophication - kg PO_4^{3-} eq	2860	3264
Water Use - m^3 H_2O	238476	243969
Cumulative energy demand - non-renewable - GJ LHV	74525	89049
Cumulative energy demand - renewable - GJ LHV	13283	2604

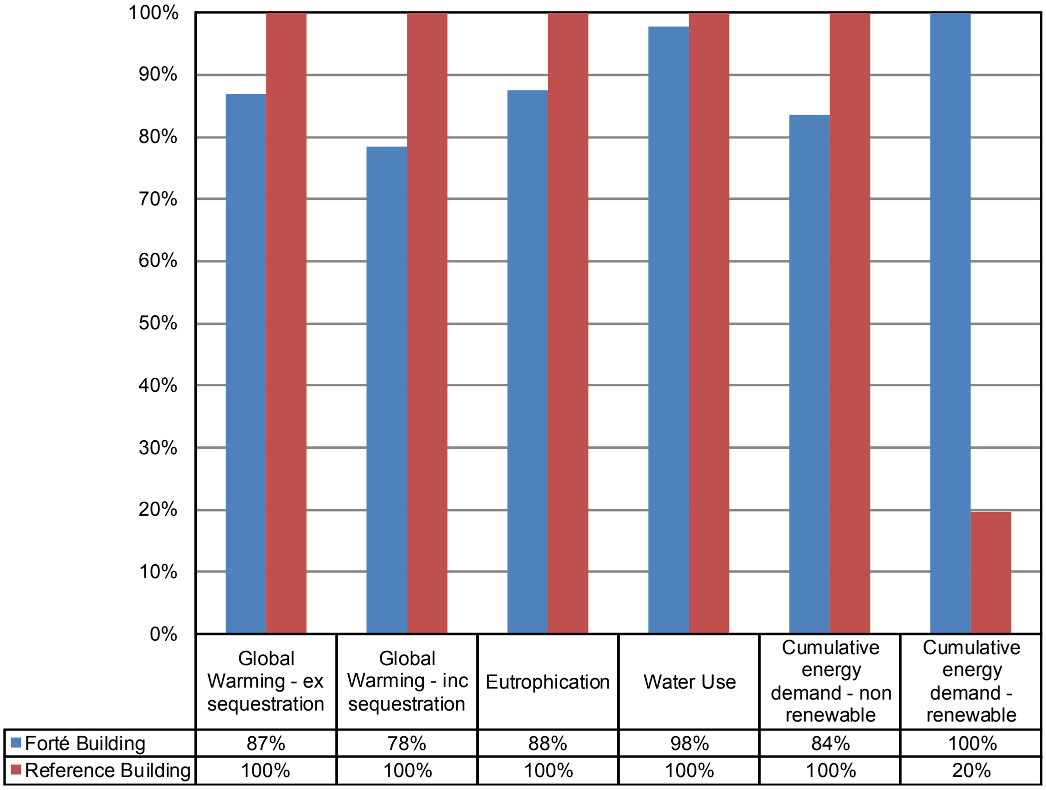


Figure 6-1: Relative impacts for the Forté building and Reference building, by category. Scaled to the highest impact for that specific category.

7 Life Cycle Interpretation

7.1 Impacts per m^2 of gross floor area

Table 7-1 provides the potential environmental impacts per square meter of gross floor area. The area is calculated by combining the area of the apartment spaces and the retail space.

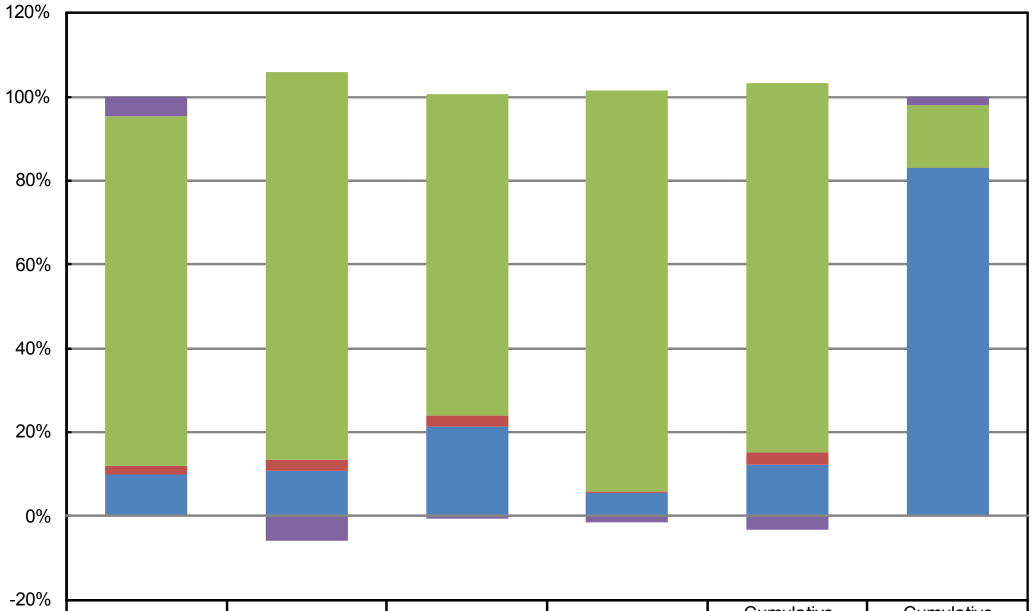
Table 7-1: Impacts per m^2 of gross floor area per year.

Impact Category	Forté Building	Reference Building
Global Warming - ex sequestration - kg CO_2 eq	54	63
Global Warming - inc sequestration - kgCO_2 eq	49	63
Eutrophication - kg PO_4^{3-} eq	0.024	0.027
Water Use - m^3 H_2O	2.0	2.0
Cumulative energy demand - non renewable - MJ LHV	613	732
Cumulative energy demand - renewable - MJ LHV	109	21

7.2 Drivers of impacts

Figure 7-1 and Figure 7-2 list the drivers of impacts for the Forté and Reference building, respectively. The impacts are scaled to total 100%. In this way the relative contribution of life cycle stages can be determined.

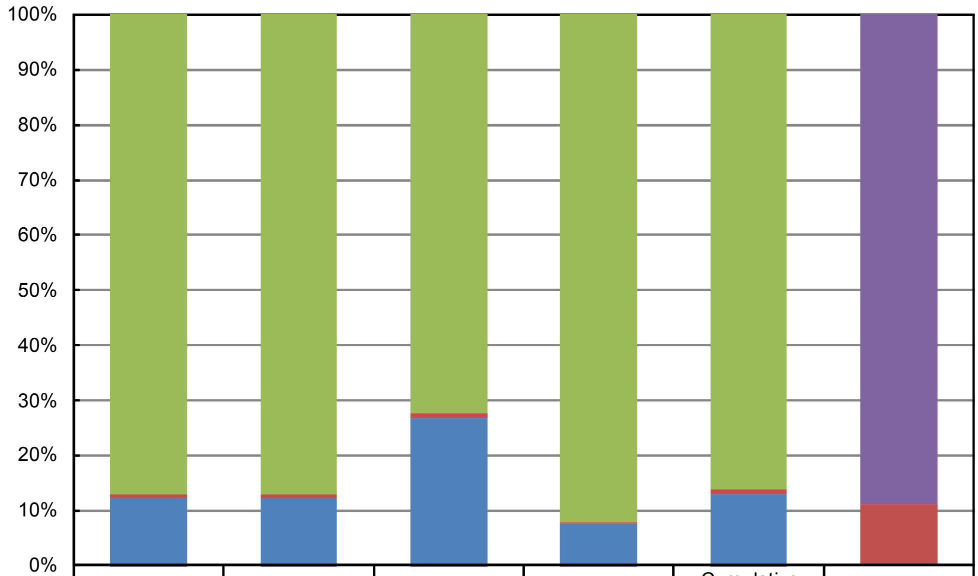
For the Forté building, the majority of the impacts on all categories, except renewable energy demand, are stemming from the use phase (77%-96%, depending on the category). The next biggest contributor is the building materials (5%-21% depending on the impact category). The other life cycle stages only have a relatively minor impact. However, if carbon sequestration is included the end of life of the Forté this yields a negative impact (or an environmental credit). That the relative magnitude of the end of life is proportional to the materials phase is coincidental; while the materials impacts are driven by a range of materials (see Figure 7-5) the end of life credits are mainly driven by the sequestration of carbon in wood (Figure 7-7). This will be discussed later.



	Global Warming - ex sequestration	Global Warming - inc sequestration	Eutrophication	Water Use	Cumulative energy demand - non renewable	Cumulative energy demand - renewable
4. Disposal Forte	5%	-6%	-1%	-2%	-3%	2%
3. Use Forte	83%	92%	77%	96%	88%	15%
2. Construction Forte	2%	2%	2%	0%	3%	0%
1. Materials Forte	10%	11%	21%	5%	12%	83%

Figure 7-1: Contribution of the different life cycle stages for Forté building. All individual columns add up to 100%. Note that the second column has some negative impacts (carbon sequestration).

Figure 7-2 shows the contributors for the reference building. The trends are quite similar; the majority of impacts originate from the use phase (75%-94% depending on the impact category), while building materials are the second biggest contributor (7%-27%). Again, transport and construction and disposal only have a minor contribution to the overall impacts.



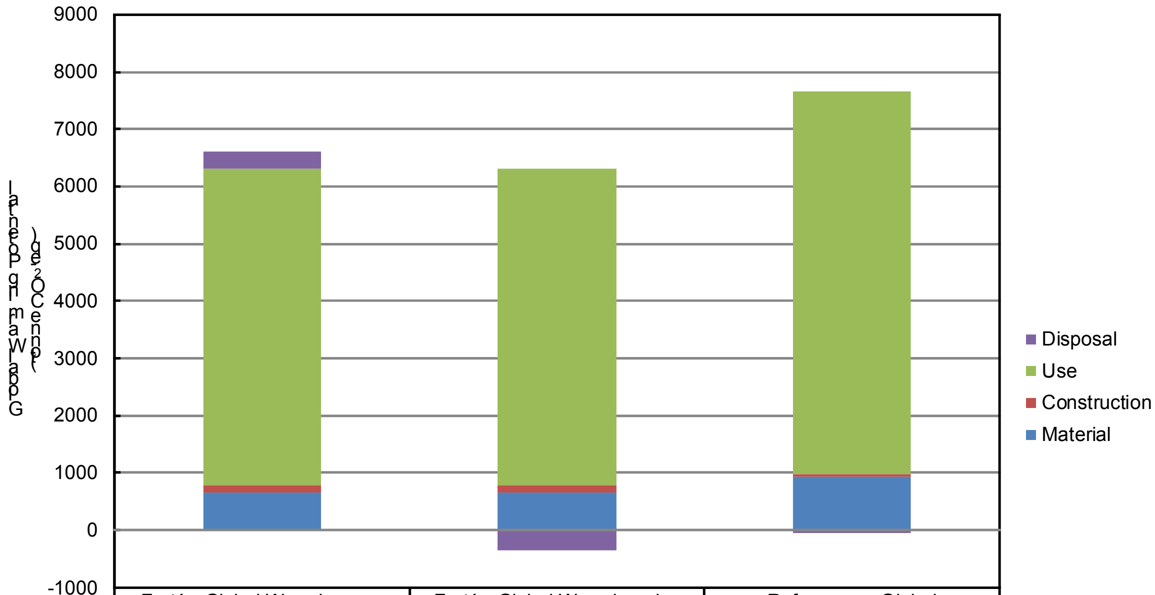
	Global Warming - ex sequestration	Global Warming - inc sequestration	Eutrophication	Water Use	Cumulative energy demand - non renewable	Cumulative energy demand - renewable
4. Disposal Reference	-1%	-1%	-3%	-2%	-2%	89%
3. Use Reference	88%	88%	75%	94%	88%	0%
2. Construction Reference	1%	1%	1%	0%	1%	11%
1. Materials Reference	12%	12%	27%	7%	13%	0%

Figure 7-2: Contribution of the different life cycle stages for reference building

The different impact categories and life cycle stages will be discussed in the following sections.

7.2.1 Global warming potential

Figure 7-3 shows the impacts on global warming potential for the Forté building (including and excluding sequestration of biogenic carbon at the end of life), and the reference building. The reference building has a higher impact on global warming, because both the use phase and the material phase emit more greenhouse gasses. The impacts on construction are higher for the Forté building than for the reference building, mainly because of more transport is required. The CLT panels (main construction material) are currently imported causing higher transport emissions than the concrete that is sourced locally. When carbon sequestration is excluded from the assessment, the disposal phase of the Forté building has a positive impact (global warming substances are emitted), mainly due to methane emissions due to wood decomposition. If carbon sequestration is included the impact reduces and becomes negative overall (a net carbon sequestration), because the vast majority of the wood will not decompose in landfill and will thus be ‘locked in’.

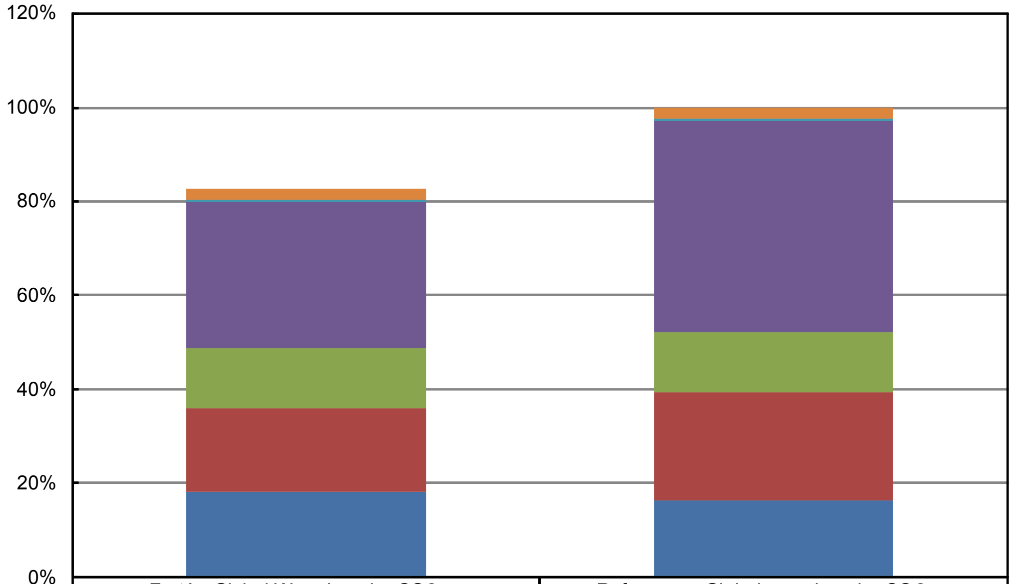


	Forté - Global Warming - ex sequestration (tonne CO2-eq)	Forté - Global Warming - inc sequestration (tonne CO2-eq)	Reference - Global Warming - ex sequestration (tonne CO2-eq)
Disposal	303	-345	-46
Use	5521	5521	6679
Construction	146	146	52
Material	649	649	931

Figure 7-3: Global warming potential for the reference building and Forté building, excluding sequestration. Including the sequestration of carbon in wood at the end of life further reduces the impacts.

The different life cycle stages will be discussed in the remainder of this section in order of environmental significance (for global warming).

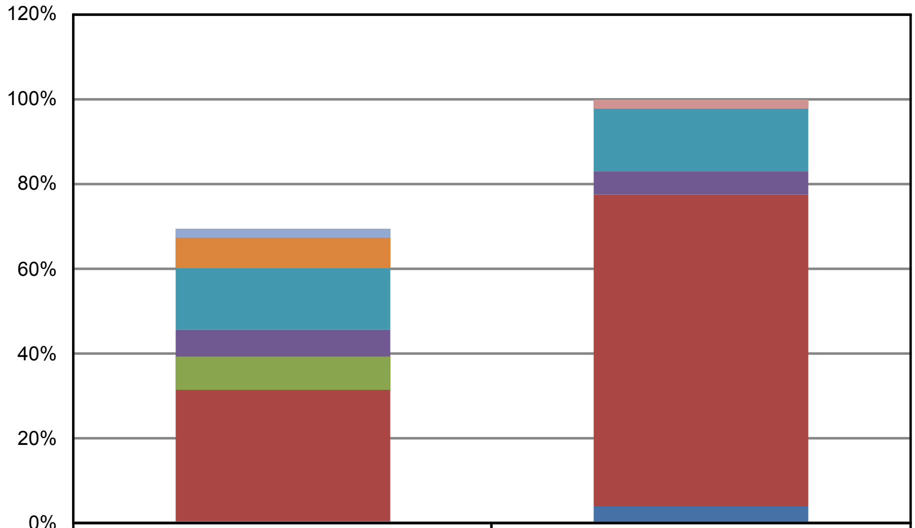
Figure 7-4 presents the drivers of global warming potential during the use phase. The Forté uses less energy during the use phase, due to decreased electricity use in heating and cooling, and decreased natural gas use for the hot water supply. As water use, wastewater and lighting are assumed to be the same for both buildings, there is no difference in impacts.



	Forté - Global Warming - kg CO2 eq	Reference - Global warming - kg CO2 eq
Wastewater treatment	2%	2%
Drinking water	1%	1%
Lighting	31%	45%
Hot water	13%	13%
Cooling	18%	23%
Heating	18%	16%

Figure 7-4: Global warming impacts during the use phase, 100%=6679 tonne CO_2-eq

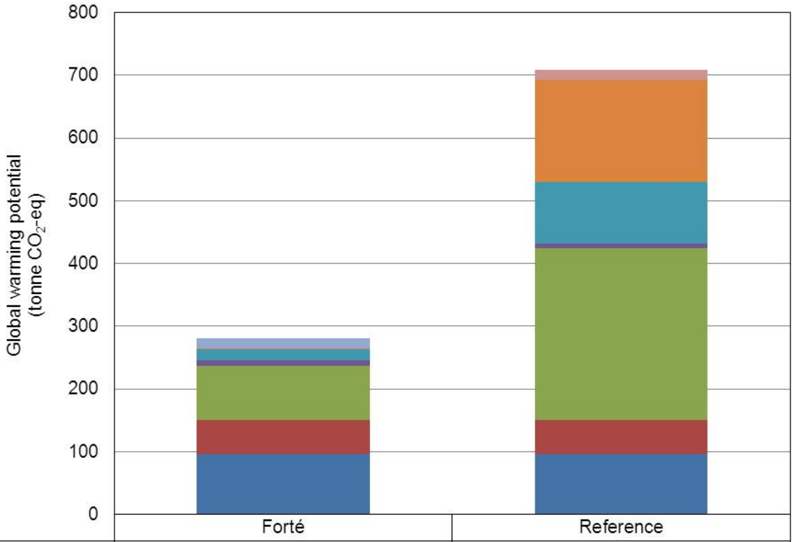
Figure 7-5 shows the drivers of global warming potential for the materials of both buildings. The impacts from concrete are a lot higher for the reference building. The concrete in the reference building substitutes the CLT, uniroll, cladding and some of the plasterboard. However the impacts of all these materials combined is still lower than the concrete impacts from the reference building (31% vs. 74%). Also more insulation is required in the reference building, further increasing the impacts from materials for the reference building. The amount of windows is the same for both buildings. Although the types differ in terms of isolative properties, the material intensity is very similar; therefore no difference in impacts is discernible from a materials impacts perspective.



	Forté - Global Warming - kg CO2 eq	Reference - Global Warming - kg CO2 eq
Insulation	0%	2%
Uniroll	2%	0%
Cladding	7%	0%
Windows and frames	15%	15%
Plasterboard	6%	6%
CLT	8%	0%
Concrete and steel reinforcement	31%	74%
Other	0.4%	4%

Figure 7-5: Global warming potential during the materials phase. 100%= 931 tonne CO_2 eq sequestration excluded.

Figure **7-6** shows the breakdown for global warming potential from concrete and the building elements. In the model it is assumed that the foundational works, ground slab and columns are the same for both buildings. However, large differences can be seen for the other building elements, such as the suspended floor slabs, internal walls, and external wall/façade. The Forté building uses some concrete in 70 mm screeds on top of the CLT floor slabs. From the figure it can be seen that the impact of those screeds is relatively small. This is due to the low volume compared to the other components and the relatively low cement content of the concrete used.



	Forté	Reference
Roof concrete	0	16
70mm concrete screed on CLT floors	16	0
Façade/external walls	3	162
Walls	17	98
Columns	8	8
Suspended slabs	87	274
Ground slab	54	54
Foundations	96	96

Figure 7-6: Breakdown for global warming potential from concrete.

The global warming potentials for disposal of the Forté building are sensitive to the inclusion or exclusion of sequestration of biogenic carbon, Figure 7-7. If carbon sequestration is not included, the overall impacts of disposal are positive (meaning there will be a net emission of greenhouse gasses), if carbon sequestration is included, the impacts are negative for this stage of the lifecycle (meaning that net more greenhouse gasses are taken out of the atmosphere than are released). Both the Forté and reference building receive credits for the recycling of construction materials. The impacts from transport to landfill site are twice as high for the reference building when compared to the Forté building.

	Forté - Global Warming ex sq - kg CO2 eq	Forté - Global Warming inc sq - kg CO2 eq	Reference - Global Warming - kg CO2 eq
Disposal CLT/wood	148.1%	-65.8%	0%
Recycling	-54.9%	-55.0%	-28.5%
Landfill of other building materials	2.2%	2.2%	4%
Transport	4.6%	-4.0%	9%

Figure 7-7: Global warming potential from disposal of materials. Scaled to the overall impact of Forté ex sequestration, 100%= 303 tonne CO_2 eq.

In the construction and transport phase, only 4% of the emissions come from excavation works, the majority (96%) is related to the transport of materials to site. For the Forté building the majority of transport impacts come from the transport of CLT (see Figure 7-8), for the reference building the transport of concrete is the biggest contributor, however the overall impact for the reference building on transport is still lower due to shorter transport distances.

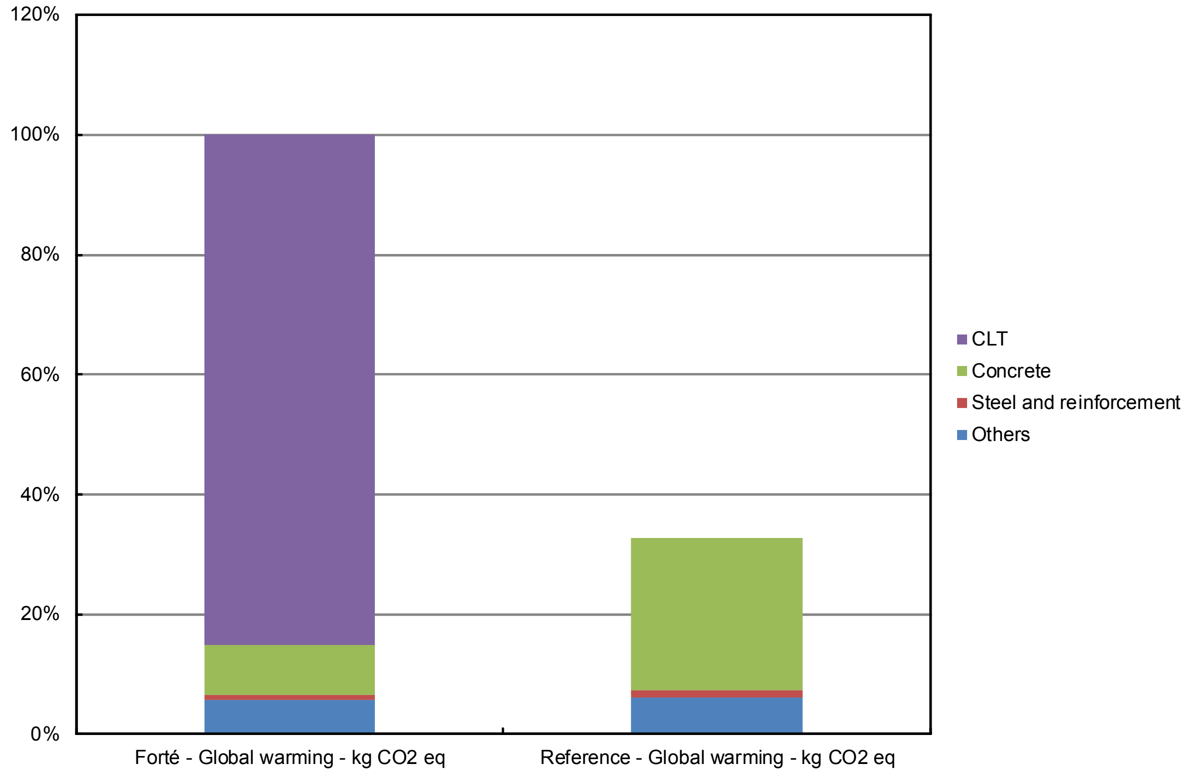
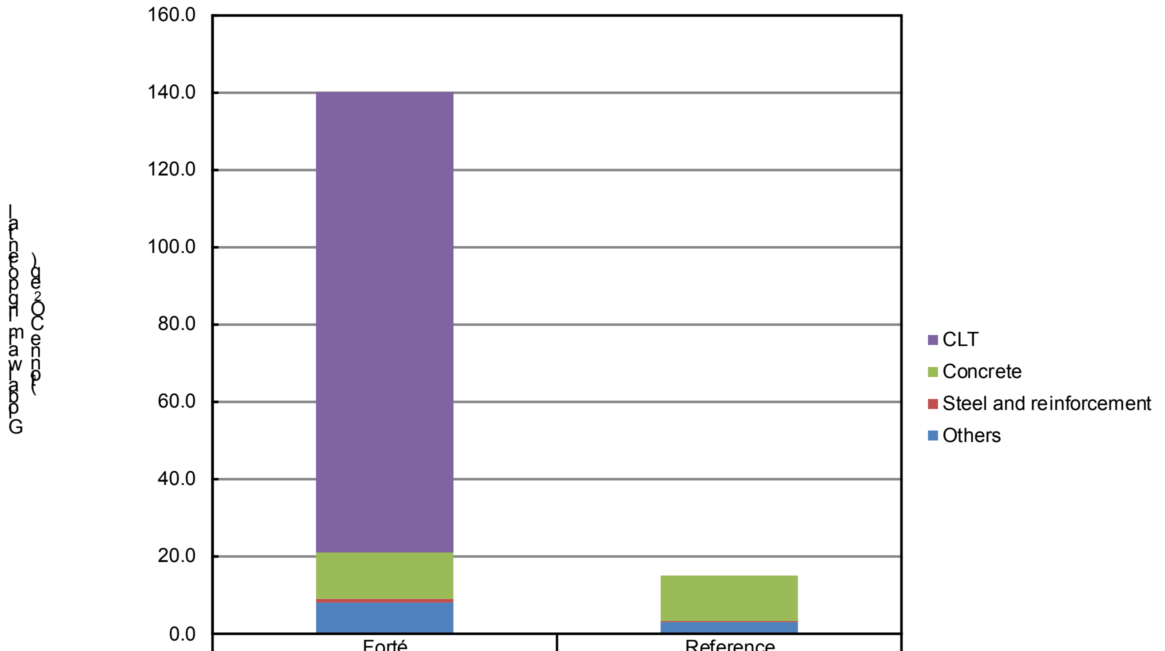


Figure 7-8: Global warming potential for transport of materials to construction site. 100%= 140.1 tonne CO_2-eq

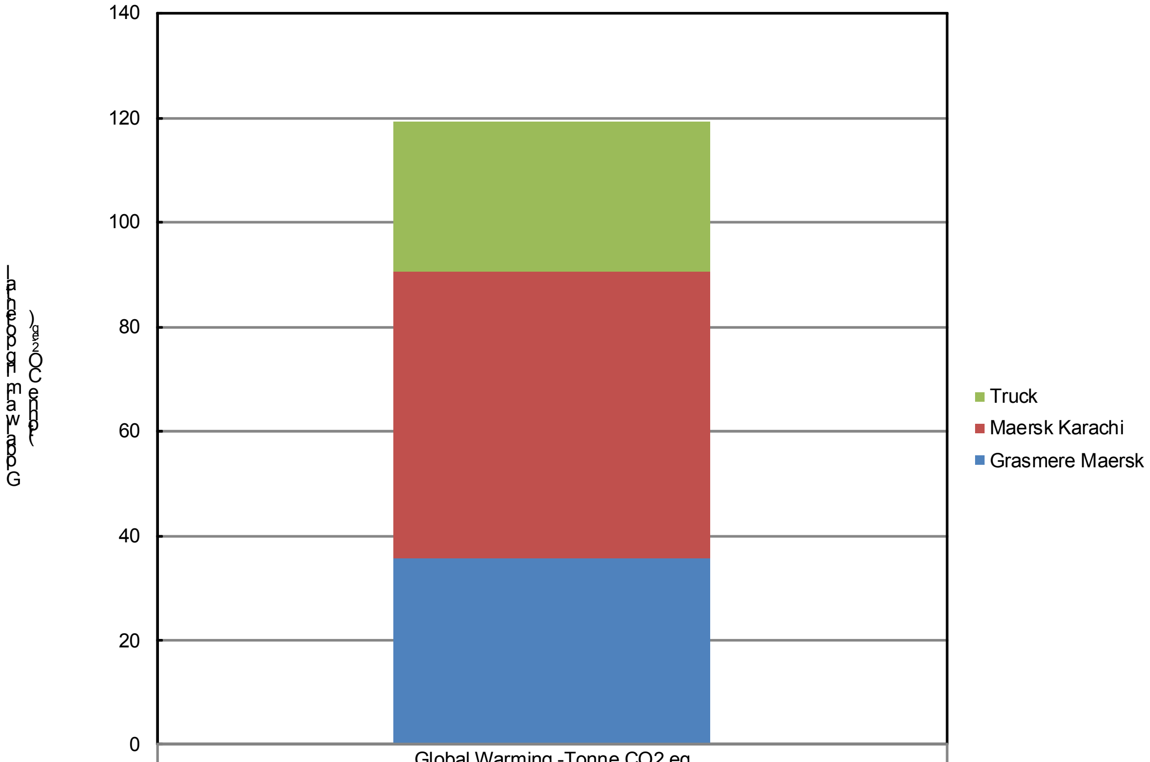


	Forté	Reference
CLT	119.2	0.0
Concrete	11.9	11.7
Steel and reinforcement	1.2	0.6
Others	7.9	2.8

Figure 7-9: Global warming potential for transport of materials to construction site.

Figure 7-10 shows that the majority of global warming potential for transport of CLT to site can be related to the shipping of the panels. The emission factors for transporting a container for a given distance on the Maersk Karachi and Grasmere Maersk container ships are of a similar magnitude.

The transport by truck also contributes a significant portion. Note that the total transport impacts only contribute, at most, 2.8% to any environmental impact of the Forté building, and therefore the influence of the individual transport steps is very small from a full life cycle perspective.

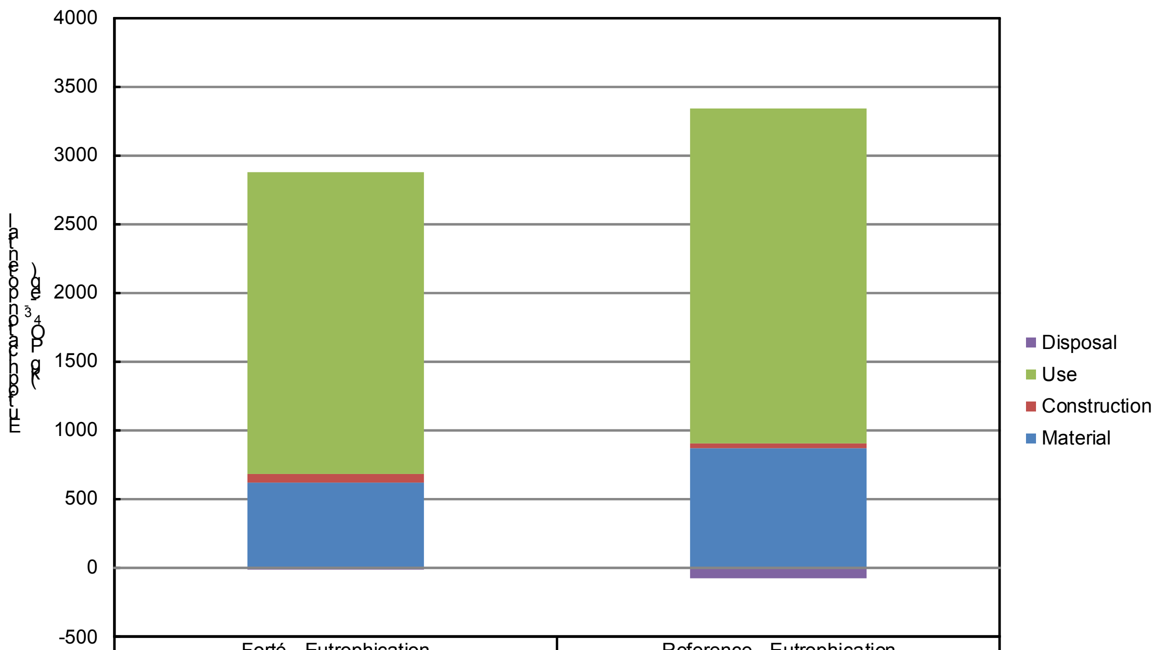


	Global Warming -Tonne CO2 eq
Truck	28
Maersk Karachi	55
Grasmere Maersk	36

Figure 7-10: Global warming potential of transport of CLT to construction site (in tonne CO_2-eq).

7.2.2 Eutrophication potential

The eutrophication potential results are shown in Figure 7-11. The impacts for the reference building are higher than for the Forté building. Especially the impacts during the materials and disposal phase are higher. The eutrophication emissions for materials are higher due to increased phosphate emissions from mainly steel making, and to a lesser extent from nitrogen oxides emissions from concrete, steel and insulation manufacture. The eutrophication potential from the transport of materials and construction is higher for the Forté, again due to increased transport (mainly due to CLT) compared to the reference building. The eutrophication potential at the end of life for the reference building are driven by ammonium ion emissions from the landfill of polyurethane.

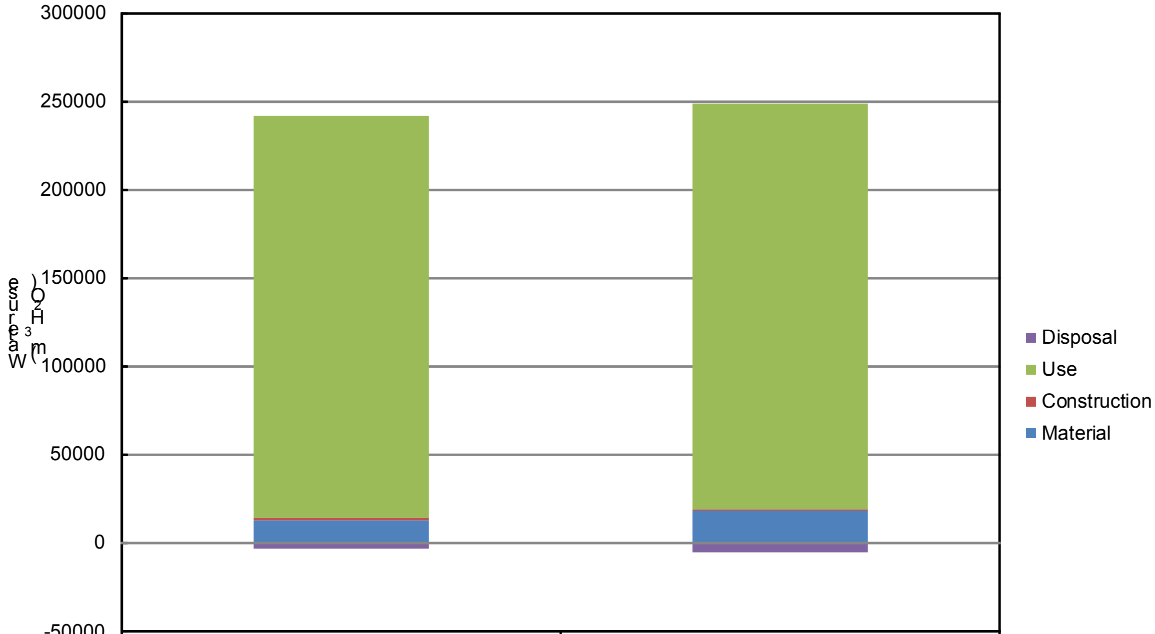


	Forté - Eutrophication	Reference - Eutrophication
Disposal	-19.61	-82.63
Use	2197.07	2444.90
Construction	67.82	31.45
Material	614.22	869.99

Figure 7-11: Eutrophication potential for the reference and Forté building in kg PO_4^{3-} (phosphate) equivalents.

7.2.3 Water use

Figure 7-12 shows the water use impacts. For both buildings, most of the water is used during the use phase, mainly as direct water use in the building. The water use in the materials phase is related to the production of a large variety of materials and their precursors, such as steel, concrete and insulation.

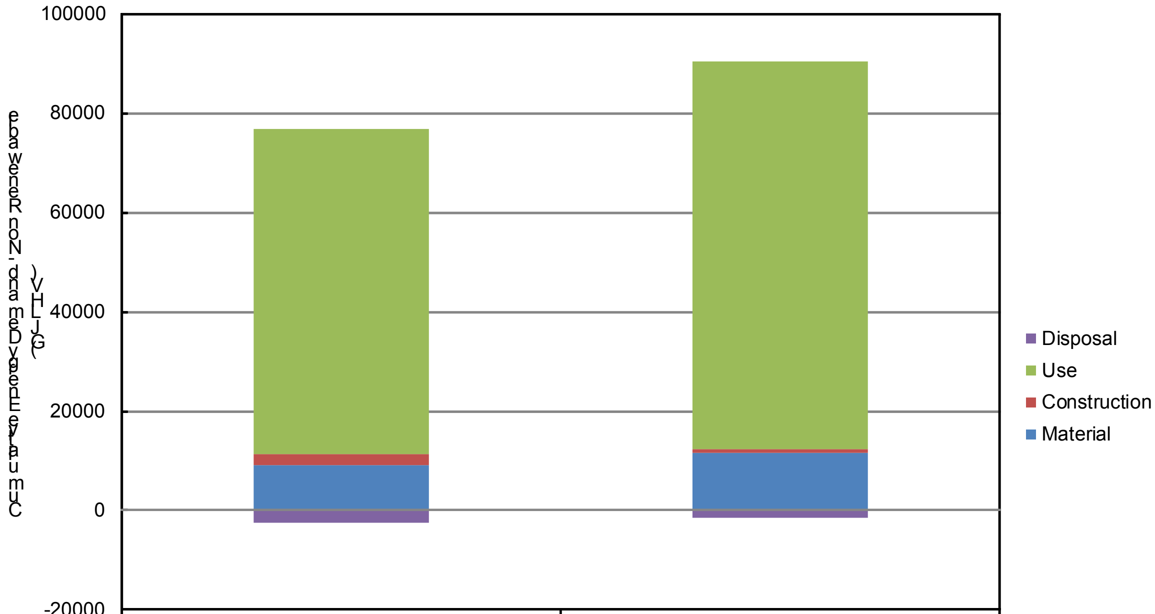


	Forté - Water use	Reference - Water use
Disposal	-3650	-5094
Use	228265	230272
Construction	928	572
Material	12932	18219

Figure 7-12: Water use for the reference and Forté building in m^3 of water

7.2.4 Non-renewable Cumulative Energy Demand

The non-renewable cumulative energy demand (shown in Figure 7-13), is driven by the use phase and relates to the embodied energy of the fossil fuels required to deliver energy during the use phase (e.g. coal). This indicator is only a prelude to environmental impacts. For greenhouse-intensive use phases, the non-renewable cumulative energy demand indicator typically follows a similar trend to greenhouse gas emissions.

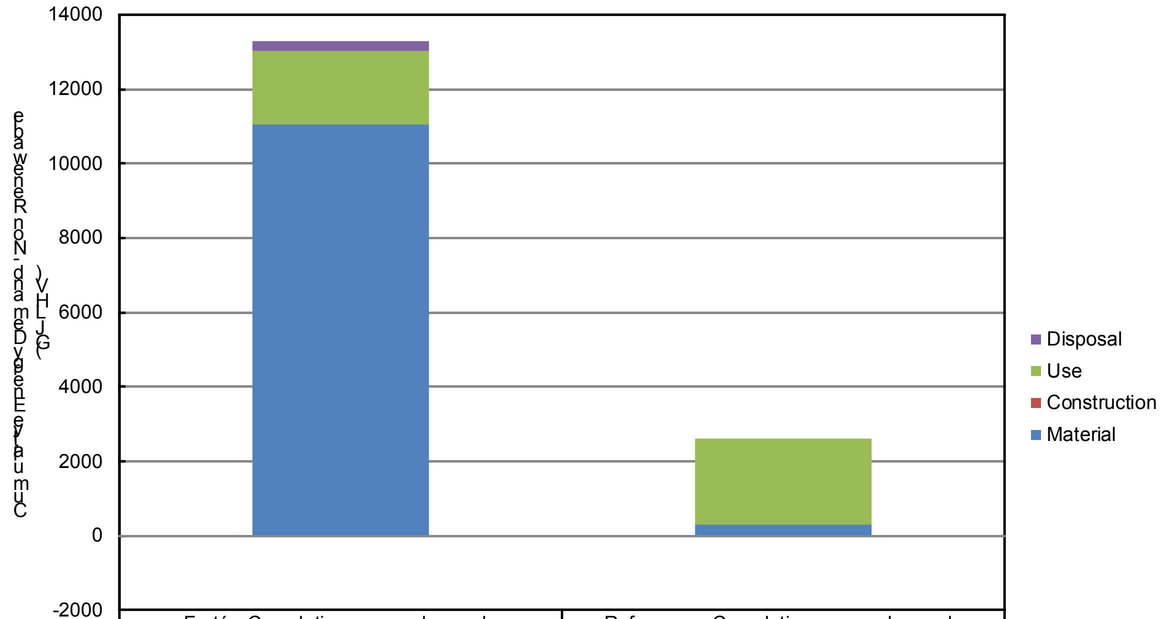


	Forté - Cumulative energy demand - non-renewable	Reference - Cumulative energy demand - non renewable
Disposal	-2397	-1422
Use	65624	78191
Construction	2096	747
Material	9202	11533

Figure 7-13: Non-renewable Cumulative Energy Demand for the Reference and Forté building in GJ LHV

7.2.5 Renewable Cumulative Energy Demand

The renewable cumulative energy demand, Figure 7-14, is higher for the Forté building than the reference building. The renewable cumulative energy demand for the Forté building is driven by the renewable energy embodied in the wood in the CLT panels.



	Forté - Cumulative energy demand - renewable	Reference - Cumulative energy demand - renewable
Disposal	260	-9
Use	1977	2324
Construction	4	1
Material	11041	288

Figure 7-14: Renewable Cumulative Energy Demand for the Reference and Forté building in GJ LHV

7.3 Sensitivity analysis

7.3.1 Lifetime assumption

There is no conclusive evidence in the literature to indicate a difference in lifetime between a CLT building and one of reinforced concrete construct. The lack of stock of existing and demolished CLT buildings means that a qualified, substantiated assessment of lifetime is not possible.

In this study, a reference lifetime of 50 years was chosen as a basis for comparison. In this sensitivity analysis this challenged by changing this lifetime from 0-100 years. The global warming potential of the buildings are shown in Figure 7-15. In Figure 7-15, beyond a lifetime of approximately 10 years, the reference building always has a higher impact than the Forté building. When the use phase is excluded (at a building life of 0 years), the global warming potential comparison between Forté and the reference building is sensitive to the sequestration assumption; when sequestration is included, Forté has lower impact, while if sequestration is excluded, the reference building has the lower impact. Also, because the energy usage for the reference building is higher, the gradient of the trend line is higher for the reference building (meaning that if the lifetime of the building increases the relative difference becomes bigger).

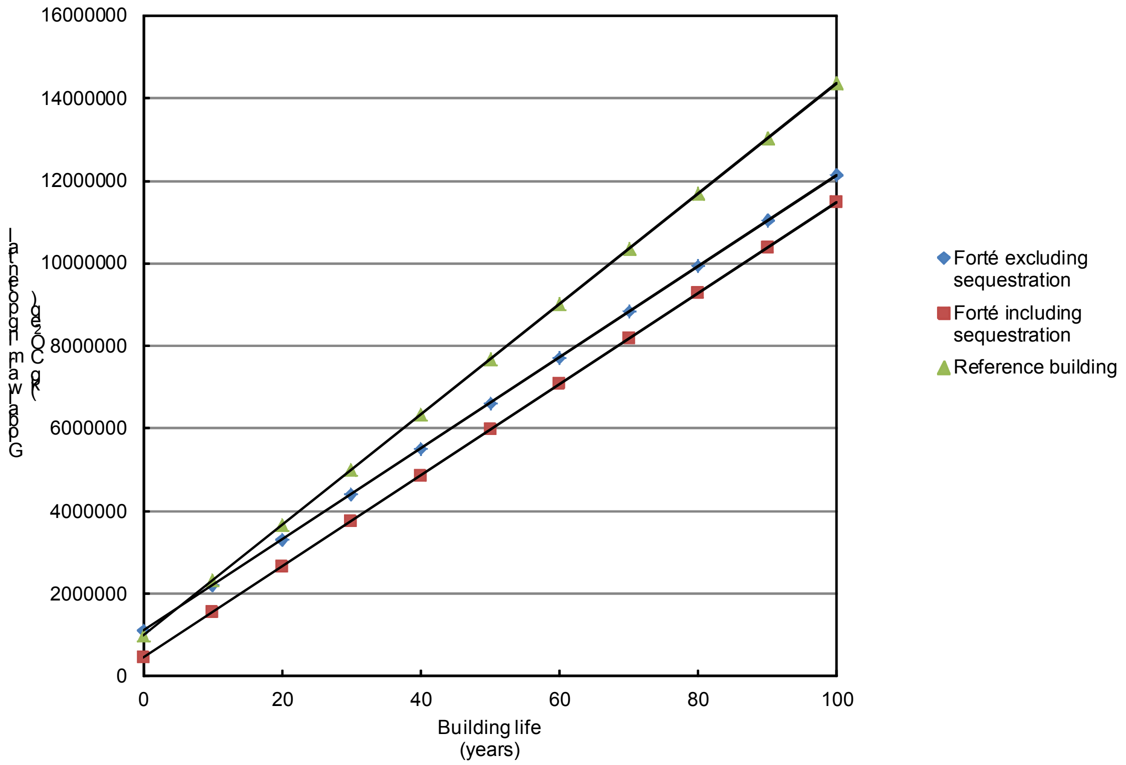


Figure 7-15: Impacts on global warming potential (y-axis) when lifetime is varied (x-axis). The trend lines and the related formulas are also shown.

If the impacts on global warming potential are plotted per year Figure 7-16, one can see that the impact decreases if the building life time is increased; the building materials impacts are distributed over a larger number of years and thus decrease in importance, rather the operational energy use becomes more important. As the modelled life time of the building is increased, the global warming potential for the Forté building including and excluding sequestration converge. The Forté building however always has a lower impact than the reference building, due to a lower operational energy use.

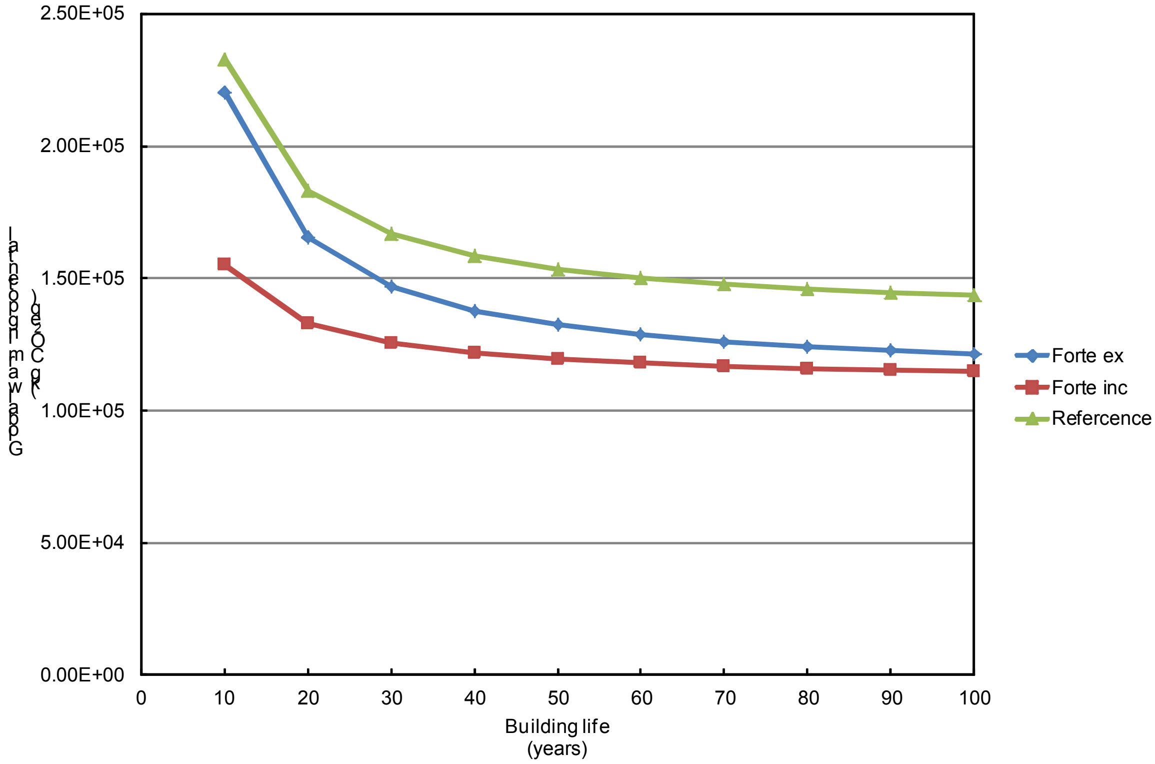


Figure 7-16: Global warming potential, in kg CO_2 equivalent per year, if the life time of the building is varied.

7.3.2 Changing the transport distances

As reported in Sections 5.3.2 and 5.4.2, a number of transport distances were estimated. For the main construction materials (CLT, Concrete), the transport distance were based on data supplied by Lend Lease. This sensitivity analysis will investigate if the transport distance assumptions for other materials affect the outcome of the study. From Figure 7-17 it can be concluded that the model shows only little sensitivity to the transport distance assumption. The global warming potential increases when transport distance is increased (as to be expected), however the magnitude is small compared to the overall impacts.

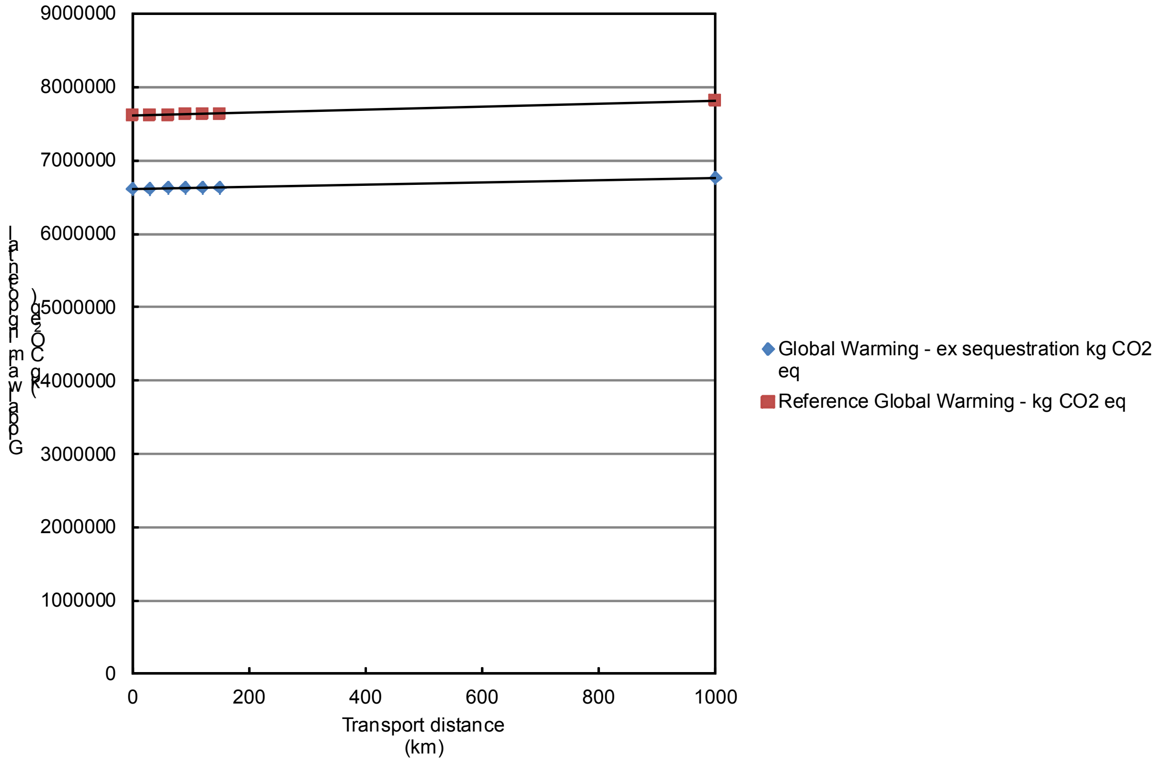


Figure 7-17: Global warming potential in kg CO_2-eq (y-axis) for varying transport distances in km (x-axis).

7.3.3 Construction impacts

As reported in the inventory section of the report, only a part of the construction impacts were included in the model (the excavation of sand and dirt from site). As no data was available on other construction works this was omitted from the model. To assess if the inclusion of these activities would influence the results of the study this sensitivity study has been undertaken. The excavator model was used as a proxy for the other construction activities (e.g. crane operation, use of power tools onsite etc.). The excavator use was increased a 100-fold to crudely model the other construction activities. In Table 7-2, the studies standard model impacts are shown next to the outcomes of this sensitivity study (relative to the highest impacts in the standard model). Therefore it can be concluded that the exclusion of construction activities does not influence the overall outcomes of the study.

Table 7-2: Sensitivity for construction impacts

Impact category	Unit	Base Case Forté	100x construction efforts - Forte	Base Case Reference	100x construction efforts - reference
Global Warming - ex sequestration	kg CO_2 eq	100.00%	115.08%	100.00%	105.84%
Global Warming - inc sequestration	kg CO_2 eq	100.00%	127.55%	100.00%	105.84%
Eutrophication	kg PO_4^{3-} eq	100.00%	114.14%	100.00%	117.96%
Water Use	m^3 H2O	100.00%	102.30%	100.00%	100.02%
Cumulative energy demand - non renewable	MJ LHV	100.00%	119.49%	100.00%	107.31%
Cumulative energy demand - renewable	MJ LHV	100.00%	19.61%	100.00%	100.08%

It is likely, however, that the construction impacts for Forté will be lower than for the reference building, given the reduced construction times and the subsequent environmental impacts associated with the construction activity (e.g. reduced crane operation etc.).

7.3.4 Degradation in landfill

The results of the degradation sensitivity for greenhouse emissions are reported in Figure 7-18. In this figure, higher degradation (DOC_f) values result in higher greenhouse impacts, due to methane emissions. Only at high DOC_f values (of about 0.75) are the life-cycle greenhouse impacts of Forté higher than the reference building. This DOC_f value is 50% higher than the default IPCC value (of 0.5) and are not consistent with other reported degradation values (refer Section 5.3.4.1). As such, these values are considered to be not reflective of what will likely occur in landfill. In this regard, it is considered that the comparative conclusions are likely to be unaffected by the choice of DOC_f values (assuming all other variables are fixed).

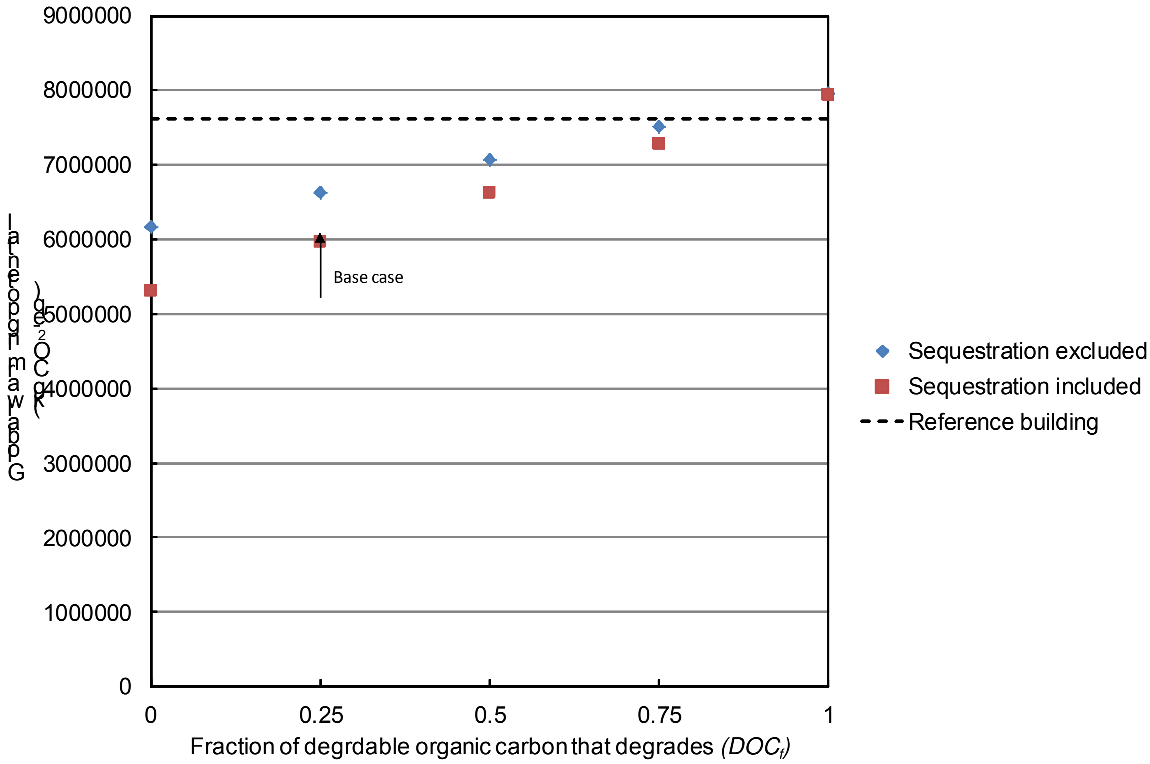


Figure 7-18: Global warming potential in kg CO_2-eq for varying DOC_f values for the disposal of wood in landfill. The base case DOC_f value for the study is 0.25.

7.3.5 Recycling of wood

The sensitivity assessment for the inclusion of recycling of wood is reported in Figure 7-19 and Table 7-3. The inclusion of recycling of the wood products (CLT and glulam), reduces global warming potential and eutrophication potential, relative to the base case. If recycling is included, the global warming potential reductions for Forté, relative to the reference building, are between 15% (excluding sequestration) and 25% (including sequestration). The reductions in impacts are the result of avoiding biogenic methane emissions from landfill and are offset by impacts associated with wood reprocessing.

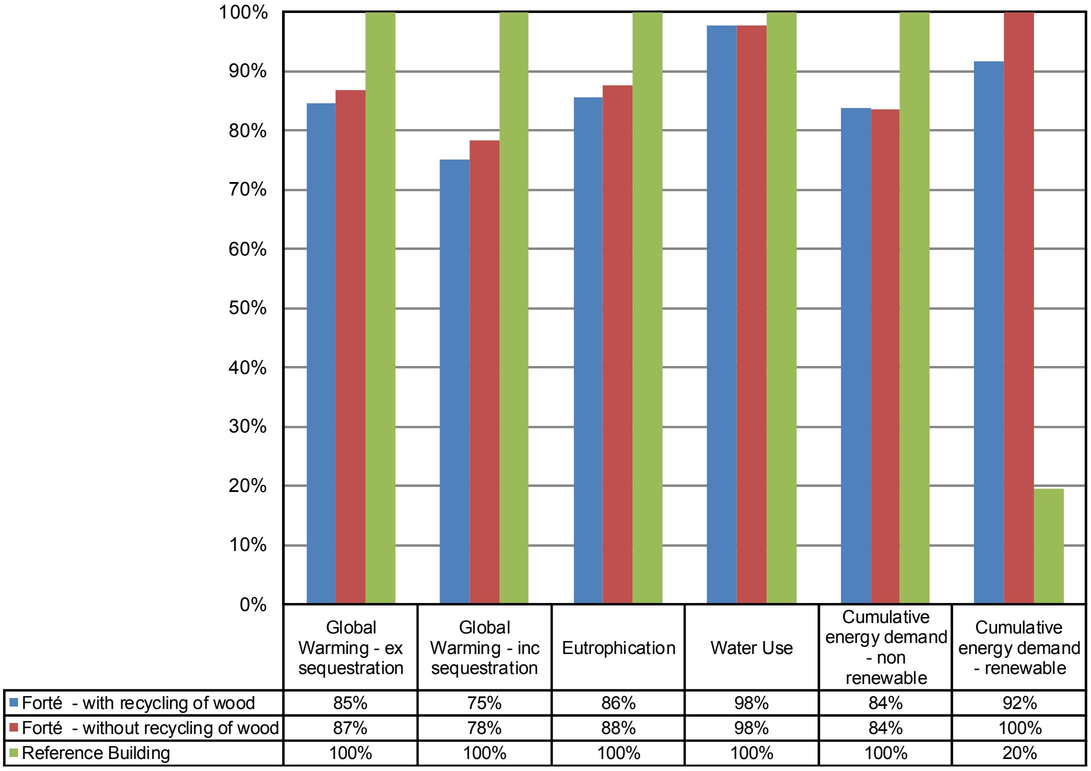


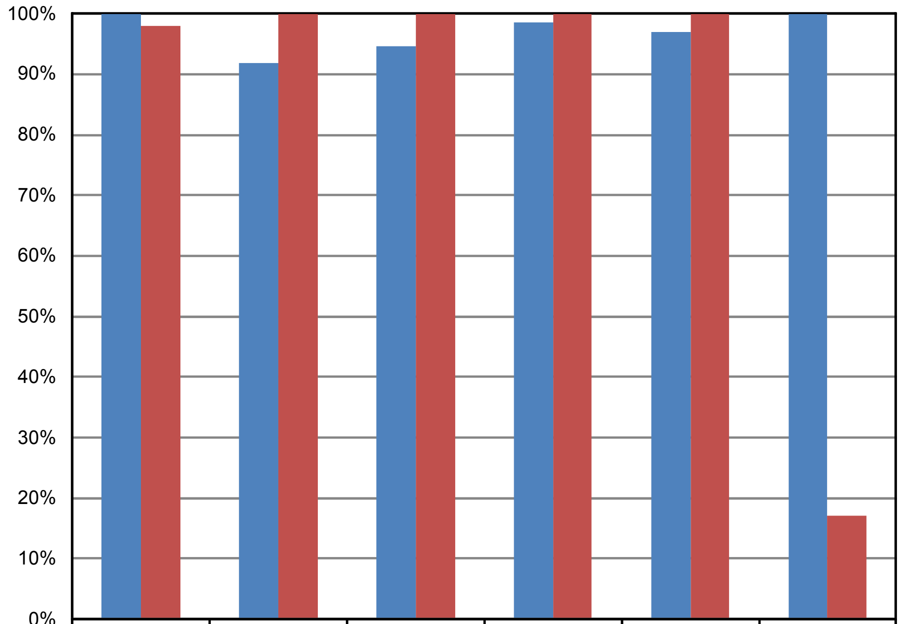
Figure 7-19: Relative impacts for the Forté building and Reference building, by category, when recycling of the wood products is included (blue). Scaled to the highest impact for that specific category.

Table 7-3: Sensitivity for recycling of wood

Impact Category	Forté - with recycling of wood	Forté - without recycling of wood	Reference building
Global Warming - ex sequestration - tonne CO_2 eq	6442	6618	7616
Global Warming - inc sequestration - tonne CO_2 eq	5718	5970	7614
Eutrophication - kg PO_4^{3-} eq	2797	2860	3264
Water Use - m^3 H_2O	238500	238476	243969
Cumulative energy demand - non-renewable - GJ LHV	74558	74525	89049
Cumulative energy demand - renewable - GJ LHV	12177	13283	2602

7.3.6 Same HVAC and lighting systems

It might be argued that similar HVAC and lighting systems are installed on other new building stock. In this sensitivity assessment, results are based on the same lighting and HVAC systems installed in the reference building. The results of this sensitivity are reported in Figure 7-20. All relative comparisons hold true, except for global warming potential, the conclusions of which are sensitive to the inclusion or exclusion of carbon sequestration credits. These results indicate that the comparative assertions regarding greenhouse impacts are limited by both the selection of the HVAC and lighting systems for the reference building, and the inclusion or exclusion of carbon sequestration credits. This finding has been included as a limitation of the report.



	Global Warming - ex sequestration	Global Warming - inc sequestration	Eutrophication	Water Use	Cumulative energy demand - non renewable	Cumulative energy demand - renewable
Forté Building	100%	92%	95%	99%	97%	100%
Reference Building	98%	100%	100%	100%	100%	17%

Figure 7-20: Relative impacts for the Forté building and Reference building, by category, when the HVAC and lighting systems in the reference building are the same as in Forté. Scaled to the highest impact for that specific category.

7.4 Validation

In this section, the results and some of the critical data points are validated by comparing them to literature sources. The operational heating and cooling energy requirements, the energy use from lighting is being compared to known benchmarks. Also some of the more important construction materials will be evaluated to equivalent products from other studies.

7.4.1 Validation of use phase energy requirements

7.4.1.1 Heating and cooling - Star rating

The Apache model is validated against an Accurate assessment. The star rating for the apartments was determined using the applicable energy use bands for Melbourne and the energy use per square meter from the Apache assessment. Also a separate Accurate assessment was undertaken. These two analyses yielded a consistent result, showing similar trends and magnitudes.

Table 7-4 shows the star ratings per apartment and the average star rating for the buildings based on Apache results. The reference building is compliant to BCA 2011 - 6 star. The Forté building has, in total, a higher star rating, which was expected too, as this building goes beyond this minimum compliance.

Table 7-4: Star rating for the Forté and reference buildings, per apartment and overall.

Forté Apartment number	Star rating	Reference Apartment number	Star rating
Apt 11	6.8	Apt 11	6
Apt 12	6.8	Apt 12	6
Apt 13	6.2	Apt 13	5.6
Apt 21	7	Apt 21	6.2
Apt 22	7	Apt 22	6.2
Apt 23	6.5	Apt 23	5.8
Apt 31	7	Apt 31	6.3
Apt 32	7	Apt 32	6.3
Apt 33	6.5	Apt 33	5.9
Apt 41	7	Apt 41	6.3
Apt 42	7	Apt 42	6.3
Apt 43	6.6	Apt 43	5.8
Apt 51	7	Apt 51	6.3
Apt 52	7.1	Apt 52	6.4
Apt 53	6.6	Apt 53	5.8
Apt 61	7	Apt 61	6.3
Apt 62	7.1	Apt 62	6.4
Apt 63	6.6	Apt 63	5.8
Apt 71	7.1	Apt 71	6.3
Apt 72	7.1	Apt 72	6.4
Apt 73	6.4	Apt 73	5.5
Apt 81	6	Apt 81	5.3
Apt 82	6	Apt 82	5.3
Total	6.8	Total	6

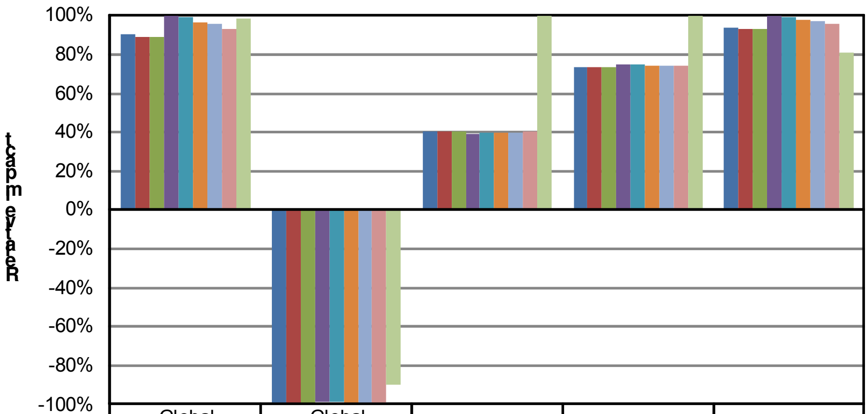
7.4.1.2 Energy use for lighting

The lighting energy use for Forté and the reference buildings was 31.09 MWh/yr and 45.22 MWh/yr, respectively. These values are an aggregate of the energy use for lighting in the commercial and dwelling areas, as well as in common areas such as corridors and plant rooms. The values correspond to a calculated energy consumption rate of 25.8 kWh/m^2/yr and 17.7 kWh/m^2/yr he values are higher than the Green Building Council of Australia's (GBCA, 2009) benchmarks for dwellings (12.7 kWh/m^2/yr) but lower than the benchmark figure for communal areas (36.8 kWh/m^2/yr). Although the retail space only accounts for ~11% of total lighting area, the energy density of the retail space is much higher (22 W/m^2) than for the residential space (between 3-5 W/m^2, refer Table 5-30 and Table 5-37). As such, the commercial lighting area contributes to a proportion of lighting energy impacts which are not linear with lighting area. For example, full occupancy and lighting energy inputs are assumed, the retail space would account for 36% of power requirements. The higher consumptions values in this study, than for the GBCA dwellings benchmark, are the result of this high demand for retail lighting.

7.4.2 CLT compared to Ecoinvent pre-stressed laminated timber

The Ecoinvent database does not contain inventories for cross laminated timber. However, there is a process for pre-stressed laminated timber: "Laminated timber element, transversally pre-stressed for outdoor use, at plant/RER U" (Werner et al., 2007). The process is modified to match the CLT process more closely by removing steel elements from the inventory and by replacing hardwood inputs with softwood.

Figure 7-21 shows the impacts of the modified Ecoinvent process and the CLT panels utilised in this study. It can be seen that the global warming potential are very similar. There are some minor discrepancies between the impacts on eutrophication and to a lesser extent water use (no valid conclusions can be drawn for land use and fossil fuels as these indicators are not supported by CLT dataset). The main driver for eutrophication in the Ecoinvent process is the disposal of spoil from lignite mining (used in German electricity production). As the KLH process is based in Austria, with a much less eutrophication intense grid, the difference could be explained by the difference in electricity inputs between the Ecoinvent process and the KLH process inputs for CLT. Likewise for water use; the UCTE grid (utilised in the Ecoinvent process), has higher water intensity than for the Austrian grid. Strong conclusions cannot be drawn on these differences due to the aggregated nature of the environmental product declaration data.



	Global Warming - IPCC 2007 - without sequestration/ uptake - kg CO2 eq	Global Warming - IPCC 2007 - with sequestration/ uptake - kg CO2 eq	Eutrophication - kg PO4--- eq	Water Use - M3 H2O	Cumulative energy demand - non renewable - MJ LHV
CLT, 090 mm thickness, 3 layer	90%	-100%	41%	74%	94%
CLT, 094 mm thickness, 3 layer	89%	-100%	41%	74%	93%
CLT, 095 mm thickness, 3 layer	89%	-100%	41%	74%	93%
CLT, 125 mm thickness, 5 layer	100%	-99%	39%	75%	100%
CLT, 128 mm thickness, 5 layer	99%	-99%	39%	75%	100%
CLT, 140 mm thickness, 5 layer	97%	-99%	40%	74%	98%
CLT, 145 mm thickness, 5 layer	96%	-99%	40%	74%	97%
CLT, 158 mm thickness, 5 layer	93%	-100%	40%	74%	96%
Laminated timber element, for outdoor use, at plant/RER U all softwood steel elements removed	99%	-90%	100%	100%	81%

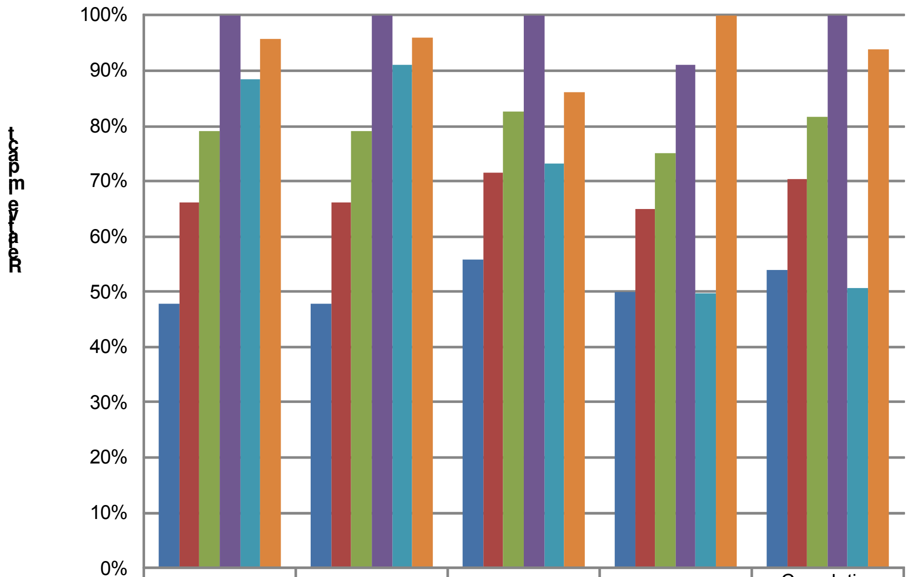
Figure 7-21: CLT panels utilised in this study compared to the modified Ecoinvent process (compared on volumetric basis).

Figure 7-21 compares the different panels and laminated timber on a volumetric basis (1 m^3), as the laminated timber element is only available in that unit. The different CLT panels are scaled to match 1 m^3 of product (e.g. 8 m^2 of 125 mm panel = 1 m^3 of CLT panel). One could interpret this as that 8 x 1m^2 panels need to be stacked to create 1 m^3 of product.

It may seem counter-intuitive that the 125 mm panel has the highest impact of all the CLT panels when compared on a volumetric basis. This impact can be explained by the number of bonds per m^3; 125mm panel has the most 'bonds' per m^3 because it is the thinnest panel with 5 layers. As thickness is irrelevant (all panels are scaled to the same volume), the number of bonds determines the relative difference between CLT panels.

7.4.3 Concrete compared to AUPLCI and Ecoinvent

Figure 7-22 shows the concrete mixes used in this study yields similar results as the Ecoinvent and AUPLCI processes for most impact categories. The impact of which are in the range between the Australian and Ecoinvent mixes. Note that for global potential, the concrete mixes in this study generally have a lower impact; due to high slag contents and reduced impacts stemming from GP cement. The 40 MPa mix is the most used concrete mix in this study.



	Global Warming - ex sequestration - kg CO2 eq	Global Warming - inc sequestration - kg CO2 eq	Eutrophication - kg PO4--- eq	Water Use - M3 H2O	Cumulative energy demand - non renewable - MJ LHV
Concrete, 15MPa, at batching plant/AU U	48%	48%	56%	50%	54%
Concrete, 32MPa, at batching plant/AU U	66%	66%	72%	65%	70%
Concrete, 40MPa, at batching plant/AU U	79%	79%	83%	75%	82%
Concrete, 50MPa, at batching plant/AU U	100%	100%	100%	91%	100%
Concrete, normal, at plant/CH U	88%	91%	73%	50%	51%
Concrete, 25MPa, at batching plant/AU U	96%	96%	86%	100%	94%

Figure 7-22: Comparison of the concrete used in this study to the Ecoinvent process and AUPLCI process.

7.4.4 Concrete compared to other studies

A study undertaken by the Centre for Design for Grocon in 2012 analysed a number of 40MPa concrete blends (Crossin, 2012). The studied impacts categories were limited to global warming potential and embodied energy. Figure 7-23 shows that the 40 MPa concrete blend in this study lies in between blends 4 and 5 from the Grocon study. The details regarding the design of these two Grocon mixes are not publically available, however the differences in impacts of the 40 MPa blend used in this study, and those of the Grocon study is likely explained by variations in types and quantities of cementitious materials, including fly-ash and ground-granulated blast furnace slag (GGBFS). Flower and Sanjayan (2007) reported an emission factor of 0.33 tonne CO_2-eq/m^3 for 40 MPa precast panels in Victoria, however the GGBFS content of this mix was not reported. A presentation by the same authors indicated an emission factor of ~0.21 tonne CO_2-eq/m^3 for 40 MPa precast concrete, with a GGBFS content of 65%. This value of ~0.21 tonne CO_2-eq/m^3 is consistent with that used in this study (222 kg CO_2-eq/m^3). Any further comparisons to the outcome from the study by Flower and Sanjayan is not appropriate, as the allocation approach taken by Flower and Sanjayan is different to that in this study.

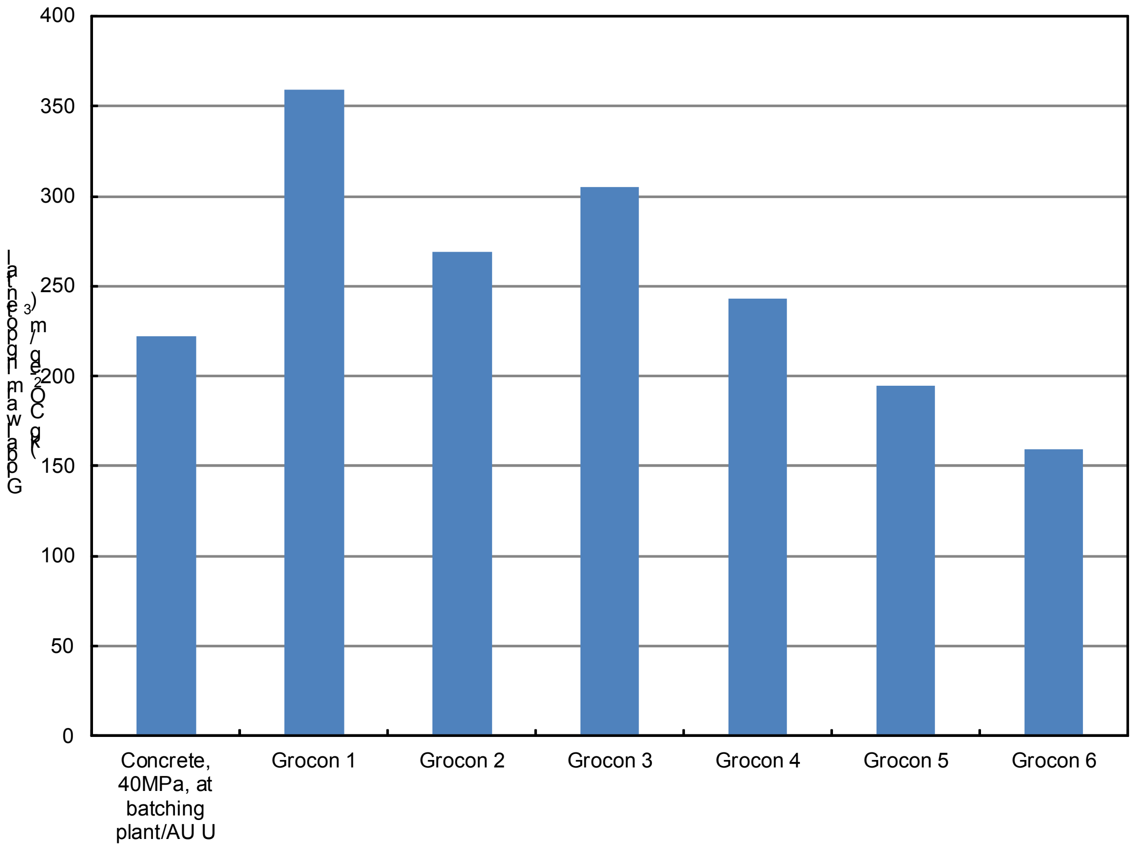
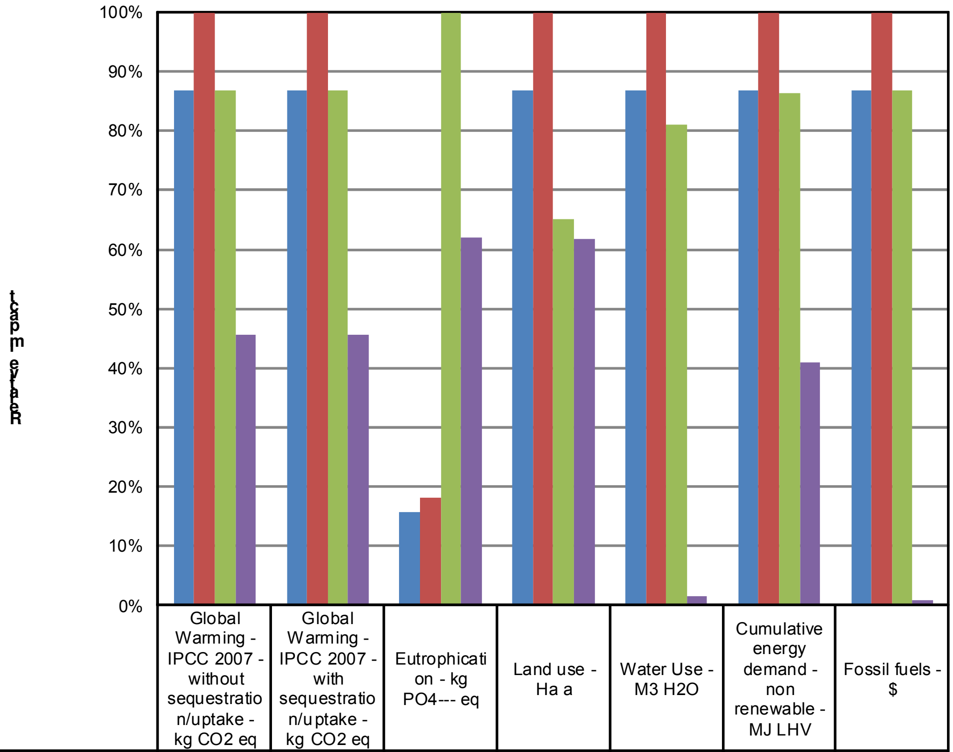


Figure 7-23: Global warming potential for 6 Grocon concrete blends and the 40MPa blend utilised in this study.

7.4.5 Container freight compared to AUPLCI and Ecoinvent data

The models used in this study are volume based (volume of a shipping container), while standard models from AUPLCI and Ecoinvent are mass based. Therefore the models are compared by either the volume shipped (50 TEU) or the total mass (501.92 tonne) of the CLT panels.

Figure 7-24 shows that the impacts related to shipping used in this study are within the range of the AUPLCI process, while the Ecoinvent process has considerably lower environmental impacts. An exception to this trend is the impacts on Eutrophication, the reason for this difference is not known, but does not affect the outcome of the study.



	Global Warming - IPCC 2007 - without sequestration/uptake - kg CO2 eq	Global Warming - IPCC 2007 - with sequestration/uptake - kg CO2 eq	Eutrophication - kg PO4--- eq	Land use - Ha a	Water Use - M3 H2O	Cumulative energy demand - non renewable - MJ LHV	Fossil fuels - $
Grasmere Maersk	87%	87%	16%	87%	87%	87%	87%
Maersk Karachi	100%	100%	18%	100%	100%	100%	100%
Shipping, International Freight/AU U	87%	87%	100%	65%	81%	86%	87%
Transport, transoceanic freight ship/OCE U	46%	46%	62%	62%	1%	41%	1%

Figure 7-24: Models for specific ships used in this study compared to standard shipping models from AUPLCI and Ecoinvent.

7.4.6 Uncertainty results

7.4.6.1 Comparative analysis

Table 7-5 shows the results of the Monte Carlo uncertainty analysis comparing Forte (Model A) to the reference building (Model B). It shows that the results are robust; impacts of the reference building are consistently higher than CLT for all runs, except for renewable energy demand.

Impact category	Instances when Forte impacts were higher than for the reference building	Mean	Median	SD	CV (Coefficient of Variation)	0.025	0.975	Std.err.of mean
Global Warming - ex sequestration	0.0%	-998000	-996000	27000	-0.0271	-1050000	-946000	-0.000857
Global Warming - inc sequestration	0.0%	-1640000	-1640000	26700	-0.0162	-1700000	-1590000	-0.000513
Eutrophication	0.0%	-403	-381	108	-0.269	-657	-250	-0.00852
Water Use	0.0%	-5490	-5480	423	-0.077	-6350	-4660	-0.00243
Cumulative energy demand - non renewable	0.0%	-14500000	-14500000	413000	-0.0284	-15400000	-1.4E+07	-0.000899
Cumulative energy demand - renewable	100.0%	10700000	10600000	1E+06	0.12	8350000	1.4E+07	0.0038

Table 7-5: Results of uncertainty analysis; 1000 runs. B > A for all runs and all impact categories.

7.5 Data quality assessment

Full details of the data sources and the uncertainty of the information are detailed in the life cycle inventory. The qualitative assessment of completeness, representativeness, consistency and reproducibility are based on expert judgement of the dataset, including databases and are provided in Table 7-6. Table 3-1 stated the minimum level of data quality that was required to be able to fulfil the study's goals, Table 7-6 assesses if these minimum requirements were met. Overall, it was considered that life cycle inventory data was complete and representative of the systems considered, and that the quality of this data was sufficient to fulfil the goal and scope of the study.

Table 7-6: Data quality assessment (very poor – poor – average – good – very good)

Data description	Cross laminated timber manufacture	Trans-oceanic container transport	Concrete manufacture	Steel manufacture	Transport of concrete and steel	Plasterboard manufacture	Window + window frame manufacture	Rain screen cladding manufacture	Disposal of building materials	Material properties (Heat resistance and thermal mass)	Wall and floor designs	Building plans	Type and efficiency of heating and cooling appliances
Time related coverage	Very good	Very good	Average	Average	Average	Average	Average	Average	Average	Very good	Very good	Very good	Very good
Geographical coverage	Very good	Very good	Good	Average	Good	Good	Good	Good	Good	Very good	Very good	Very good	Very good
Technology coverage	Very good	Very good	Good	Good	Good	Good	Good	Good	Good	Very good	Very good	Very good	Very good
Precision	Very good	Very good	Good	Good	Good	Good	Good	Good	Good	Very good	Very good	Very good	Very good
Completeness	Very good	Very good	Good	Good	Good	Good	Good	Good	Good	Very good	Very good	Very good	Very good
Representativene ss	Very good	Very good	Good	Good	Good	Good	Good	Good	Good	Very good	Very good	Very good	Very good
Consistency	Very good	Very good	Good	Good	Good	Good	Good	Good	Good	Very good	Very good	Very good	Very good
Reproducibility	Very good	Very good	Good	Good	Good	Good	Good	Good	Good	Very good	Very good	Very good	Very good
Primary Sources of data	Very good	Very good	Average	Average	Good	Average	Average	Average	Good	Very good	Very good	Very good	Very good
Uncertainty	Good	Good	Average	Average	Average	Average	Average	Average	Average	Good	Good	Good	Good

8 Conclusions

1. The Forté building has lower environmental impact on all assessed categories, except renewable energy demand, compared to the reference building.
   a. If carbon sequestration is included the Forté building's impacts are 22% lower on global warming potential, if sequestration is not included in this indicator, Forté's impacts are 13% lower.
   b. Eutrophication potential is 12% lower for Forté when compared to the reference building.
   c. Water use is 2% lower.
   d. Non-renewable cumulative energy demand is 16% lower.
2. The reductions in environmental impacts are primarily driven by the use of more efficient HVAC and lighting systems in Forté than for the reference building.
3. The operation of the building contributes to between 75% and 96% of environmental impact, depending on the impact category and the building considered. The main drivers of impacts in the use phase are space conditioning (heating and cooling), lighting and hot water supply. Domestic water use is the main driver of water use impacts.
4. The global warming potential of the building materials (cradle to gate) for the Forté building are 30% lower than the reference building. If the materials' construction, transport and end-of-life impacts are included, the global warming potential of Forté's building materials are 15% higher (if sequestration is excluded) or 52% lower (if sequestration is included).
5. Even though the CLT is imported (whereas the reference building's materials are mostly locally produced), the Forté building still has a lower impact for materials and transport combined when compared to the reference building (which utilises concrete).

8.1 Limitations

1. There was **no building specific data** available for **hot water use**. The energy use for heating water was estimated using current literature.
2. **Limited data availability CLT**. The data in the Environmental Product Declaration (EPD) for cross-laminated timber (CLT) does not provide data to allow assessments regarding the land use, land use change or fossil fuel depletion impact indicators. These indicators could therefore not be assessed in this study.
3. There is no publically available evidence regarding the **end of life fate of CLT, including potential degradation in landfill**.
4. The comparative assertions regarding **greenhouse impacts** are sensitive to both the **selection of the HVAC and lighting systems** for the **reference building**, and the **inclusion or exclusion of carbon sequestration** credits.
5. The management of **waste produced during manufacture** has been omitted from the inventory for some materials, although this is considered not to affect the overall conclusions of this study.
6. It is not clear what **impact assessment model is used in the EPD**. This is considered to not affect the conclusions of the study considering the difference in impacts between product systems considered and the relatively limited contribution of CLT to the overall life cycle impacts.
7. **Shipping.** Two ship specific emission profiles were used to model the transport of CLT from Slovenia to Australia. However, specific information for two other ships that were used in the transport (as containers were shipped in two batches), is not available.
8. **Greenhouse impacts associated with electricity** may be under or overestimated due to possible discrepancies between actual and modelled emissions. Potential discrepancies are considered not likely to affect the direction of the conclusions relating to greenhouse impacts.
9. **Impact assessment.** In assessing potential environmental impacts, the study does not differentiate between local and global impacts. For certain environmental indicators, this can be important. LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks and, when included as a part of the LCA.
   a. The cumulative energy demand (CED) indicator does not directly relate to environmental impacts, but can be a precursor to environmental impact. In instances where fossil-based energy is used, CED can correlate to global warming potential. However, where renewable energy systems are used, CED will not correlate with any environmental

indicator.

b. The water use indicator includes the consumption of potable, process and cooling water. This consumption may impact on water quality, water depletion, and biodiversity. The water use indicator does not address issues such as the capacity of the environment from which the water was extracted to support the extraction.

10. **Impact assessment results.** The results of the study are not intended to reflect an industry-wide outcome of production in Australia, or to describe potential environmental impacts of utilising the studied products considered in all circumstances.

11. This study is intended to be used as a supporting document for decision making, and is **not intended to be the sole decision driver**. The assessment of the options considered will require consideration for a range of topics beyond the scope of this study, including economic considerations, risk, brand suitability, social aspects and implementation strategies.

9 References

9.1 Background databases utilised

Table 9-1: Background databases

Database name	Description
Australasian Unit Process Life Cycle Inventory (AUPLCI) September 2010	Australian LCA database developed from 1998 up to 2008 by Centre for Design from data originally developed with the CRC for Waste Management and Pollution Control, as part of an Australian Inventory data project. The data from this project has been progressively updated, particularly the data for metals production, energy, transport and paper and board production.
Ecoinvent 2.2	A large, network-based database and efficient calculation routines are required for handling, storage, calculation and presentation of data and are developed in the course of the project. These components partly take pattern from preceding work performed at ETH Zurich (Frischknecht & Kolm 1995).
USLCI	The Unit States life cycle inventory is a publically available database developed by the National Renewable Energy Laboratory (NREL). Various US government agencies environmental consultancies, private companies and industry associations have contributed to the inventory database.

9.2 Literature references

AGO 2004. AGO Factors and Methods Workbook. *In:* OFFICE, A. G. (ed.). Commonwealth of Australia.

ALUBOND. 2011. *Alubond specifications* [Online]. Available: http://www.alubond.com/technical-info-specifications.php [Accessed].

CARBON WAR ROOM 2011. Methodology: Shippingefficiency.org – Efficiency Rating for Existing Ships. Carbon War Room.

CITY WEST WATER 2007. Benchmarking report.

CROSSIN, E. 2012. Comparative Life Cycle Assessment of Concrete blends. Melbourne: Centre for Design, RMIT University.

CROWTHER, P. 2000. Building deconstruction in Australia. *Overview of Deconstruction in Slected Countries. CIB Rport No. 252.*

DEPARTMENT OF ALTERNATIVE ENERGY DEVELOPMENT AND EFFICIENCY Project on Studying of Energy efficiency index in rubber industry. Department of Alternative Energy Development and Efficiency, Thailand.

DOKA, G. 2009. Life Cycle Inventories of waste treatment services. econinvent report No. 13. Dübendorf: Swiss Centre for Life Cycle Inventories.

ELEAZER, W. E., ODLE, W. S., WANG, Y.-S. & BARLAZ, M. A. 1997. Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills. *Environmental Science & Technology,* 31**,** 911-917.

FLOWER, D. & SANJAYAN, J. 2007. Green house gas emissions due to concrete manufacture. *The International Journal of Life Cycle Assessment,* 12**,** 282-288.

GBCA 2009. Multi Unit Residential V1 green house gas emissions guide.

GEORGE WILKENFELD & ASSOCIATES PTY LTD 2008. Victoria's Greenhouse Gas Emissions 1990,1995,2000 and 2005 - End use allocation of emissions.

GRIFFITH, C. & PICKIN, J. 2007. Review of Methane Recovery and Flaring from Landfills. Hyder Consulting for the Australian Greenhouse Office.

HEIDRICH, C., HINCZAK, I. & RYAN, B. 2005. SCM's potential to lower Australia's greenhouse gas emissions profile. *Australasian Slag Association Conference.* Sydney.

HYDER CONSULTING PTY LTD 2011. Construction and Demolition Waste Status Report

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 2006a. ISO 14025: Environmental labels and declarations - type III environmental declarations - Principles and procedures. Geneva: International Organization for Standardization.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 2006b. ISO 14040: Environmental management - Life cycle assessment - Principles and framework. Geneva: International Organization for Standardization.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 2006c. ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and guidelinges. Geneva: International Organization for Standardization.

IPCC 2006a. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 1. General Guidance and Reporting. Kanagawa: Intergovernmental Panel on Climate Change.

IPCC 2006b. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5. Waste. *In:* EGGLESTON, S., BUENDIA, L., MIWA, K., NGARA, T. & TANABE, K. (eds.). Kanagawa: Intergovernmental Panel on Climate Change.

IPCC 2007. *Climate Change 2007: The Physical Science Basis,* Cambridge, Cambridge University Press.

KELLENBERGER, D., ALTHAUS, H., KUNNIGER, T., LEHMANN, M., JUNGBLUTH, N. & THALMAN, P. 2007. Life Cycle Inventories of Building Products - Ecoinvent report No. 7. Dubendorf.

KLH MASSIVHOLZ GMBH 2012. Environmental product declaration KLH Solid Timber Panels (Cross-laminated timber).

PORTWORLD.COM. 2011. *Portworld distance calculator* [Online]. Available: http://www.portworld.com/map/ [Accessed 1 July 2011].

SHIPPINGEFFICIENCY.ORG. 2012. *Shippingefficiency.org vessel search* [Online]. Available: http://search.shippingefficiency.org/ [Accessed].

TAYLOR, J. & WARNKEN 2008. Wood recovery and recycling: A source book for Australia. Report for Forest & Wood Products Australia. Clayton South: CSIRO Materials Science and Engineering.

U.S. ENVIRONMENTAL PROTECTION AGENCY 2006. Solid Waste Management and Greenhouse

Gasses - A Life-cycle Assessment of Emissions and Sinks. Washington DC, USA: U.S. EPA.
VICTORIAN GOVERNMENT DEPARTMENT OF SUSTAINABILITY AND ENVIRONMENT 2011. Victorian Water Accounts 2009–2010. *In:* ANDREW MACRAE (ed.). Melbourne.
WANG, X., PADGETT, J., DE LA CRUZ, F. & BARLAZ, M. 2011. Wood Biodegradation in Laboratory-Scale Landfills. *Environmental science and technology*, 6864-6871.
WEIDEMA, B. P. 2001. Avoiding Co-Product Allocation in Life-Cycle Assessment. *Journal of Industrial Ecology,* 4**,** 11-33.
WEIDEMA, B. P. 2003. Market information in life cycle assessment.
WEIDEMA, B. P. & WESNAS, M. S. 1996. Data quality management for life cycle inventoriesâ€"an example of using data quality indicators. *Journal of Cleaner Production,* 4**,** 167-174.
WERNER, F., ALTHAUS, H., KUNNIGER, T., RICHTER, K. & JUNGBLUTH, N. 2007. Life Cycle Inventories of Wood as Fuel and Construction Material - ecoinvent report no. 9. Dubendorf: Ecoinvent.
XIMENES, F. 2012. Carbon storage in engineered wood products in landfills. NSW Department of primary industries.

10 LCA Methodology

The following sections provide a brief description of the LCA methodology. The most important terminology is explained, as well as how to interpret outcomes of the assessment.

LCA is the process of evaluating the potential effects that a product, process or service has on the environment over the entire period of its life cycle. Figure 5-1 illustrates the life cycle system concept of natural resources and energy entering the system with products, waste and emissions leaving the system.

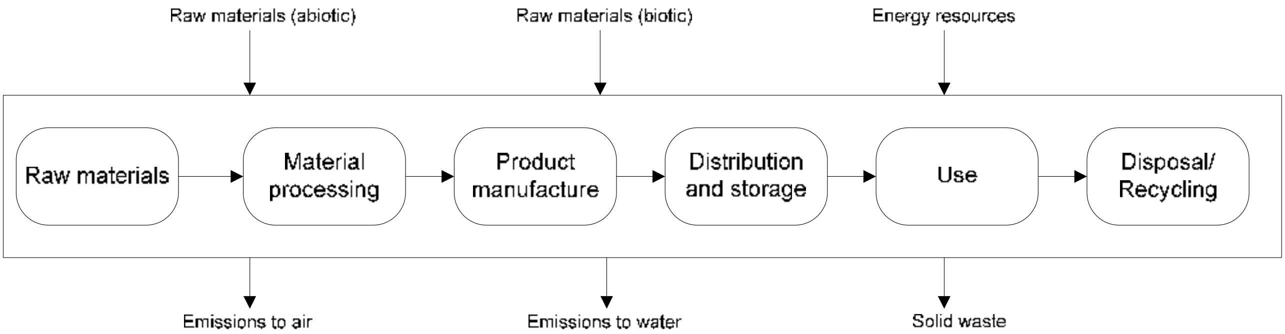


Figure 10-1 Life cycle system concept the figure

The International Standards Organization (ISO) defines LCA as:

"[A] Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its lifecycle" ((International Organization for Standardization, 2006b) pp.2).

The technical framework for LCA consists of four components, each having a very important role in the assessment. They are interrelated throughout the entire assessment and in accordance with the current terminology of the International Standards Organisation (ISO). The components are goal and scope definition, inventory analysis, impact assessment and interpretation as illustrated in Figure 3-2.

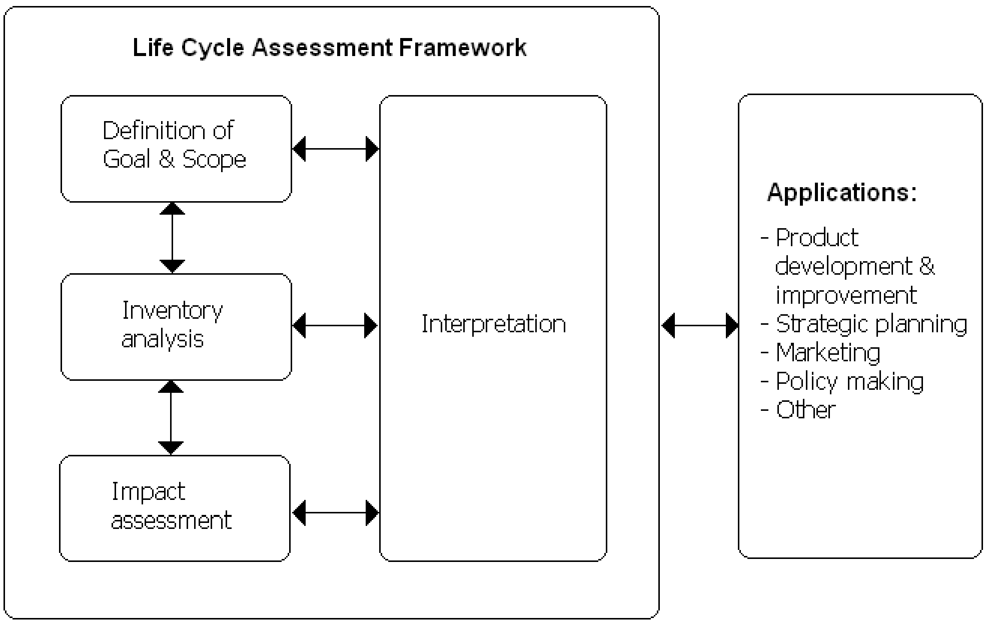


Figure 10-2: The Framework for LCA from the International Standard (ISO 14040:2006(E) pp.8)

10.1 Goal and scope definition

At the commencement of an LCA, the goal and scope of the study needs to be clearly defined. The goal should state unambiguously the intended application/purpose of the study, the audience for which the results are intended, the product or function that is to be studied, and the scope of the study. When defining the scope, consideration of the reference unit, system boundaries and data quality requirements are some of the issues to be covered.

10.2 Inventory analysis

Inventory analysis is concerned with the collection, analysis and validation of data that quantifies the appropriate inputs and outputs of a product system. The inventory can include process flow charts, details of raw material inputs, environmental emissions and energy inputs associated with the product under study. These process inputs and outputs are typically reported in inventory tables.

10.3 Impact assessment

Impact assessment identifies the link between the product's life cycle and the potential environmental impacts associated with it. The impact assessment stage consists of three phases that are intended to evaluate the significance of the potential environmental effects associated with the product system:

- The first phase is the characterisation of the results, assigning the elemental flows to impact categories, and calculating their contribution to that impact.
- The second phase is the comparison of the impact results to total national impact levels and is called normalisation.
- The third phase is the weighting of these normalised results together to enable the calculation of a single indicator result. In this study, only the first two phases are undertaken.

10.4 Interpretation

Interpretation is a systematic evaluation of the outcomes of the life cycle inventory analysis and/or impact assessment, in relation to the goal and scope. This interpretation result into conclusions of the environmental profile of the product or system under investigation, and recommendations on how to improve the environmental profile.

10.5 SimaPro®

The LCA comparison was undertaken using the SimaPro® software package to model the life cycle of each product (or system), which could then be analysed to determine relevant potential environmental impacts.

10.6 Understanding process trees

The inventory section presents the data sources and assumptions used in modelling the life cycle stages. Most of the data are contained and modelled in LCA software and consists of hundreds of individual unit process processes. To help provide transparency on the inventories used for the background processes, process network diagrams are presented.

To interpret the process network, start at the top of the tree representing the functional output of the process (e.g. petrol premium unleaded, show in Figure 3-3). The amount and unit of the process is shown in the upper number in the unit process box (1 kg). The lower number (in the bottom left hand corner) represents an indicator value which, in this case, is set to show cumulative greenhouse gas contributions in kilograms of equivalent carbon dioxide (CO_2 eq). The arrow thickness represents the indicator value (the thicker the arrow the more impact that process is contributing). Note that minor processes may not be physically shown in the process network if the indicator value falls below a specific cut off level, though their contribution to the overall functional unit (the top box in the diagram) is still included. The network diagram may also be truncated at the bottom to improve readability of the networks. Finally, some diagrams may not show the process flows for confidentiality reasons.

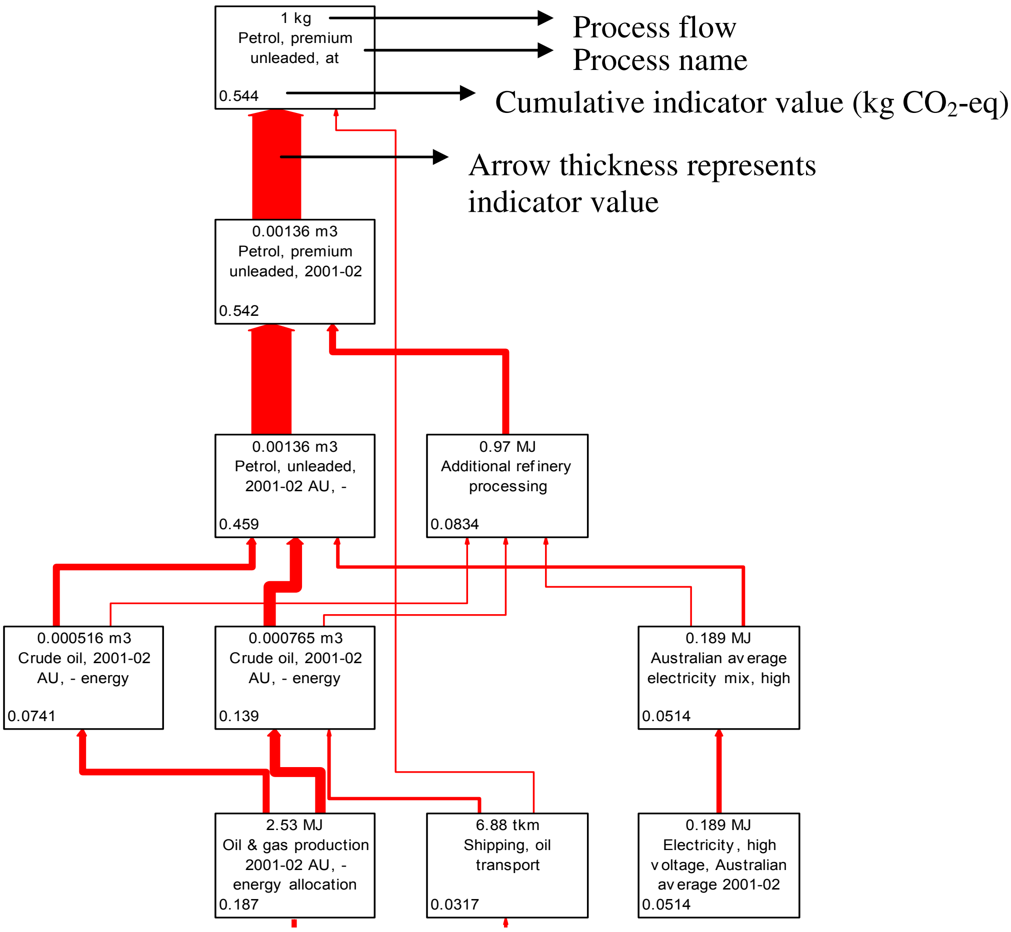


Figure 10-3: Example of process tree.

Appendix A. Characterisation Factors

Supplied in separate excel file.

Appendix B. Peer review comments and actions

Comment #	Section in reviewer report	Reviewer comment	Response
1	4.2.3	Note that the header of *paragraph 2.3* indicates that the intended audience is introduced, while in the text it is not.	First sentence of the paragraph extended to include the intended audience.
2	4.2.5	It would be beneficial for the reader if a strong reference to the stage 1 report is introduced in section 3.1.	A reference has been added to the end of the paragraph.
3	4.2.6	It would be advisable to add some information that describes the building after the functional unit. For example, that this is a 9-storey building with … apartments, …m2 living space, …m2 commercial area, etc.	The functional unit has been adjusted to exclude the term Forté (as this is essentially one of the systems under comparison) and include general descriptors (9 story, with 197 m^2 retail space and 23 apartments with an area of 1558 m^2). This should also further clarify on what basis the buildings are compared. They provide the same level of comfort and living space, but utilise different materials and HVAC systems. Therefore they will differ in both operation and material impacts.
4	4.2.7	The text and the graph are not unambiguous about the inclusion of demolition. The list of life cycle stages in the text implies that demolition is excluded, while the graph shows that demolition is included. This needs to be clarified. Note that in chapter 5 the headers and content are also not clear about demolition.	Modified bullet point list of system boundary inclusions to include “Demolition of the building at end of life and subsequent waste management.”
5	4.2.7	The graph is unclear about inclusion of building maintenance, which is part of the main part of the graph, but then also listed under excluded processes.	Maintenance has been removed from the main part of the graph.
6	4.2.7	Construction waste appears to be omitted across all materials. This omission has negligible impacts on the results, but it does mean that the cut-off of 1% is probably not achieved.	Included additional text in Section 3.3: “The management of waste produced during manufacture has been omitted for some materials, including concrete and steel, while other materials included waste management under elementary environmental flows (e.g. mass of dross and spent lining from aluminium production) or in the aggregated life cycle inventory (CLT materials).” Modified text in cut-off criteria text to: “It is estimated that elementary flows representing approximately 1% of the cumulative mass flows have been omitted, including emissions associated with management of waste produced for some of the materials included. Likewise, it is estimated that elementary

Comment #	Section in reviewer report	Reviewer comment	Response
			flows representing approximately 1% of the cumulative energy flows have been omitted. These cut-off criteria are considered not to influence the directional outcomes of this study." Included a limitation as follows: "4. The management of waste produced during manufacture has been omitted in the inventory for some materials, although this is considered not to affect the overall conclusions of this study."
7	4.2.7	It could be argued that some energy flows are missing from the use stage of the building, e.g. energy use by appliances. These would likely contribute more than 1% to the total impacts if included. It is recommended to describe these issues clearly in both system boundaries and cut-off criteria.	Agree, this will be clarified to not be part of the scope and system boundaries. Also it is more specified what is *included:* HVAC, lighting and (hot) water use. Also clarification is added in the text above figure 3-1.
8	4.2.8	The allocation procedures for multi-input processes, multi-output processes (co-production) and recycling processes are not clearly identified in the goal and scope definition of the report. The generic principles should be stated in the goal and scope, and specific allocation practices related to the data should then be clarified in the life cycle inventory.	Allocation procedures have been clarified and documented.
9	4.2.8	One (multi-output) process (steel and blast furnace slag) is described. Other processes where allocation is expected are "recycling of aluminium" (recycling) and "landfill" (multi-input). These should be discussed in the LCA as well.	Allocation procedures have been clarified and documented
10	4.2.8	In section 3.9 it is stated that "this assumption [considering slag as a by-product of steel] will be further tested in this [sic] report." Further tests were not found by the reviewer, so they should either be included or the sentence in 3.9 should be removed.	The sentence has been removed.
11	4.2.9	The selection of environmental indicators is included in the scope of the LCA report. However, the justification why these indicators are reported is missing.	Justification for the use of these environmental indicators has been provided in Section 3.10 Life Cycle Impact Assessment method. The justification includes the focus on greenhouse emissions, together with a statement regarding trade-offs and limitations of LCIA coverage in the supporting EPDs.
12	4.2.9	Section 8.1 mentions the lack of data for land use and fossil fuel	As above – included in Section 3.10.

Comment #	Section in reviewer report	Reviewer comment	Response
		depletion. If these indicators were initially selected for the LCA, they should be mentioned in section 3.10 as well.	
13	4.2.9	The Australian Impact Method consists of indicators and models developed by a range of institutions. Therefore it is probably more accurate to replace "developed" by "compiled" in the first sentence of section 3.10.	Agree, developed has been changed to compiled.
14	4.2.9	The cumulative energy demand (CED) for non-renewable energy sources is included, but given forestry products are heavily featured in the LCA, it would make sense to also include CED for renewable energy.	The focus of the assessment was on non-renewable energy resources. It is recognised that renewable energy could be an important point of discussion. To account for this, results now include a renewable energy indicator. Renewable energy inputs from the EPD have been added to the inventory tables in Section 5. Text has been modified in Section 5.2.1.1 (for the interpolation approach) to include renewable energy. As part of this modification, it was realised that "Energy, from solar" was included in the non-renewable impact assessment method. This flow has been removed from this method and included in the renewable energy CED indicator.
15	4.2.9	In section 3.10.1 an explanation of two models is given. The second item states [carbon dioxide will not be released] "in the time period considered". It needs to be explained if (and for how long) a specific time period was considered in the LCA.	The part time period considered is removed. What was meant by this statement was that when looking on longer timescales (>100 year) it is hard to predict what will happen to land fill sites and the material present in them.
16	4.2.9	The last paragraph on page 15 "Based on these guidelines… …relative to fossil methane." Is technically correct, but might be unclear to an average reader. Consider editing the text.	Additional space is added to clarify that the there are two separate issues. (treatment of biogenic carbon, and biogenic methane)
17	4.2.9	The description below figure 3-2 doesn't necessarily relate directly to the graph. If the time periods are also included in the graph it would be much easier to understand.	Changed figure caption to "Schematic differentiating different types of carbon flows." Schematic modified to include time periods.
18	4.2.10	The list of predominantly building materials for which primary data are sought raises some questions. It is believed that not all of these materials actually required primary (production) data, but rather the quantities applied in the two buildings. Please describe clearly what data or what process primary data have been sought for.	This has been listed perhaps more clearly in the table below the section referred to here. The paragraph has been revised.
19	4.2.11	It would be useful to repeat some of the key limitations that were identified in the stage 1 report; i.e. the fact that a proxy concrete mix design is used could be considered a significant value choice (and	Actual mix designs are used in both the Stage 1 and Stage 2 report. The proxy in the Stage 1 report referred to the use of 15 MPa as a proxy for 25 MPa concrete. For the Stage 2 report, an

Comment #	Section in reviewer report	Reviewer comment	Response
		perhaps limitation) that needs to be stated in paragraph 3.11.	updated inventory has been used, which no longer includes 25 MPa concrete. Therefore, no action is required on this.
20	4.2.11	Another key value-choice or limitation that might impact on the results is likely to be found in the operational energy and water modelling. This should be discussed in 3.11.	Included the following text in Section 3.11: "Operational impacts are based on modelling and may not reflect actual environmental impacts."
21	4.3	Section 5.1: Is the concrete alternative building an alternative design for the Forté building or a standard 9-storey building?	Additional explanation added to 5.1.2
22	4.3	Table 5-1: Please explain the difference in area of glazing and window frames.	See comment 29
23	4.3	Table 5-4: Why was this end-of-life scenario chosen? It could be expected that some of the materials other than aluminium are recycled as well.	See comment 48 this is now changed to reflect more current recycling practices. Table 5-4 and 5-8 have been adjusted
24	4.3	Table 5-7: Why is the water quantity used in the reference building lower than in the Forté building (table 5-3)? This is inconsistent with section 5.3.3.2.	The water use numbers should be the same. There was a typo in the total water use for the Forté building. Corrected
25	4.3	Table 5-12: The header says "concrete manufacturing in Australia". As the mix is not necessarily representative for Australia, it could avoid confusion if "in Australia" is removed or if a caveat is added.	"in Australia" removed from the caption
26	4.3	After table 5-12: Check definitions. Fine aggregate (sand) is typically <5mm.	Agree revised to refer to just coarse aggregate.
27	4.3	After table 5-12: A reference is made to table 5-5. However, there is no mention of 25MPa concrete in table 5-5.	Sentence removed
28	4.3	Section 5.2.1.2.1: Structural steel is typically made via the BF/BOS steel process, while reinforcement steel is often created using the EAF route. Why was structural steel chosen?	This is a mistake in the report, in fact the eco-invent process for reinforcement steel was adapted to Australian conditions, this uses a mix of EAF and BF/BOS.
29	4.3	Section 5.2.1.3: Unfortunately, the ecoinvent process for aluminium frames appears unrealistic. The amount of aluminium used per m2 of window is very high. This figure should be cross-checked with other sources (such as BPIC data).	This is because the surface area does not relate to the glazing but to the visual surface of the frame. This is explained in Ecoinvent documentation. An explanation and reference has been added.
30	4.3	Table 5-15: Does the inventory (weight of glass) align with the prescribed thickness of the glass?	Yes, although the windows have a different prescribed U value, the construct is very similar as to what is described in the Ecoinvent report.
31	4.3	Table 5-15: Where is 0.3 kg aluminium per m2 window used, given that the frames are included elsewhere?	It is used as a spacer to divide the glass panes to allow for an air gap (or gas filled). This spacer runs along the entire

Comment #	Section in reviewer report	Reviewer comment	Response
			circumference of a window. See Ecoinvent report. No changes made to the report.
32	4.3	Section 5.2.1.4: The SimaPro process "Electricity, average, low voltage/AU" results in an emission factor of 0.96 kg CO2e/kWh. The latest Australian average emission factor from the National Greenhouse Accounts 2012 (NGA) is 1.03 kg CO2e/kWh. As the NGA factor is likely to be more accurate than the SimaPro factor, it would be desirable to perform a high level analysis on the impact of this discrepancy across the LCA (not just plasterboard).	There is no evidence to indicate that the NGA factors are more accurate than the unit process used in the modelling. In addition, the NGA values are factors, not inventories. Inventories are needed so other impacts (e.g. water use, eutrophication) can be assessed. Regardless, it is recognised that there is a discrepancy. Further analysis on this issue would require an audit of the NGA determination of this, which is beyond the scope of this study. A comment on this will be added as a limitation. Given that the majority of greenhouse impacts are as a result of the operational phase, and that the grid is the same in both cases (Forté and the reference building), the discrepancy between greenhouse impacts between NGA and the inventories used is considered not to affect the directional conclusions of this study. Added the following limitation: Greenhouse impacts associated with electricity may be under or overestimated due to possible discrepancies between actual and modelled emissions. Potential discrepancies are considered not likely to affect the direction of the conclusions relating to greenhouse impacts.
33	4.3	Table 5-17: Is there a special reason for using the "Hot rolling, steel" process for what is in fact an aluminium product? It would be better to use an aluminium manufacturing process, as this would account for production losses of the correct material.	Changed to hot rolling aluminium sheet.
34	4.3	Section 5.2.1.6.2: Uniroll is manufactured using *recycled* foam rubber. As a proxy is used, an uplift factor might be reasonable to err on the side of caution. Note that Uniroll is not mentioned in table 5-1.	Recycled added to the description. Inventory updated to include conversion processing of recycled rubber. Uniroll now reported in new table. Inventory text modified as follows: The Uniroll products are likely to be formed using a calendaring process. The average energy use (MJ/kg) for the forming recycled rubber products is approximately three times that for virgin materials. This factor was applied to the energy requirements for calendaring (0.505 kWh/kg, from ecoinvent), and added to the inventory. The inventory for this is shown in

Comment #	Section in reviewer report	Reviewer comment	Response
			Table 5 19.
35	4.3	Table 5-18: It would be useful to insert which density has been applied to glass wool insulation to allow conversion between table 5-1 (in m3) and table 5-18 (in kg).	14 kg/m^3. This is added in the text above Table 5-18
36	4.3	Table 5-20: The transport distances for many materials seem quite low. For example, Uniroll is manufactured in Sydney and therefore the transport distance would have to be much larger than 30 km. In light of the comparison, it would be good practice to apply conservative estimates to transport of materials used in the Forté building.	Agree transport distance for uniroll revised to 900 km. The other estimated distances are upped to 50 km. This will be further tested in the sensitivity by changing it to all from Sydney.
37	4.3	Table 5-23: The fuel use of the excavator (0.131 kg/hr) appears extremely low. Depending on the type and operation mode a large excavator could easily use more than 20 litres of fuel per hour, which is more than 120 fold the current use. Note that a change in consumption here will have an impact on section 7.3.3 as well.	Agree – appears to be far too low. Modified inventory based on estimate of fuel consumption from John Deere specifications. Section 7.3.3 updated.
38	4.3	Section 5.2.2.2: It would be useful to include the hours of operation in the inventory.	Cross reference to Tables with hours of operation now included.
39	4.3	Table 5-24: It would be helpful to explain the abbreviations (COP, EER, SHGC) in a footnote.	Added to table and supporting text: coefficient of performance, energy efficiency ratio, solar heat gain coefficient and heat transfer coefficient.
40	4.3	Table 5-24: The COP and EER of the heating and cooling system will have an impact on the overall building energy requirements. Can Lend Lease confirm that the COP and EER used in the model are similar to the values of the actual systems installed?	Lend Lease have confirmed that the COP and EER for the Forté building are the actual values of the installed equipment as is mentioned in the table, the COP and EER for the reference are based on requirements from BCA 2011.
41	4.3	Table 5-24: There appear to be some typos in the units of the U-value and internal heat gains.	The units for U-value are W/K.m^2, corrected. Internal heat gains are W/person, corrected. Comments included on estimated occupancy profiles.
42	4.3	Table 5-25 lists the energy requirements for the Forté building. Unfortunately the values are impossible to verify by start2see. Has any other verification or audit process taken place on the thermal modelling?	This has been compared to an Accurate assessment undertaken by us, and an assessment done by LendLease prior to the LCA. They were found to be consistent. The energy requirements should be validated when the building is in actual operation. However, this is beyond the scope of the project. A limitation has been added to describe the issue.
43	4.3	Table 5.26 indicates that an Eastern Australian grid emission factor was used to model operational electricity for the building. It would	Agree, this has been changed to Victoria. Concrete has also been changed to the Victorian grid. The credits applied to

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		be better to use a state specific grid factor, as the connection between states in Australia is limited. 1 The information from AEMO shows that there is likely to be limited influence from interstate suppliers. The electricity price is also set at state level. Furthermore, state based emission factors as published in NGA2012 have been corrected for imports/exports of electricity from/to other states (as evidenced by the large variation in the Tasmanian grid factor when imports from Victoria increased). Given the significant difference between the East Australian grid factor (1.08 kg CO2e/kWh) and the Victorian grid factor (1.35 kg CO2e/kWh) a recalculation of the LCA results is warranted.	landfill methane capture are also now based on the Victorian grid, with rates of capture and efficiency based on a report by Hyder.
44	4.3	Table 5.27: There is an error (typo?) in the yearly water use residential space.	Typo corrected.
45	4.3	Table 5.27: The formula used to calculate the energy use for hot water supply results in 295,000 MJ. The result (295 GJ) is therefore correct, but it would be clearer to apply the units correctly.	Changed to MJ.
46	4.3	Table 5.27: Make sure units and rounding are applied correctly.	Rounding changed for yearly water use in retail space.
47	4.3	Below table 5-28 a reference is included to the process that was used to model hot water supply. It appears that this dataset is missing from the report.	This has been clarified. Text altered to: The heat for the hot water system is supplied by natural gas (see Table 5 27). The AUPLCI unit process, "Energy, from natural gas/AU U" inventory was used to model heat for the gas water heater.
48	4.3	Section 5.2.4: Why was decided that most materials will end up in landfill? A reasonable amount of concrete and other construction materials are already recycled in Victoria.	This is changed to reflect more real recycling practices. Hyder data from a 2011 report has been used to determine the average recycling rate for the dominant construction materials and these have been applied for both buildings. This has been added in the report and model.
49	4.3	Section 5.2.4.2.2: Explain if time is an important factor for the degradation of wood as well and whether the 16-20 year time period from Ximenes 2012 is sufficient to estimate final degradation.	This section has undergone a major revision, including the degradation modelling. The default landfill model is now based on the Tier 2, IPCC First Order Decay (FOD) model, rather than the Tier 1 IPCC mass balance model. This model is in better alignment with reported studies and is considered more appropriate. Definitions of DOC, DOCf are now better aligned with that of the IPCC. "Time in landfill" has been included in the list of factors. Updated "Method" column in Table 5-30 to indicate that IPCC is calculated. Timeframes are now included

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			for the US EPA and the Wang et al. studies referenced. Relabelled Table 5-30 to “Degradation amounts…” (was Degradation rates …”. Initial carbon contents have been reported.
50	4.3	Section 5.2.4.2.2: It is stated that the value used for DOCf is more accurate than the default IPCC factor. Given the importance of this factor, please explain the rationale behind this choice.	This is no longer applicable.
51	4.3	Section 5.2.4.2.2: A sensitivity analysis on this topic is warranted, as is recognised in the text. However, there is no sensitivity analysis regarding DOCf in section 7.3.	A sensitivity study has been included, which investigates the effects of different DOC_f (and hence $DDOC_{m0}$) values
52	4.3	Section 5.2.4.2.2: Use a consistent spelling of factors (e.g. Mox, DOCf).	Spelling made more consistent
53	4.3	Section 5.2.4.2.2: It would add a lot of clarity if figure 5-2 could be repeated with the flows and values filled in.	It was considered an additional figure would not clarify the model. Rather, a table of parameters has been included to clarify the modelling assumptions.
54	4.3	Section 5.2.4.2.2: Check the references IPCC 2006b and IPCC 2006c. They appear to relate to the same document.	References have been consolidated. 2006c removed from reference list.
55	4.3	Section 5.2.4.3: Recycling is a process that requires allocation. A description of how allocation was dealt with is in order.	A description of allocation for recycling processes has been added.
56	4.3	Section 5.3.1.4: Only PUR is presented. Are other materials missing from the report or was there a conscious decision to present only PUR wall insulation? In the latter case this should be explained.	Also glass wool is used as an insulation material a reference has been added in a new section (5.3.1.4.2) referring back to 5.2.1.6.1.
57	4.3	Table 5-32: Only emissions of pentane (blowing agent) during production are reported in the ecoinvent process. During the lifetime of the PUR it is likely that (almost) all the pentane will diffuse and is therefore emitted.	Agree, however due to application (being sealed into pre-cast concrete panels, this could be a very slow process. Also the emission of pentane does not affect any of the considered indicators. It is known to contribute to photochemical oxidant formation, but this is outside of the scope of the study. However, for completeness this flow has been added to the inventory.
58	4.3	Table 5-34: The COP and EER have apparently been modified to make the reference building comply with a 6 star energy rating. This could be a crucial choice in the LCA, as it potentially shifts the balance from a building comparison to an HVAC equipment comparison. If the concrete reference building as designed by Lend Lease, using the same HVAC system as in the Forté building,	The reason for the Stage 2 study was to assess not only CLT, but also the other systems (including HVAC and lighting) that are used in the Forte building. This reason has been clarified in the goal and scope, along with other sections which document the reasons why the study was undertaken.

Comment #	Section in reviewer report	Reviewer comment	Response
		exceeds the 6 star energy rating then this would have to be modelled in order to create a fair comparison between two building designs.	Given the uncertainty regarding the choice and applicability of HVAC (COP and EER values) and lighting (W/m^2) performance on the reference building, a sensitivity has been included which investigates life cycle impacts if the same HVAC and lighting systems are applied to both buildings.
59	4.4	Table 6-1: There appears to be an error in either the units or the values of this table. start2see advises to check all tables in the report thoroughly.	Acknowledged.
60	4.4	Figure 6-1: The figure indicates a comparison of buildings, while the caption indicates a comparison of materials. The latter is incorrect.	Caption adjusted
61	4.5	The figures throughout section 7 need to be checked for correct use of units. E.g. figure 7-3 presents the Forté building in tonnes and reference building in kg. Consistency between both axes, values in the data tables and caption of the figures is preferred. In figure 7-6 units are missing altogether.	Noted, this has been adjusted.
62	4.5	Section 7.2.1: The last sentence before figure 7-5 (The amount of windows […] impacts perspective.) requires explanation or adjustment.	Explanation added.
63	4.5	Figure 7.5: The contribution of insulation to the reference building's climate change impacts appears very high. The result is almost impossible to reproduce with the data provided in the report and points towards a modelling error (incorrect unit) as the most logical explanation. An alternative explanation is that the density of PUR is estimated incorrectly.	A density of $300kg/m^3$ was used. It is acknowledged that this may be at the upper end of PUR rigid foams densities, and that a lower density is more appropriate http://www.puren.eu/industry-products/puren_industry.pdf shows that density can range from 30-300 kg/m^3. The PUR,rigid Ecoinvent inventory has been adjusted for Australian conditions, and has a GWP emission factor of 4.46 $kgCO_2eq/kg$. As $110m^3$ has been used (or 110*.300 = 33 tonne) this equates to an total GWP impact of 147.2 tonne CO_2eq impact for PUR which is in line with the reported figure in 7-5 (14%*1030=144.2). The density is adjusted to 30 kg/m3 which is more appropriate for the application. This will reduce the impacts with a factor 10, to ~ 14 tonne CO_2eq. The inventory and results have been adjusted.
64	4.5	Section 7.2.1: Following figure 7-5 it is stated that the foundation, slabs and columns are assumed to be similar for both buildings.	The columns and foundation is similar for both buildings. This is based on actual data provided by LendLease for the Forté

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		The assumption is probably a worst case estimate for the Forté building, as it is lighter than the reference building. Also, rather than assuming these design aspects, one would expect Lend Lease to have supplied these data.	building. As the concrete building is fictitious, no actual information is available for the additional columns and foundations required. It is acknowledged that this is therefore an optimistic estimate for the concrete building, as the building is heavier.
65	4.5	Page 59: The word “disposal” is missing from the first sentence.	Added
66	4.5	Section 7.2.2: Explain what causes the nitrous [sic] emissions at the landfill site.	This is an error in the report. It is in fact ammonium emissions at the landfill site from disposal of PUR. Report has been modified to: “The eutrophication potential at the end of life for the reference building are driven by ammonium ion emissions from the landfill of polyurethane.”
67	4.5	Section 7.2.3: The statement that water use in the materials phase is predominantly related to concrete manufacture is incorrect. Concrete manufacture is the step where aggregates, binders and water are mixed and this process does not require huge volumes of water. Direct water use in concrete manufacture would explain ca. 2% of the total materials phase water use. Likely, concrete manufacture refers to cradle-to-gate processes. The key driver for water use should then be more accurately pinpointed and discussed.	This is an error in the report. In fact there is no single source that is dominant, although the concrete cradle-to-gate processes are significant. Agree with reviewer that concrete manufacture is not a major driver. Text is adjusted to: “The water use in the materials phase is related to the production of a large variety of materials and their precursors, such as steel, concrete and insulation.”
68	4.5	Section 7.2.4: More explanation and analysis is required.	More analysis has been added. A section on renewable energy demand has also been included. Given that the CED indicators are only a prelude to potential environmental impacts, the discussion on these sections has been kept to a minimum.
69	4.5	Building comparison or material comparison	As addressed previously – the reasons for the study have been clarified.
70	4.5	The data quality assessment in section 7.6 is reported clearly, but it is hard to believe each process scores so consistently across a range of data quality indicators.	The data quality assessment was reviewed. Minor changes to some indicators have been made, particularly for the indicator “primary sources of data”. The other assessments were considered to be reflective of the data used. No other changes are considered appropriate.
71	4.5	Section 7.3.1: “There is no strong evidence in the literature that…” Could the lack of evidence be caused by the fact that there are not that many CLT buildings? If so, this statement should be rephrased.	Clarification has been added and sensitivity added assuming different lifetimes as suggested in comment 73.

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72	4.5	Figure 7-13 & Figure 7-15: The formulas in the top right hand corner need an explanation.	The formula in 7-15 removed as did not add information, explanation added to figure 7-13.
73	4.5	Section 7.3.1: An alternative analysis could show a concrete building with a 100 year lifetime compared against two CLT buildings with a 50 year lifetime.	There is no evidence to indicate that the lifetime of a CLT building is different (or half that) of a concrete building. This comparison is considered not to be justified without sufficient evidence.
74	4.5	Section 7.3.1: Please explain how maintenance is or isn't incorporated in the figures (especially when considering 100 year timeframe).	Given that the external and interior surfaces of both buildings are similar, maintenance is considered to be similar for both buildings. The exclusion would therefore not affect the directional nature of the comparisons. This justification has been added to the report.
75	4.5	Section 7.3.2: Not all materials require a similar transport distance. Nevertheless, a maximum transport distance from Sydney or Brisbane to Melbourne would test the maximum sensitivity.	The sensitivity now extends to a maximum transport distance of 1000 km.
76	4.5	Table 7.3: Energy use is not for total, but for HVAC only.	Table amended.
77	4.5	Section 7.4.1.2: The conclusion that the lighting energy use of this study is in line with the GBCA's benchmark is not really substantiated. As the area size for each user type is known, an average lighting energy benchmark can be calculated.	This section has undergone major revision. Now reads as follows: The lighting energy use for Forté and the reference buildings was 31.09 MWh/yr and 45.22 MWh/yr, respectively. These values are an aggregate of the energy use for lighting in the commercial and dwelling areas, as well as in common areas such as corridors and plant rooms. The values correspond to a calculated energy consumption rate of 25.8 kWh/m2/yr and 17.7 kWh/m2/yr he values are higher than the Green Building Council of Australia's (GBCA, 2009) benchmarks for dwellings (12.7 kWh/m2/yr) but lower than the benchmark figure for communal areas (36.8 kWh/m2/yr). Although the retail space only accounts for ~11% of total lighting area, the energy density of the retail space is much higher (22 W/m2) than for the residential space (between 3-5 W/m2, refer Table 5 24 and Table 5 36). As such, the commercial lighting area contributes to a proportion of lighting energy impacts which are not linear with lighting area. For example, full occupancy and lighting energy inputs are assumed, the retail space would account for

Comment #	Section in reviewer report	Reviewer comment	Response
			36% of power requirements. The higher consumptions values in this study, than for the GBCA dwellings benchmark, are the result of this high demand for retail lighting.
78	4.5	Figure 7-16: Land use and fossil fuel depletion have not been reported for CLT. Therefore it is suggested to use "n/a" rather than 0%.	Columns have been removed as they did not add any information.
79	4.5	Sections 7.4.3 & 7.4.4: The concrete comparison is difficult to understand without knowing details about mix designs and cement data.	This section has undergone a major revision and now includes a comparison to another Victorian study. Text now reads as follows: A study undertaken by the Centre for Design for Grocon in 2012 analysed a number of 40MPa concrete blends (Crossin, 2012). The studied impacts categories were limited to global warming impacts and embodied energy. Figure 7 21 shows that the 40 MPa concrete blend in this study lies in between blends 4 and 5 from the Grocon study. The details regarding the design of these two Grocon mixes are not publically available, however the differences in impacts of the 40 MPa blend used in this study, and those of the Grocon study is likely explained by variations in types and quantities of cementitious materials, including fly-ash and ground-granulated blast furnace slag (GGBFS). Flower and Sanjayan (2007) reported an emission factor of 0.33 tonne CO_2-eq/m^3 for 40 MPa precast panels in Victoria, however the GGBFS content of this mix was not reported. A presentation by the same authors indicated an emission factor of ~0.21 tonne CO_2-eq/m^3 for 40 MPa precast concrete, with a GGBFS content of 65%. This value of ~0.21 tonne CO2-eq/m^3 is consistent with that used in this study (222 kg CO_2-eq/m^3).
80	4.5	Section 7-5: Significant uncertainty might exist in concrete data and operational energy use. These items are not discussed in section 7-5. Why?	All data was subject to uncertainty analysis, which is why specific mention of concrete and energy use has not been made. We disagree that there is high uncertainty in the concrete data; the concrete mixes are well known and supplied by the concrete manufacturer. Australian data was used to model the concrete mix. The uncertainty regarding operational energy use

Comment #	Section in reviewer report	Reviewer comment	Response
			has been tested in the Monte Carlo simulations, and there are a number of limitations on the operational energy use already. No further amendments have been made.
81	4.5	Table 7-5 compares embodied impacts only. Why isn't the complete life cycle compared?	This was carried over from the Stage1 report. The comparative analysis covers the full life cycle. Statement has been removed.
82	4.5	The conclusions are reported in chapter 8. Before the conclusions are presented, an evaluation of the type of comparison that has been undertaken is in order. There is interaction between building materials, building thermal performance and HVAC equipment efficiency that has significant impact on how the results can and should be used.	The goal and scope of the study has been amended to better reflect the intention of the commissioning parties. In addition, HVAC efficiency has been addressed in a sensitivity study.
83	4.5	The most important consideration is whether the COP and EER of the HVAC system in the reference building should be identical to the one in the Forté building.	The goal and scope of the study has been clarified. As is described in the goal of the study, the intent is to compare the Forté design (including, construction, HVAC and lighting) to a 'standard' building compliant to BCA code typical for currently built apartment buildings. The Forté is thus not only different in construction, but also employs other features (beyond compliance), the effect of which should become clear through the comparison. As the reference building is not 'real' there is always a level of subjectivity in the choice of equipment etc, and various strategies have been used (e.g. same systems, same energy use during operation
84	Email 10/12/2012	Construction waste has been omitted. You have included manufacturing waste, but construction waste is equally relevant for cut-off.	Included a statement in system boundary section "Construction waste has been omitted from the system boundary".
85	Email 10/12/2012	I don't necessarily agree that there is no evidence that NGA is of higher quality than what's in SimaPro. As NGA is based on NGER, there is a clear underlying methodology and audit system involved. I'm not too sure about the SimaPro data... However, I'll just make a minor note on this and no need for you to do anything	No action taken.
86	Email 10/12/2012	item 3 and 4 of your conclusions are open for misinterpretation when read on their own. The 30% improvement in materials is correct when considering cradle-to-gate only. When adding transport to site and waste treatment (both are directly related to material choice), the picture becomes more complete and balanced.	Clarified the conclusion as follows: "The global warming potential of the building materials (cradle to gate) for the Forté building are 30% lower than the reference building. If the materials' construction, transport and end-of-life impacts are included, the global warming potential of Forté's

Comment #	Section in reviewer report	Reviewer comment	Response
		Can you clarify these points by stating more clearly what's included, and by giving a material life cycle comparison rather than a cradle-to-gate comparison?	building materials are 15% higher (if sequestration is excluded) or 52% lower (if sequestration is included)."
87	Email 10/12/2012	Also, by only stating the difference in materials and transport, it could be assumed that these are the key drivers for differences in the life cycle. Can you add explicitly that there are efficiency differences in HVAC and lighting systems?	Added a new conclusion: "The reductions in environmental impacts are primarily driven by the use of more efficient HVAC and lighting systems in Forté than for the reference building.
88	Email 10/12/2012	Comment #15: in your reply you included the wrong symbol (< instead of >)	Corrected to >
89	Email 10/12/2012	Comment 55: please add your response to the table. You've already dealt with it in the report.	Added response – see above.

Appendix C. Non assessed substances

Supplied in separate excel file

Appendix D. KLH EPD for cross laminated timber

Supplied in separate pdf.

Appendix E. Inventory

Supplied in separate xls. file.

Appendix F. Final review statement

START2SEE
LIFE CYCLE ASSESSMENTS

ISO14040 REVIEW OF LCA OF A CROSS-LAMINATED TIMBER BUILDING

STAGE 2 FINAL REVIEW STATEMENT

RMIT, CENTRE FOR DESIGN
10 DECEMBER 2012
S1112

Project Details

Project Title
CfD – ISO14040 Review of LCA of a cross-laminated timber building

Client Details
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Report version	Author(s)	Date
Final review statement V2.0	**Rob Rouwette**	**10 December 2012**

If you would like to discuss any of the topics or have any questions please feel free to contact start2see (Rob Rouwette) on mobile +61 403 834 470.

Final Review Statement

The Centre for Design (CfD) at the Royal Melbourne Institute of Technology (RMIT University) has conducted an environmental Life Cycle Assessment (LCA) of a cross-laminated timber building. The study is conducted in two separate stages: the first stage considers the building materials used, while the second stage considers the use of the materials in a particular building (the Forté building). Stage 2 also includes a comparison between the Forté building and a conventional reference building. The LCA is undertaken with the requirements of the ISO 14040 Standard (Environmental Management – Life Cycle Assessment – Principles and Framework) and ISO 14044 Standard (Environmental Management – Life Cycle Assessment – Requirements and Guidelines) in mind.

The commissioners of the LCA, Lend Lease and Forest and Wood Products Australia (FWPA), would like to use the results for external purposes and as such the LCA needs to be critically reviewed by an independent and qualified expert. This review report was commissioned to provide the critical review that provides an additional level of robustness and credibility to the LCA results.

The initial review was undertaken on the draft LCA report: "*Life Cycle Assessment of a cross laminated timber building. Stage 2: Full building life cycle*", version 2.3, dated 27 September 2012.

The final review was undertaken on the final LCA report: "*Life Cycle Assessment of a cross laminated timber building. Stage 2: Full building life cycle*", version 2.5, dated 28 November 2012.

The critical reviewer (R. Rouwette) has found that in the final LCA report:

- the methods used to carry out the LCA are consistent with ISO14040/14044 standards for LCA;
- the methods used to carry out the LCA are scientifically and technically valid;
- the data used are appropriate and reasonable in relation to the goal of the study;
- the interpretations reflect the limitations identified and the goal of the study; and
- the study report is transparent and consistent.

The conclusion is therefore that the final LCA report is in line with the requirements and guidelines from the ISO standards 14040 and 14044.

In start2see's opinion, the stage 2 report does not contain any material errors and the overall conclusions are considered valid. Please note:

- The comparison of the two buildings is heavily influenced by choices and limitations in the building design, data and modelling. The results are therefore not necessarily transferable to other – on the surface similar – situations. It is recommended that readers familiarise themselves with the differences in building materials, HVAC and lighting systems, as well as the impact inclusion/exclusion of carbon sequestration has on the results.
- start2see has not verified the correctness of the thermal modelling results used in the report.
- The electricity emission factors used in the LCA vary somewhat from the 2012 NGA factors. Although this deviation from NGA factors is not expected to have an impact on the directional results of the LCA, it will have an effect on the absolute results.

It is recommended that this final statement, as well as the initial review report and the practitioner's responses, are incorporated into the LCA report.

Rob Rouwette

Director, start2see Pty Ltd

10 December 2012