Forest&Wood Products Australia
Knowledge for a sustainable Australia

MARKET ACCESS

PROJECT NUMBER: PRA344-1415 July 2015

A comparative Life Cycle Assessment of Two Multi Storey Residential Apartment Buildings

This report can also be viewed on the FWPA website
www.fwpa.com.au
FWPA Level 11, 10-16 Queen Street,
Melbourne VIC 3000, Australia
T +61 (0)3 9927 3200 F +61 (0)3 9927 3288
E info@fwpa.com.au W www.fwpa.com.au

A comparative Life Cycle Assessment of Two Multi Storey Residential Apartment Buildings

Prepared for

Forest & Wood Products Australia

by

Andrew Carre & Enda Crossin

Publication: A comparative Life Cycle Assessment of Two Multi Storey Residential Apartment Buildings

Project No: PRA344-1415

This work is supported by funding provided to FWPA by the Department of Agriculture, Fisheries and Forestry (DAFF).

© 2015 Forest & Wood Products Australia Limited. All rights reserved.

Whilst all care has been taken to ensure the accuracy of the information contained in this publication, Forest and Wood Products Australia Limited and all persons associated with them (FWPA) as well as any other contributors make no representations or give any warranty regarding the use, suitability, validity, accuracy, completeness, currency or reliability of the information, including any opinion or advice, contained in this publication. To the maximum extent permitted by law, FWPA disclaims all warranties of any kind, whether express or implied, including but not limited to any warranty that the information is up-to-date, complete, true, legally compliant, accurate, non-misleading or suitable.

To the maximum extent permitted by law, FWPA excludes all liability in contract, tort (including negligence), or otherwise for any injury, loss or damage whatsoever (whether direct, indirect, special or consequential) arising out of or in connection with use or reliance on this publication (and any information, opinions or advice therein) and whether caused by any errors, defects, omissions or misrepresentations in this publication. Individual requirements may vary from those discussed in this publication and you are advised to check with State authorities to ensure building compliance as well as make your own professional assessment of the relevant applicable laws and Standards.

The work is copyright and protected under the terms of the Copyright Act 1968 (Cwth). All material may be reproduced in whole or in part, provided that it is not sold or used for commercial benefit and its source (Forest & Wood Products Australia Limited) is acknowledged and the above disclaimer is included. Reproduction or copying for other purposes, which is strictly reserved only for the owner or licensee of copyright under the Copyright Act, is prohibited without the prior written consent of FWPA.

ISBN: 978-1-925213-26-3

Researchers:
RMIT
Mr. Andrew Carre
Dr. Enda Crossin

Final report received by FWPA in June 2015

Forest & Wood Products Australia Limited
Level 11, 10-16 Queen St, Melbourne, Victoria,
3000 T +61 3 9927 3200 F +61 3 9927 3288
E info@fwpa.com.au
W www.fwpa.com.au

A Comparative Life Cycle Assessment of Two Multi Storey Residential Apartment Buildings

Prepared for:

Forest and Wood Products Australia and Australand

FWPA - Dr. Chris Lafferty

Australand – Paolo Bevilacqua

Issue:	1 June 2015
Version:	Final

Authors:

Mr. Andrew Carre

Dr. Enda Crossin

CONTACT
Sustainable Building Innovation Laboratory (SBi Lab)
School of Property, Construction and Project Management
RMIT University
GPO Box 2476
Melbourne VIC 3001
Tel: + 61 (03) 9925 2230
Fax: + 61 (03) 9925 1939

.

Table of Contents

Table of Tables

Table of Figures

1 Executive Summary

This study compares the life cycle environmental impacts of two multilevel residential buildings built in Melbourne, Australia. The study was commissioned by Australand and funded by Forest and Wood Products Australia (FWPA).

The first building considered, the 'Study Building', incorporated an innovative light weight building approach utilising a stick-built timber frame and a 'cassette floor' building system. The second building, the 'Reference Building' utilised a more typical building approach, incorporating precast concrete panels and suspended concrete slab floors (Table 1).

Table 1 Summary of building features.

	Study Building	**Reference Building**
Exterior view		
Location	Parkville, Victoria	Parkville, Victoria
Number of levels	5 storeys plus basement car park	8 storeys plus basement car park
Gross Dwellable Area (apartment and balcony space)	3,895 m^2 (including 328 m^2 private balcony space)	5,912 m^2 (including 565 m^2 private balcony space)
Number of apartments	57: one, two and three bedroom units	91: one, two and three bedroom units
Average apartment NatHERs rating	7 Stars	7 Stars
Building structure	Light weight timber frame on concrete and screw-pile foundations. Exterior walls of rendered phenolic foam panels. Floor system employing engineered timber joists installed in 'cassette' modules. Filled concrete block lift and stair core.	Precast concrete panels installed on a concrete and pile foundation. Floors of post-tensioned concrete slabs cast in-situ. Exterior walls of precast concrete panels. Precast concrete panel lift and stair core.
Building material mass	618 kg per m^2 of gross dwellable area (GDA)	1,653 kg per m^2 of gross dwellable area (GDA)

Objectives

The primary goal of the study was to compare the potential environmental impacts of the above buildings across their respective life cycles. Secondary goals included:

a) Comparing the outcomes of the study to the findings developed for the Forte building described by Durlinger, Crossin and Wong (2012), and
b) Calculating Green Star points that may be earned by the Study Building under the Green Building Council of Australia's Innovation Challenge – Materials Life Cycle Impacts (GBCA 2014)

Methodology

The study employed the LCA methodology described by the ISO14044 standard to undertake the comparison of the buildings. The analysis addressed a building life cycle scope which was prescribed by GBCA (GBCA 2014), which in turn based the boundary definition on the EN15978 standard, as shown in Figure 1. Although EN15978 was used to define the scope of the LCA, the study is not intended to be fully compliant with the standard.

Product Stage	Construction Process	Use Stage	End of Life	Beyond Building Life Cycle
• Raw material extraction • Transport • Manufacturing of materials (including waste allowance)	• Material transport to site from point of manufacture • Construction installation process • Cutting waste disposal	• Heating and cooling energy use • Lighting energy use • Hot water system energy use • Water use • Building maintenance and refurbishment (including waste disposal)	• Demolition process • Transportation to recycling/disposal location • Recycling process impacts • Disposal process impacts (including degradation in landfill)	• Avoided burdens due to the recovery of raw materials at the end of building life

Common Systems Included

- Energy supply including fossil fuel extraction/refining, electricity generation/supply
- Water supply
- Infrastructure including roads and other capital equipment

System Boundary

Key Exclusions

- Onsite installation processes, beyond excavation
- Apartment appliances, beyond HVAC
- Lift system
- Hot water system
- Temporary works such as scaffolding, formwork, site buildings
- Refrigerant leakage from HVAC systems

Figure 1 System boundary.

The functional unit (the unit of comparison) adopted was broadly prescribed by the GBCA (GBCA 2014). The essential service provided by the residential apartment building was deemed to be the provision of gross dwellable area (GDA), however a precise definition of GDA was not provided by the GBCA. After consideration of a number of possible definitions, GDA was defined as:

Total apartment area = Area within each apartment plus the balcony area.

This definition was selected as it best reflected the primary function of the building: to provide living space for inhabitants[1].

The functional unit (unit of comparison) adopted for the study was therefore:

Functional unit: Provision of 1m^2 of GDA for 60 years.

The environmental impacts of the buildings over their life cycles were assessed using impact categories prescribed in GBCA (2014). The impact categories assessed are briefly described in Table 2. A complete description of methods used to calculate impact category indicators is included in the body of the report.

Other methods were employed to address the secondary objectives of the study:

i) Comparison of the Study Building was drawn to findings from Durlinger, Crossin and Wong (2012) where it was reasonable to do so. Some manipulation of findings from Durlinger, Crossin and Wong (2012) was required to draw comparisons fairly.

ii) The GBCA's Innovation Challenge – Materials Life Cycle Impacts (GBCA 2014) procedure was employed to calculate available Green Star points for the Study Building.

---

[1] It is recognised that the definition of GDA could impact upon study conclusions. This is investigated as a sensitivity study in Section 7.

Table 2 Impact assessment method.

Impact Category	Unit	Summary Description
Climate change	kg CO_2 eq	Measurement of greenhouse gas emissions into the atmosphere, which cause absorption of infrared radiation that, would have otherwise escaped into space. Increased absorption of infrared radiation leads to an increase in the average temperatures of the Earth and climate change.
Stratospheric ozone depletion potential	kg CFC 11 eq	Release of chemicals into the atmosphere which deplete the Earth's ozone layer.
Acidification potential of land and water	kg SO_2 eq	Release of chemicals into the atmosphere which contribute to 'acid rain' causing the acid related damage to land and waterways.
Eutrophication potential	kg PO_4 eq	The release of nutrients (mainly phosphorous and nitrogen) into land and water systems, which may alter biota, and potentially increase algal growth and related toxic effects.
Photochemical oxidation (smog)	kg C_2H_4 eq	Measurement of the increased potential of photochemical smog events due to the chemical reaction between sunlight and specific gases released into the atmosphere.
Mineral and fossil fuel depletion (abiotic depletion)	kg Sb eq	Measurement of the use of scarce mineral and fossil resources extracted from the environment, which in turn contributes to resource scarcity.

Results: Study Building and Reference Building Compared

Results showed that the Study Building generated reduced environmental impacts in three out of five impact categories considered (climate change: 2% better, ozone depletion: 17% better, abiotic depletion: 3% better) versus the Reference Building (Table 3). In one impact category, photochemical oxidation, the Study Building was shown to be more impactful than the Reference Building (Reference Building 9% better than Study Building). Two impact categories, eutrophication and acidification are found to be inconclusive under uncertainty analysis.

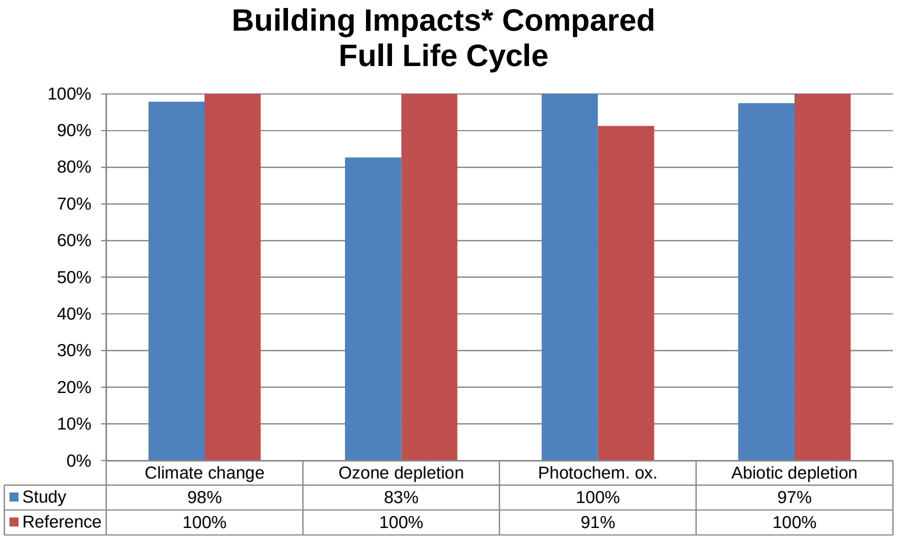
Table 3 Impact assessment results for 1 functional unit (1m^2 GDA provided for 60 years), incorporating results from uncertainty analysis.

Impact Category	Unit	Study Building	Reference Building	Difference (Reference less Study)	Confidence in differential finding under uncertainty analysis*
Climate change	kg CO2 eq	4,062.8	4,152.4	89.6	90%
Ozone depletion	mg CFC-11 eq	26.5	32.0	5.6	90%
Acidification	kg SO2 eq	8.9	8.8	Inconclusive	40%
Eutrophication	kg PO43- eq	2.4	2.4	Inconclusive	30%
Photochem. ox.	g C2H4 eq	279.8	255.4	- 24.4	80%
Abiotic depletion	kg Sb eq	28.9	29.6	0.7	90%

* Interval over which the directional finding is consistent over 1000 simulations. Rounded to nearest 10%

When tested under uncertainty analysis, a confidence greater than 90% was achieved for directional findings in the impact categories of climate change, ozone depletion and abiotic depletion. Confidence in directional outcomes for impact categories of acidification, eutrophication and photochemical oxidation was found to be less than 90% due to uncertainty in the underlying data. Although confidence in photochemical oxidation was shown to be less than 90%, the differential result was still reported as it was felt to be of significance (as opposed to acidification and eutrophication differences which were too close to draw conclusions from).

Results shown in Table 3 are presented in a relative fashion in Figure 2. In this diagram, the building with the largest impact in a given impact category is allocated 100% and building with the smaller impact result is presented as a percentage of the larger impact.



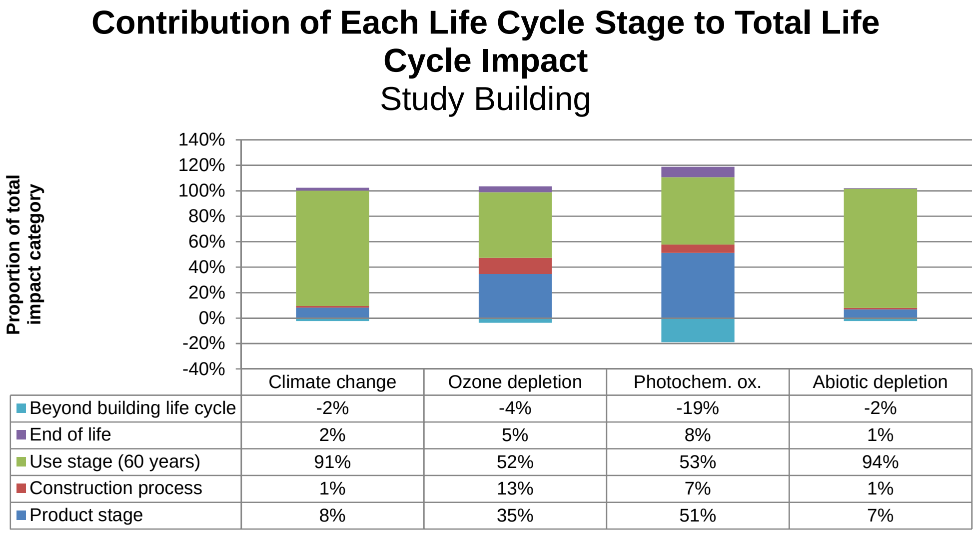
	Climate change	Ozone depletion	Photochem. ox.	Abiotic depletion
🟦 Study	98%	83%	100%	97%
🟥 Reference	100%	100%	91%	100%

* Acidification and eutrophication results were considered to be too uncertain to draw meaningful conclusions from so are excluded from the diagram.

Figure 2 Life cycle impacts compared.

When considered across the entire building life cycle the Study Building achieved 98% of the climate change impacts of Reference Building, 83% of the ozone depletion impacts and 97% of the abiotic depletion impacts. The Reference Building was found to have 97% of the photochemical oxidation impacts of the Study Building, excluding the Use Stage (Figure 4). The environmental advantage of the Study Building in most categories was found to stem from its light weight design which uses one third of the materials of the Reference Building to achieve the same function, and from the use of lower intensity materials. The larger photochemical oxidation impact of the Study Building is due to expected emissions from timber as it degrades in landfill and due to transport related emissions associated with the material supply chain of the Study Building.

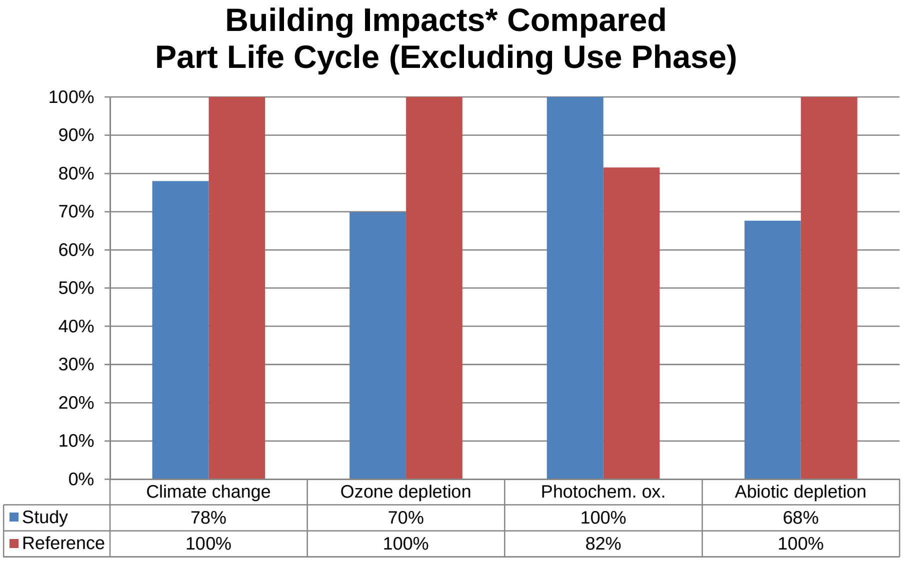
The stages of building life which cause the bulk of life cycle impacts vary between impact categories. Figure 3 shows how each life cycle stage contributes to the total life cycle impact for each impact category. The figure shows that the Use Stage of life causes 91-94% of climate change and abiotic depletion impacts, and 52-53% of ozone depletion and photochemical oxidation impacts for the Study Building. Both ozone depletion and photochemical oxidation are more strongly influenced by the Product life cycle stage (materials). Negative contributions, shown in the Beyond Building Life Cycle stage reflect environmental credits due to the recovery and recycling of building materials at the end of life. The pattern of contributions to life cycle impact is similar for the Reference Building (not shown).



	Climate change	Ozone depletion	Photochem. ox.	Abiotic depletion
Beyond building life cycle	-2%	-4%	-19%	-2%
End of life	2%	5%	8%	1%
Use stage (60 years)	91%	52%	53%	94%
Construction process	1%	13%	7%	1%
Product stage	8%	35%	51%	7%

Figure 3 Contribution of life cycle stages to total life cycle impact - Study Building. Excludes inconclusive impact categories (acidification and eutrophication).

When considered in the absence of the building Use Stage, the Study Building achieved 78% of the climate change impacts of Reference Building, 70% of the ozone depletion impacts and 68% of the abiotic depletion impacts. The Reference Building was found to have 82% of the photochemical oxidation impacts, excluding the Use Stage (Figure 4). Reasons for the differences are essentially the same as for the building life cycle described above as both buildings achieve similar impacts across the Use Stage.



	Climate change	Ozone depletion	Photochem. ox.	Abiotic depletion
🟦 Study	78%	70%	100%	68%
🟥 Reference	100%	100%	82%	100%

* Acidification and eutrophication results were considered to be too uncertain to draw meaningful conclusions from so are excluded from the diagram.

Figure 4 Building impacts compared - partial life cycle (excluding Use Phase). Excludes inconclusive impact categories (acidification and eutrophication).

<u>Results: Study Building compared to Forte building described by Durlinger, Crossin and Wong (2012),</u>

The study also addressed the secondary objective of comparing Study Building findings to those published for the Forte building, described in Durlinger, Crossin and Wong (2012). The building features of the two buildings are compared in Table 4.

Item	Study Building	Forte
Gross Floor Area*	5315 m^2	2431 m^2
Number of apartments	57	23
Number of floors	5 + carpark	9 + retail podium
Location	Parkville, Victoria	Docklands, Victoria
Construction type	Light-weight timber frame on concrete and screw-pile foundations. Exterior walls of rendered phenolic foam panels. Floor system employing engineered timber joists installed in ‘cassette’ modules. Filled concrete block lift and stair core. The building incorporates a basement carpark.	"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." (Durlinger, Crossin & Wong 2012, p5)
Building mass**	453 kg per m^2 GFA	987 kg per m^2 GFA

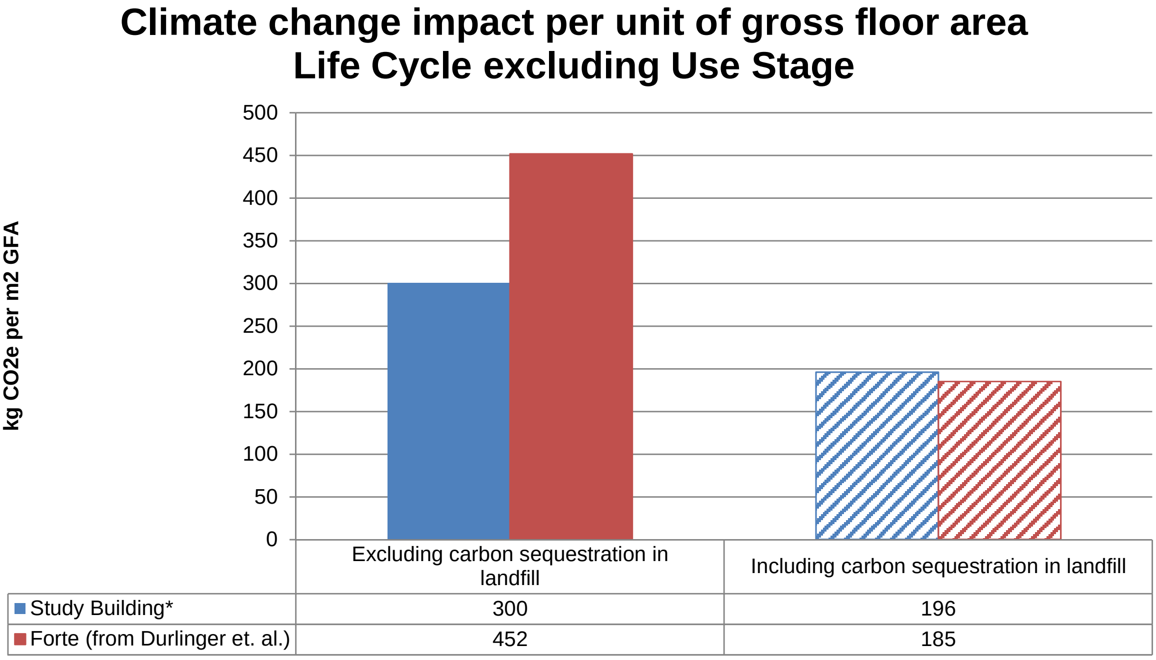
* Forte GFA calculated by dividing cumulative energy demand from table 6.1 by (50 years x cumulative energy demand from table 7.1) of Durlinger, Crossin and Wong (2012).

** Forte total mass calculated from table 5.4 and 5.8 divided by GFA of 2431 m^2 Durlinger, Crossin and Wong (2012).

Table 4 Study Building features compared to Forte (as described in Durlinger, Crossin and Wong (2012).

Comparison of the Study Building to Forte was possible for all life cycle stages except the Use Stage, due to differences in the way this stage was modelled. Only the climate change impact category was compared due to differences in the way other impact categories were disclosed in the reports[2]. Comparison was undertaken on a Gross Floor Area (basis) as GDA was not calculated by Durlinger, Crossin and Wong (2012).

Although demonstrably different buildings, climate change impacts associated with the building life cycle, excluding the Use Stage, were shown to be lower in the Study Building versus Forte on a GFA basis. The comparison was done under the two assumptions used in Durlinger, Crossin and Wong (2012), the first excludes the storage of carbon in landfill, as is the case in this study, and the second includes the storage of carbon in landfill (Figure 4).



	Excluding carbon sequestration in landfill	Including carbon sequestration in landfill
🟦 Study Building*	300	196
🟥 Forte (from Durlinger et. al.)	452	185

* Study building adjusted to exclude fit-out as per Durlinger et. al. (2012)

Figure 5 Climate change impacts of Study Building compared to Forte (as reported in Durlinger et. al. (2012)). Calculations detailed in Section 8.2.

The results shown in Figure 5 demonstrate the significant affect the sequestration assumption, mentioned above has on the climate change impact for the Forte building as it contains a large mass of wood materials. If these materials store carbon in landfill in the long term, then this results in a substantial reduction in life cycle climate change impacts of the Forte building due to its large wood mass.

Under the assumption that no carbon is permanently stored in landfill at the end of the building life, then the Study Building has 66% of the climate change impacts of the Forte building. The main reason for the improved outcome for the Study Building in this instance is due to the significantly lighter weight of the Study Building, weighing approximately 46% of the mass of Forte per unit of GFA provided. If, however, carbon is stored in landfill at the end of building life then Forte would have a climate change impact of 94% that of the Study Building. As mentioned above, the reason for this is the large amount of carbon stored in the building materials disposed of to landfill, which partially offsets manufacturing impacts associated with the larger material mass.

There are sound arguments supporting the inclusion of carbon sequestration in wood products in use and in landfill, however such sequestration is not formally recognised in IPCC guidelines for national greenhouse gas inventories (IPCC 2006) used for reporting under the Kyoto Protocol. As there is no consensus around the treatment of biogenic carbon between methods available in LCA (Levasseur et al. 2013), the approach taken is decided differently from report to report making comparisons between reports difficult, as is the case here. In the base analysis undertaken in this study, the decision to assess flows of biogenic carbon in a manner consistent with the IPCC approach (i.e. treat them as neutral) stems from the authors interpretation of the GBCA requirement to assess climate change

---

[2] Durlinger, Crossin and Wong (2012) used Apache Sim to model the Forte podium space and Accurate (NatHERS) for the apartment spaces. They did not model hot water, and used a mix of HVAC efficiency assumptions. In all, it was considered too difficult to draw a fair comparison between the buildings during the Use Stage.

impacts using the approach employed in the IPCC's forth assessment report (GBCA 2014). The methods adopted in Durlinger, Crossin and Wong (2012) were not aimed at GBCA compliance so adopted an IPCC approach and a storage approach, recognising the lack of agreement in the area. The inconsistency of the approaches taken in the two studies means that comparison between the Study Building and Forte cannot be simply drawn and requires some interpretation.

In Figure 5 the 'excluding sequestration' approach includes climate impacts associated with cultivating, processing and disposing of wood products, however it also assumes that carbon stored in the products themselves or in landfill remains part of a natural cycle so neither causes nor mitigates climate change impacts. Under the IPCC guidelines for national greenhouse gas inventories this would be considered the 'default' accounting approach. From a building design perspective the accounting approach rewards the efficient use of wood materials in construction as reduced material use tends to reduce impacts.

The 'including sequestration' approach shown in Figure 5 considers the cultivating, processing and disposing processes, described above, plus the growth of carbon stock stored in wood products or landfill facilities. The approach considers that a large amount of carbon in wood products is likely to be stored for extended periods of time in use and in landfill so is therefore removed from the natural carbon cycle. From a building design perspective this accounting approach encourages the use of massive wood elements which will store carbon. The approach can represent a paradigm shift because increased use of material can lead to reduced climate change impacts in a building.

In comparing these two buildings it is recognised that they have adopted quite different strategies to achieving their climate change goals. The Study Building has sought to reduce impacts by using all materials as efficiently as possible, whereas the Forte building, it is assumed, has employed an approach that sought to store carbon in the long term. Both approaches reflect rational design responses in an area where consensus around the 'right' approach is yet to coalesce. It is outside the scope of this study to determine which design approach is better however some conclusions can still be drawn from the result.

The Study Building achieves a significantly reduced climate change impact under the base study assumptions and a result that is roughly equivalent to Forte (within the accuracy range of the two studies) under a sequestration scenario. The result shows that in this case the light weight approach of the Study Building achieves climate change impacts comparable to Forte or better, depending on which carbon accounting approach is adopted.

The above comparison provides further evidence that the light weight approach adopted in the Study Building provides significant climate change advantages versus other construction techniques, however it is unlikely to represent a 'final word' on the matter. Both the CLT approach employed in Forte and the light weight approach used in the Study Building are relatively new to Australia so it is likely that both will continue to improve from a climate change perspective as more is learned about each system.

Results: Calculation of Green Star points

An additional objective of the study was to assess the number of Green Star points that could be earned under the GBCA's Green Star Innovation Challenge – Materials Life Cycle Impacts. Green Star innovation points available were shown to be minimal (1.6 of a total of 6 available), as the scheme is highly influenced by building operational impacts, rather than the material innovation exhibited by the Study Building (Table 5). Note that as part of this comparison, the impact categories of acidification and eutrophication are included under the GBCA method even though sufficient confidence in these findings was not achieved.

Table 5 Calculation of Green Star points associated with the Innovation Challenge using the methodology outlined in (GBCA 2014). The column excluding shown excluding the Use Stage (shown in italics), is a theoretical calculation only, and not part of the Innovation Challenge approach.

		Full life cycle			***Excluding Use***		
Impact category	**Unit**	**Study Building**	**Reference Building**	**Percentage change ((Ref-Study)/Ref)**	***Study Building***	***Reference Building***	***Percentage change ((Ref-Study)/Ref)***
Climate change	kg CO2 eq	4062.8	4152.4	2.2%	*382.1*	*489.7*	*22.0%*
Ozone depletion	mg CFC-11 eq	26.5	32.0	17.3%	*12.8*	*18.3*	*30.1%*
Acidification	kg SO2 eq	8.9	8.8	-1.1%	*1.3*	*1.2*	*-7.1%*
Eutrophication	kg PO43- eq	2.4	2.4	1.2%	*0.3*	*0.3*	*9.5%*
Photochem. ox.	g C2H4 eq	279.8	255.4	-9.6%	*131.9*	*107.6*	*-22.6%*
Abiotic depletion	kg Sb eq	28.9	29.6	2.5%	*1.8*	*2.7*	*32.4%*
			Total percentage reduction	**12.6%**			***64.2%***
			Divide by 20				
			Total points generated (rounded)	0.6			*3.2*
			plus 1 point for completing an LCA	1.0			*1.0*
			Total points achieved	**1.6**			***4.2***

As a theoretical exercise, points were recalculated for a partial life cycle that excluded the Use Stage showing the Study Building would earn 4.2 of 6 points available if this approach were to be adopted. The exercised showed that exclusion of the Use Stage may represent a more targeted way of rewarding material innovation, in keeping with the GBCA's stated objective for the materials LCA credit.

It was also noted through this exercise that the points earned by the Study Building were highly influenced by the choice of Reference Building. In this study an actual Reference Building (rather than theoretical) was selected which achieved a similar operational performance to the Study Building in order to illustrate the differences in the buildings due to materials, as is the stated intent of the materials LCA credit. Under the rules of the materials LCA credit a building could have been selected that performed at a 'Deemed to Satisfy' level for energy efficiency (6 Stars rather than 7 Stars), which would have increased the points earned by the Study Building, without any change to materials selections. Clearly this is not the intent of the credit, yet it is allowable under the current rules.

Conclusions

The study set out to better understand the life cycle environmental impacts of the Study Building, incorporating an innovative construction approach, versus the Reference Building, which incorporated a typical construction approach, albeit at a standard that exceeds minimum requirements. The comparison utilised a Reference Building that achieved a similar operational performance to the Study Building in order to illustrate the impact that material selection and construction approach have upon the building life cycle.

When compared, the Study Building was found to perform better than the Reference Building in most indicators over the life cycle. Improvements were most noticeable when the Use Stage of the buildings was excluded from the comparison (which is similar for both buildings). When compared to another innovative building, Forte, described by Durlinger, Crossin and Wong (2012), the Study Building achieved significant reductions in the climate change impact category under the base-case assumption set (excluding carbon sequestration in landfill).

The study also served as an early implementation of the GBCA's Innovation Challenge – Materials Life Cycle Impacts (GBCA 2014). The findings showed that although highly innovative from a materials standpoint, the Study Building was not well rewarded under the scheme which favours operational performance improvement rather than material impact improvement, in contrast to its stated intent. There appears to be some good opportunities to improve the innovation challenge structure to better target materials innovation.

Limitations to Findings

LCA is a powerful methodology for objectively assessing the environmental impacts of buildings, however the approach has its limitations. Although significant effort (refer Section 3.5 and Section 7) has been made to verify the study outcomes, some key limitations to findings remain:

a) Uncertainty analysis shows that and comparative conclusions cannot be drawn for acidification and eutrophication indicators assessed.

b) Some uncertainty remains with respect to the photochemical oxidation findings drawn. Confidence in this indicator is less the other indicators assessed.

c) Although not a driver of difference in this study, the estimation of building operational energy use is notoriously difficult. Energy use estimates informing Use Stage outcomes represent a significant source of uncertainty in both buildings. The mix of fuel sources used to generate electricity, for example, is constantly changing (refer Section 5.3.1) making long term predictions of environmental impact difficult.

d) Impacts associated with End of Life and Beyond Building Life Stages involve predictions of material degradation behaviour in landfill and recycling rates. As these processes occur over extended periods some considerable time in the future, prediction of their impacts is difficult at best. An advantage of the EN15978 standard, used in this study to guide system boundaries, is that it prescribes a standard approach to this issue.

2 Introduction

This study compares the life cycle environmental impacts of two multilevel residential buildings built in Melbourne, Australia. The first building, the 'Study Building' incorporates an innovative light weight building approach utilising a stick-built timber frame and a 'cassette floor' flooring system. The second building, the 'Reference Building' utilises a more typical building approach, incorporating precast concrete panels and suspended concrete slab floors. The buildings are compared us the life cycle assessment (LCA) methodology as described by ISO14044 standard.

2.1 Commissioning parties

The study was commissioned by Australand and funded by Forest and Wood Products Australia (FWPA). Australand is a member of Frasers Centerpoint and is a property group with activities in residential, commercial and industrial property sectors. Both the Study Building and the Reference Building addressed by this study have been developed by Australand.

FWPA is a not for profit company that provides integrated research and development services to the Australian forest and wood products industry.

2.2 Peer review

The study has been peer reviewed by Jonas Bengtsson of Edge Environment. Comments raised during peer review and author responses have been noted in Appendix E.

2.3 Acknowledgements

The authors would like to thank Australand and their joint venture partner Citta Property Group for providing the building case studies and supporting data for analysis.

In addition we wish to acknowledge the contributions of the following people. Firstly to Paolo Belivacqua of Australand who conceived of the study and Chris Lafferty of FWPA who supported its development. A special thank you to Simon O'Brien who supported much of the data collection activity and Kase Jong who answered many questions regarding the Study Building design. Thanks also to Ellie Raad and Sam Gallagher of Buildcorp, and Robert and Darius from Promat for supporting data collection and answering queries.

Finally the authors would like to thank Dr James Wong who helped with the thermal modelling undertaken and Dr. Rebecca Yang who helped reviewing report drafts.

3 Goal and Scope

3.1 Goal of the study

The primary aim is to compare the potential life cycle environmental impacts of a multi-storey residential building constructed using a light-weight approach to the impacts of a building constructed using a typical, heavy-weight approach. In doing so the comparison seeks to quantify the difference in expected environmental impacts and identify life cycle stages that cause these differences.

A secondary aim is to compare the outcomes of the study to the findings developed for the Forte building described by Durlinger, Crossin and Wong (2012). Forte is a 10 storey residential apartment building recently constructed in Docklands, Victoria. The building incorporates an innovative timber structure (Cross Laminated Timber panels) incorporating 23 apartments on top of a concrete retail podium.

In consideration of these aims, the study adopts an approach that is consistent with the Green Building Council of Australia’s Innovation Challenge – Materials Life Cycle Impacts (GBCA 2014) which allows Green Star points to be earned if certain criteria are met when a life cycle assessment (LCA) is undertaken for a building.

3.2 Intended audience

The study is intended to be read by a broad audience and will be made public.

3.3 Scope

Study scope can be considered in terms of the buildings that are considered and the stages of building life which are addressed, as described in the following sections.

3.3.1 Buildings considered

The study considers two multi-storey residential buildings of similar scale and location that provide comparable functions. The first building, the Study Building, comprises five storeys and a basement carpark connected by a central lift core (Figure 6). The building has a gross floor area (GFA) of 5,315 m^2 incorporating 57 separate one, two and three bedroom apartments and 943 m^2 of undercover carpark space. Overall the building provides 3,895 m^2 of private apartment area of which 328 m^2 is balcony space.

Figure 6 Study Building exterior.

The building has been built in Parkville, a suburb of Melbourne, Australia. It is built upon a reinforced concrete slab foundation anchored to steel screw piles upon which a light-weight structure is erected. The structure of the building is made up of a concrete block central lift/stair core around which prefabricated timber wall frames are assembled. The floor structure of the building is a concrete suspended slab at the ground floor, which changes to timber ‘cassette’ floor systems for the upper levels. A section through the building is shown in Figure 7.

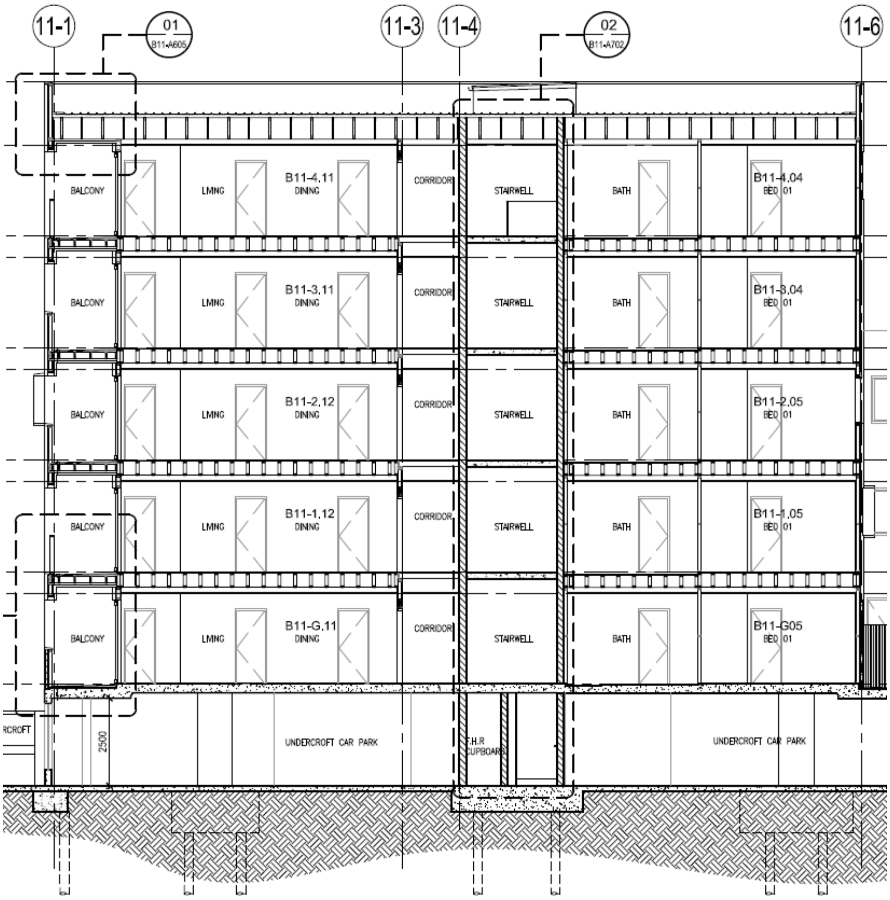


Figure 7 Study Building section.

The cassette floor system incorporated in the Study Building is relatively unique in Australia and provides particular advantages during assembly, such as reduced on-site assembly time and increased site safety. Each floor of the building is divided into roughly 60 cassettes, each of which is individually hoisted into position. Each cassette comprises composite metal/timber joists and cement board floor surface panels.

The roof of the building comprises a steel deck supported upon engineered timber trusses.

The second building, the Reference Building, comprises eight storeys and a basement carpark connected by a central lift core (Figure 8). The building has a GFA of 8,282 m^2 incorporating 91 separate one, two and three bedroom apartments and 1,687 m^2 of undercover carpark space. Overall the building provides 5,912 m^2 of private apartment area of which 565 m^2 is balcony space.

Figure 8 Reference Building exterior.

The Reference Building is built upon a reinforced concrete slab foundation anchored to concrete piles. The walls of the building are largely precast panels (external and party walls) erected around a precast central lift and stair core. Floors are suspended slabs which are cast in place and post-tensioned. The roof of the building is also a concrete slab.

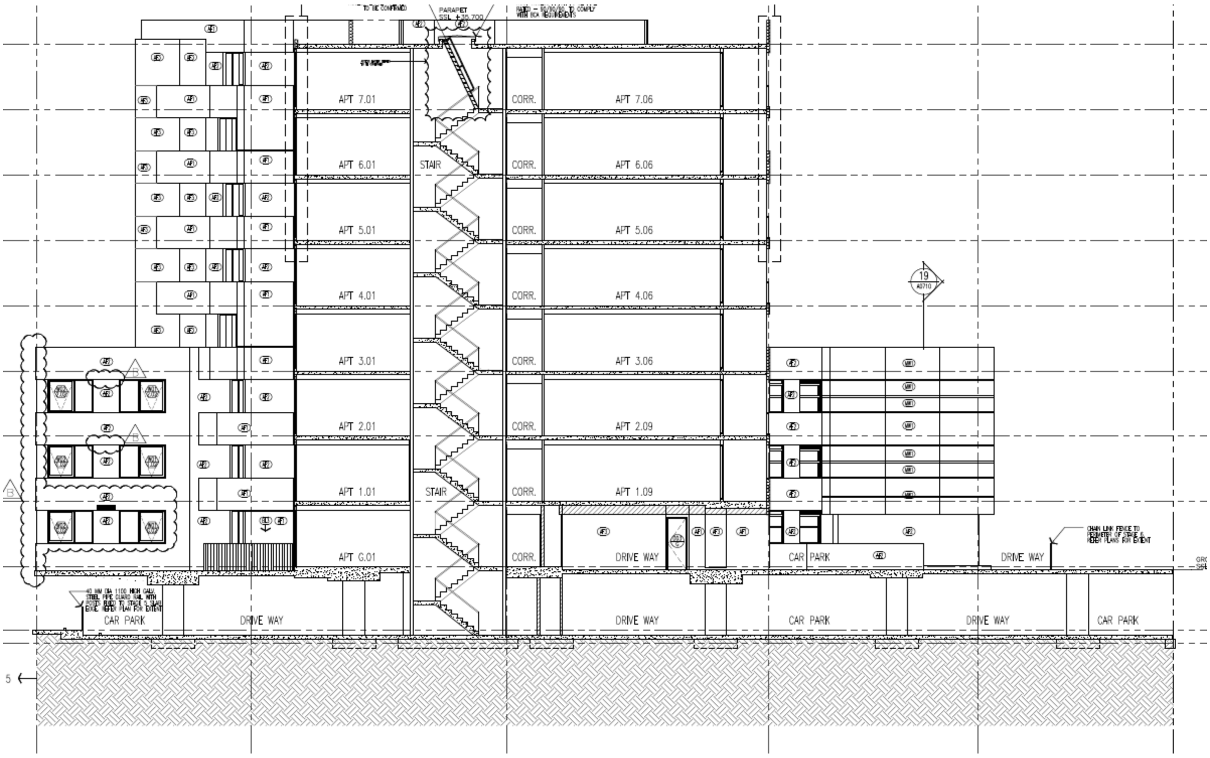


Figure 9 Reference Building section.

Although differing in scale, the Reference Building was selected for comparison as it meets a number of important benchmarking criteria, as follows:

- It is under construction at the time of report writing. It therefore reflects contemporary construction practice and building code compliance.
- It is under construction at the same location (Parkville) as the Study Building so shares construction boundary conditions such as soil conditions and thermal environment.
- Importantly, as an Australand/Citta project, the information regarding the design was available.

A section through the Reference Building is shown in Figure 9.

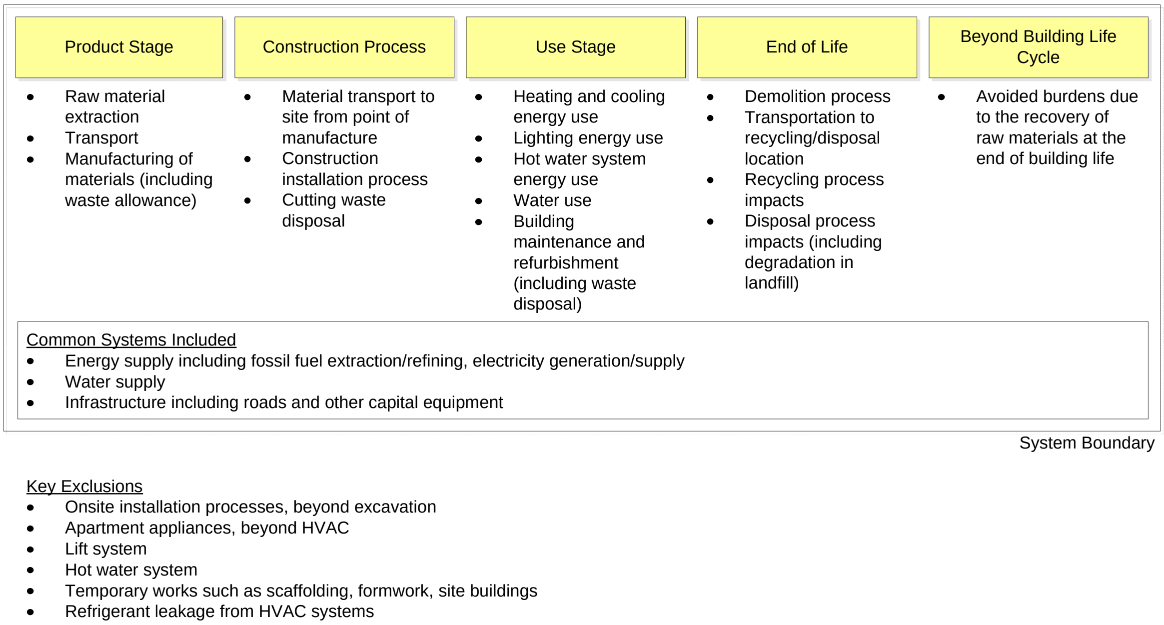
3.3.2 Building life cycle stages considered

The building life cycle stages considered are those described by EN15978 (2011) – Sustainability of Construction Works – Assessment of Environmental Performance of Buildings – Calculation Method. The standard has been selected to guide the system boundary definition as it provides a well-considered breakdown of the building life cycle into stages which can then be compared to other studies. The standard is also relevant as it is referred to by GBCA's Materials Innovation Challenge (GBCA 2014).

The building life cycle stages considered in the study are shown within the system boundary shown in Figure 10. The building life cycle is deemed to commence at the Product Stage, which includes those processes needed to extract raw materials from the environment and manufacture them into useful building materials. The stage includes all impacts generated during activities as well as impacts due to supporting processes such as the generation of electricity or the provision of suitable fossil fuels. Indeed, all project stages incorporate the supporting common systems associated with energy provision, material transportation, water supply and infrastructure.

Materials addressed in the Product Stage include all those needed to complete the building foundations, structure and fabric. Materials also include those needed to fit-out, each apartment and common area (floor & wall coverings, plumbing, wiring, cabinetry and appliances).

The Construction Process stage includes the transport of materials from point of manufacture to the construction site. Importantly, the stage includes the production and disposal of construction related waste materials that are ordered in excess of what is technically required in the building's finished condition.



Product Stage	Construction Process	Use Stage	End of Life	Beyond Building Life Cycle
• Raw material extraction • Transport • Manufacturing of materials (including waste allowance)	• Material transport to site from point of manufacture • Construction installation process • Cutting waste disposal	• Heating and cooling energy use • Lighting energy use • Hot water system energy use • Water use • Building maintenance and refurbishment (including waste disposal)	• Demolition process • Transportation to recycling/disposal location • Recycling process impacts • Disposal process impacts (including degradation in landfill)	• Avoided burdens due to the recovery of raw materials at the end of building life

Common Systems Included

- Energy supply including fossil fuel extraction/refining, electricity generation/supply
- Water supply
- Infrastructure including roads and other capital equipment

System Boundary

Key Exclusions

- Onsite installation processes, beyond excavation
- Apartment appliances, beyond HVAC
- Lift system
- Hot water system
- Temporary works such as scaffolding, formwork, site buildings
- Refrigerant leakage from HVAC systems

Figure 10 System boundary.

Unfortunately, little is known about the detailed impacts of on-site machinery beyond simple excavation and site levelling. The other on-site machinery usage is therefore excluded from the study.

The Use Stage includes the energy needed to heat and cool the building and to provide lighting and hot water. Also included are maintenance activities such as repainting and periodic apartment refurbishment and the related waste disposal.

The End of Life stage addresses those processes needed to demolish the building and recover or dispose of the building’s materials. The stage includes the processing of waste in landfill and the associated emissions generated, particularly those for organic materials. Where materials are recovered for recycling, the stage includes the recovery processes and material reprocessing impacts. Importantly, the stage does not include avoided burdens or other benefits associated with materials extracted by recycling activity. These are addressed in the Beyond Building Life Cycle stage.

The final stage addressed is the Beyond Building Life Cycle stage. This stage relates to benefits that occur due to the recovery of materials after the building is demolished. In this study, the stage relates to avoided burdens due to the recovery of materials from waste streams during construction and after it is demolished.

3.4 Functional Unit

The assessment of the potential environmental impacts of buildings is made more useful if results can be related in some way to the provision of service. Indeed the LCA standard, ISO14044, requires that the connection between building impacts and services be drawn by defining a functional unit for a building to which building life cycle impacts are related. The challenge of the approach is that it involves the reduction of the myriad of services provided by a building to something essential, such as the provision of conditioned and outdoor living space. In reducing the function to the provision of space many of the aspects that make buildings important to people are ignored, such as their liveability or aesthetic value. Although the standardisation of building function, and therefore study results, helps make buildings comparable, the limitations of the reduction involved need to be kept in mind.

In this study the functional unit adopted is broadly described by the GBCA (2014). The essential service provided by the residential apartment building is deemed to be the provision of gross dwellable area (GDA), however a precise definition of GDA is not provided by the GBCA. Without a definition of GDA, three area definitions were considered:

1) Gross floor area (GFA) – total area provided on each floor of the building including: lifts, corridors, foyers, stairwells, apartment interiors, car parking and apartment balconies.
2) Enclosed apartment area – Area within each apartment, excluding balconies.
3) Total apartment area – Area within each apartment plus the balcony area.

After consideration of the three area definitions above, definition 3) was selected to represent GDA as it best reflected the primary function of the building – to provide living space for inhabitants[3].

The functional unit is therefore defined as follows, adopting the GBCA default building life requirement of 60 years:

Functional unit: Provision of 1m^2 of GDA for 60 years.

3.5 Data quality requirements

The primary aim of the study is to compare the potential life cycle impacts of two buildings across the life cycle stages defined by Figure 10. Data must therefore be of sufficient quality to support a conclusion of difference between the buildings, and the quantum of this difference. Unfortunately, as LCA involves a myriad of data points and modelling decisions, objectively specifying data quality needed to draw a conclusion is problematic. Instead the approach taken in this study is to employ a number of strategies that seek to manage data quality transparently and qualify conclusions accordingly. The strategies employed are detailed in the following sections.

3.5.1 Data consistency

As a comparative study it is imperative that data be selected that are consistent between the buildings being considered. For example, electricity used in the operation of the buildings should be estimated using the same modelling approach and elementary flows (such as greenhouse gas emissions) should be derived from the same production model. Further, it is important that common materials used in the buildings (such as glass and steel) should be derived from consistent production models (where locally sourced). Integrity should also extend to differing materials employed that share identical production factors such as electricity or diesel fuel. For example, diesel fuel used in the excavation of the building site should be from the same production model as diesel fuel used for truck transport.

Consistency between building life cycle models is achieved by using a common background database of life cycle inventories for both models. The background database is essentially an interlinked set of life cycle inventories that can be assembled as building blocks to form the building model. Figure 11 illustrates the approach by showing how consistency is maintained between background production inventories in a common LCI database.

---

[3] It is recognised that the definition of GDA could impact upon study conclusions. This is investigated as a sensitivity study in Section 7.

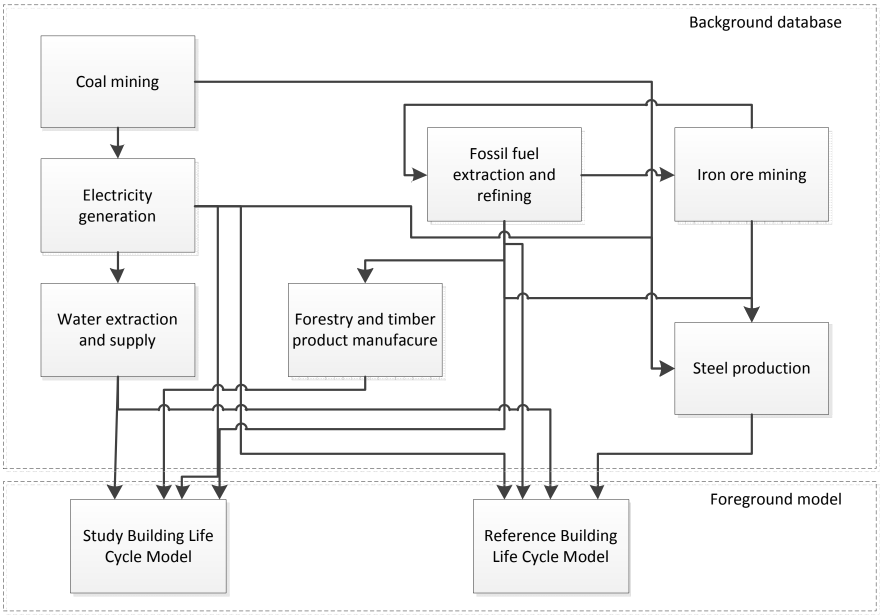


Figure 11 Foreground versus background example.

Wherever possible, life cycle inventories in this study have been taken from the AusLCI Database developed by the Australian Life Cycle Assessment Society (ALCAS), and distributed in Sima Pro format by Life Cycle Strategies. The AusLCI dataset supports two classes of data: 1) original data sets prepared in accordance with the AusLCI project which are based on inventory data collected from Australian processes in accordance with the AusLCI protocol, and 2) shadow data sets which are based on EcoInvent data which typically refer to European production processes. Shadow inventories have been modified where possible to utilise Australian sources of energy and fossil fuel.

The advantage of the AusLCI Database is that it contains a wide range of materials which employ reasonably consistent energy supply assumptions. As most models are transparently documented, overall transparency of the database is reasonable and can be modified where needed.

In situations where this has not been possible (for example when an inventory does not exist in AusLCI) inventories have been selected from the Australasian LCI Database (AUPLCI) which is maintained by Life Cycle Strategies, and checked for supply chain consistency. Both databases contain inventories that are appropriate to local and international production conditions.

When selecting inventories within the database, the most recent, geographically appropriate and technologically appropriate inventories were selected where multiple options existed.

In addition to consistency within the LCI database, it is important that the quantities of background inventories employed in the foreground model have been derived using similar techniques. In this study two key techniques drive much of the life cycle model quantities: The first is the development of the bill of quantities and the second is the estimation of operational energy and water use.

The bill of quantities for both buildings has been developed directly from the construction drawings by the study authors. Although introducing some systematic uncertainties with respect to drawing measurement and interpretation, consistency is improved as both building quantities have been developed using an identical approach. This approach was considered to be superior to individual quantity surveyor estimates which are likely to employ inconsistent approaches, geared to a cost estimate rather than component material mass estimate.

Additionally, the operational energy and water use estimates employ a consistent estimation approach by utilising the Green Star Multiunit Residential Greenhouse Gas Calculator (v1) which in turn employs the NatHERS protocol to estimate heating and cooling energy loads.

3.5.2 Data transparency

Wherever possible data have been selected that are timely, geographically appropriate and technically appropriate, however good data quality is not achieved for every point in the LCA model. To address this shortcoming each data point in the foreground model is assessed and reported in the study inventory. This approach allows areas of quality deficiency to be addressed using alternative techniques such as uncertainty analysis, benchmarking and sensitivity analysis.

Within the foreground model described by Figure 11 data have two elements. Firstly, each point typically contains a quantity of a material or process and secondly it specifies a life cycle inventory from the background database that represents the material or process being specified. For example, a building life cycle inventory might contain a quantity of inbound truck transport, measured in tonne.kilometers (t.km), needed to bring component materials to the building site. Data quality in this case has two dimensions, the first is associated with error (deviation from actual) in the quantity specified, and the second is associated with the representativeness of the trucking model selected.

To assess the error in the quantity of materials or processes employed, the Pedigree Matrix has been employed for each foreground element in the LCA model, as described in the following Section 3.5.3. To assess the representativeness of the LCI selected from the background inventory a subjective assessment of inventory appropriateness has been undertaken in Section 5.7.

In addition to providing a transparent data quantity assessment for all foreground inventory elements, the study also provides sources for background life cycle inventories and quantity data employed, enhancing study reproducibility.

3.5.3 Data uncertainty analysis

Quantities of materials and processes employed in the LCA model deviate from actual quantities to varying degrees. To assess the uncertainty of the foreground model quantities and many of the background model quantities, the Pedigree Matrix has been employed. In this study the data Pedigree Matrix utilised by Ecoinvent (Frischknecht & Jungbluth 2004) is used and identical ‘basic uncertainty’ factors adopted. The method requires that each foreground data point be assessed in terms of the dimensions described in Table 6 and given a score out of 5. These scores are used with underlying ‘basic uncertainties’ to develop a lognormal standard deviation measure for the respective data point.

Table 6 Pedigree Matrix (Frischknecht & Jungbluth 2004).

Reliability	Score	Completeness	Score	Temporal correlation	Score	Geographical correlation	Score	Further technological correlation	Score	Sample size	Score
a. Verified data based on measurements	1	a. Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	1	a. Less than 3 years of difference to our reference year (2010)	1	a. Data from area under study	1	a. Data from enterprises, processes and materials under study (i.e. identical technology)	1	a. >100, continous measurement, balance of purchased products	1
b. Verified data partly based on assumptions OR non-verified data based on measurements	2	b. Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	2	b. Less than 6 years of difference to our reference year (2010)	2	b. Average data from larger area in which the area under study is included	2	b. NOT USED	2	b. >20	2
c. Non-verified data partly based on qualified estimates	3	c. Representative data from only some sites (<<50%) relevant for the market considered OR >50% of sites but from shorter periods	3	c. Less than 10 years of difference to our reference year (2010)	3	c. Data from smaller area than area under study, or from similar area	3	c. Data on related processes or materials but same technology, OR Data from processes and materials under study but from different technology	3	c. > 10, aggregated figure in env. Report	3
d. Qualified estimate (e.g. by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)	4	d. Representative data from only one site relevant for the market considered OR some sites but from shorter periods	4	d. Less than 15 years of difference to our reference year (2010)	4	d. NOT USED	4	d. Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	4	d. >=3	4
e. Non-qualified estimate	5	e. Representativeness unknown or data from a small number of sites AND from shorter periods	5	e. Age of data unknown or more than 15 years of difference to our reference year (2010)	5	e. Data from unknown OR distinctly different area (north america instead of middle east, OECD-Europe instead of Russia)	5	e. Data on related processes or materials but on laboratory scale of different technology	5	e. unknown	5

A benefit of the approach, and a reason for its development, is that it also provides a semi-quantitative approach to analysing the aggregate uncertainty of the study results. This is possible because similar uncertainty analysis has been undertaken for much of the background inventory data which the study utilises, facilitating the use of Monte Carlo simulation to estimate aggregate result uncertainty.

3.5.4 Data benchmarking

In this study, the key point of difference between the building life cycles considered is their material make up (both perform in an operationally similar fashion). This means that the impact profiles of dominant construction materials such as concrete, timber and steel are likely to drive differences between the buildings. For this reason, these materials and others have been impact assessed in unit form (per kilogram or per cubic meter) and results compared to similar studies and alternative life cycle inventory databases. This approach reduces the likelihood of error existing within the background inventories applied in both life cycle models.

3.5.5 Sensitivity analysis

In instances where data quality is insufficient sensitivity analysis is employed to assess the impact on study conclusions. This approach involves altering the data point in question and reviewing the impact on study conclusions. Sensitivity analyses are presented in Section 7.

3.6 Treatment of missing data

Where data were not available for the project, qualified estimates have been employed and such estimates documented in the study inventory. In situations where a range of possible estimates exist to fill a data gap, the chosen data point was selected to advantage the Reference Building over the Study Building. This approach, when combined with the uncertainty analysis described in Section 3.5.3, sought to eliminate any advantage that may be ascribed to the Study Building due to missing data.

3.7 Cut-off criteria

Cut off criteria were based on mass flow. Although impossible to objectively assess, it is estimated that mass flows representing 1-2% of total building mass have been omitted from the study.

3.8 Allocation procedures

A number of processes within the system boundary are associated with having multiple inputs and/or outputs. For delivering the functional unit, a procedure for partitioning impacts associated with these processes is required.

ISO 14044:2006 contains a hierarchal procedure for partitioning:

> *Step 1: Wherever possible, allocation should be avoided by:*
>
> *a) 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*
>
> *b) expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3.*
>
> *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.*
>
> *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 accordance to ISO 14044:2006, where possible, allocation has been avoided by using systems expansion.

In this study, the systems which have been subject to the ISO 14044:2006 hierarchy are multi-input, multi-output and recycling processes. Allocation for multi-input processes is based upon the physical composition of the inputs, with emissions from related stoichiometric reactions. The impacts of transport tasks have been allocated based on the mass of the materials being transported and the distance travelled.

The most significant allocation decision in this study involves the calculation of benefits due to recycling which are addressed in the Beyond Building Life Cycle stage (refer Figure 10). These benefits have been simply determined by calculating the quantities of reprocessed materials generated by reprocessing activities and subtracting the environmental burdens of an equivalent quantity of material produced from resources extracted from the environment. This approach reflects a form of system boundary expansion.

3.9 Impact Assessment

Impact assessment method employed in the study is that prescribed in GBCA (2014). The indicators assessed are as shown in Table 7.

Table 7 Impact assessment method.

Impact Category	Unit	Description
Climate change	kg CO_2 eq	Measurement of greenhouse gas emissions into the atmosphere, which cause absorption of infrared radiation that, would have otherwise escaped into space. Increased absorption of infrared radiation leads to an increase in the average temperatures of the Earth and climate change. 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 Fourth Assessment Report.
Stratospheric ozone depletion potential	kg CFC 11 eq	Release of chemicals into the atmosphere which deplete the Earth's ozone layer. The characterisation model is developed by the World Meteorological Organisation (WMO) and defines ozone depletion potential of different gases. Source: CML-IA Method as published in Sima Pro. Version 3.01 (2014)
Acidification potential of land and water	kg SO_2 eq	Release of chemicals into the atmosphere which contribute to 'acid rain' causing the acid related damage to land and waterways. Acidification potential expressed in kg SO2 equivalents per kg emission. Model is developed by Huijbregts. Source: CML-IA Method as published in Sima Pro. Version 3.01 (2014)
Eutrophication potential	kg PO_4 eq	The release of nutrients (mainly phosphorous and nitrogen) into land and water systems, which may alter biota, and potentially increase algal growth and related toxic effects. Eutrophication potential developed by Heijungs et al and expressed in kg PO4 equivalents per kg emission. Source: CML-IA Method as published in Sima Pro. Version 3.01 (2014)
Photochemical oxidation (smog)	kg C_2H_4 eq	Measurement of the increased potential of photochemical smog events due to the chemical reaction between sunlight and specific gases released into the atmosphere. The model is developed by Jenkin & Hayman and Derwent and defines photochemical oxidation expressed in kg ethylene equivalents per kg emission. Source: CML-IA Method as published in Sima Pro. Version 3.01 (2014)
Mineral and fossil fuel depletion (abiotic depletion)	kg Sb eq	Measurement of the use of scarce mineral and fossil resources extracted from the environment, which in turn contributes to resource scarcity. Abiotic depletion (elements, ultimate reserves) is related to extraction of minerals due to inputs in the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals (kg antimony equivalents/kg extraction) based on concentration reserves and rate of deaccumulation. Abiotic depletion of fossil fuels is related to the Lower Heating Value (LHV) expressed in MJ per kg of m3 fossil fuel. The reason for taking the LHV is that fossil fuels are considered to be fully substitutable. Source: CML-IA Method as published in Sima Pro. Version 3.01 (2014)

3.10 Treatment of biogenic flows

The treatment of carbon dioxide emissions from biogenic sources (plant or animal origin) can materially impact the quantification of climate change impacts in a study such as this. Failure to properly account for carbon from biogenic sources can lead to a material understatement or overstatement of climate change impacts. To avoid this problem, this study adopts the IPCC guidelines adopted for the development of greenhouse gas inventories, as follows:

> ”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 2006)

Based on these guidelines and to ensure carbon balance, biogenic carbon dioxide inputs and air emissions were assigned a climate change 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_2e per kilogram relative to fossil methane.

The treatment of non-degraded biogenic carbon in landfill is modelled as a non-assessed flow (as opposed to carbon sequestration). In this study, the sequestration of biogenic carbon landfill within landfill would impact upon the timber product life cycle most significantly.

4 Methodology

The study employed the LCA method described by ISO14044 to address the primary objective of comparing the Study Building and the Reference Building. This method represents the bulk of work undertaken in completing the study, however complementary methods were required to address the secondary study objectives. The methods used are explained more fully in the following sections.

Table 8 Methods employed.

Objective	Method
Primary: Compare the environmental impacts of the Study Building and the Reference Building	ISO 14044
Secondary: Compare the outcomes of the study to the findings developed for the Forte building described by Durlinger, Crossin and Wong (2012)	Comparison of the Study Building was drawn to findings from Durlinger, Crossin and Wong (2012) where it was reasonable to do so. Some manipulation of findings from Durlinger, Crossin and Wong (2012) was required to draw comparisons fairly.
Secondary: Calculating Green Star points that may be earned by the Study Building under the GBCA's Innovation Challenge – Materials Life Cycle Impacts (GBCA 2014)	The GBCA's Innovation Challenge – Materials Life Cycle Impacts (GBCA 2014) procedure was employed to calculate available Green Star points for the Study Building.

4.1 Comparing the Study Building and the Reference Building

The study employed the LCA framework described by ISO 14044:2006 to undertake the comparison of the Study Building and the Reference Building. The standard defines LCA as:

> "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its lifecycle" (ISO 14040:2006 pp.2).

The technical framework for LCA consists of four components, each having a very important role in the assessment. The components are goal and scope definition, inventory analysis, impact assessment and interpretation as illustrated in Figure 12.

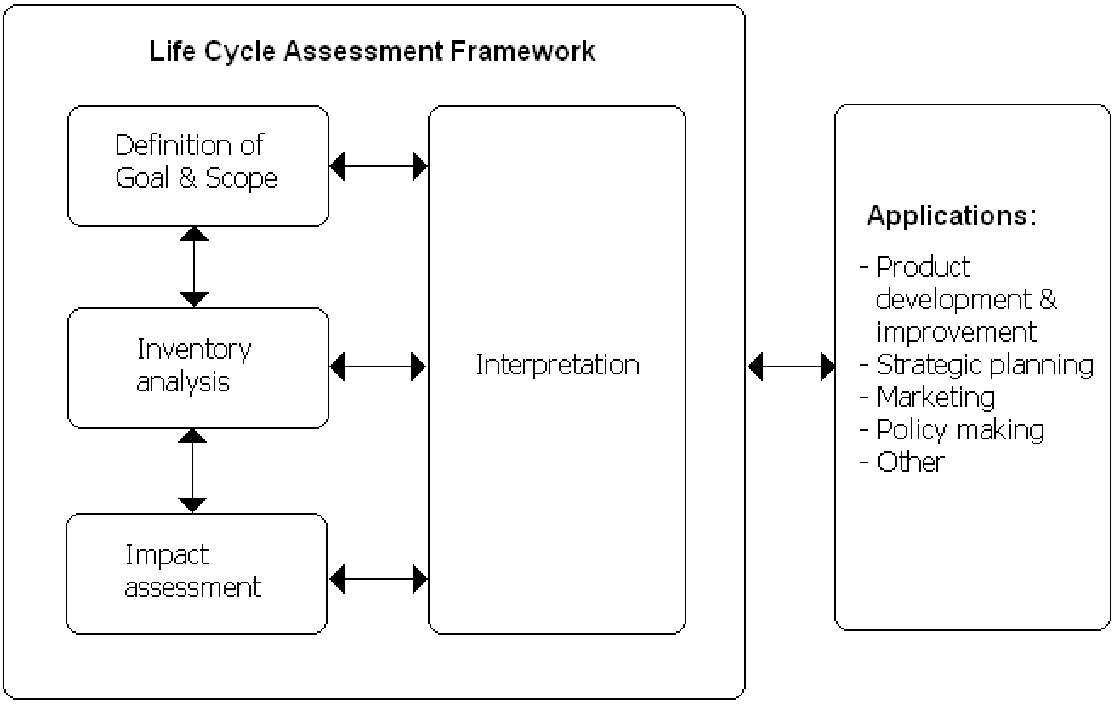


Figure 12 The Framework for LCA (ISO14044:2006)

As shown in Figure 12 the LCA process is not necessarily implemented in a linear fashion. Each of the component stages relates closely to each other stage and there is a lot of back and forth as analysis is completed.

In this study, the LCA framework was implemented in the following fashion.

4.1.1 Goal and scope development

The goals of the study were developed in consultation with Australand following a series of discussions. These goals are documented in Section 3. Key decisions such as the nature of the system boundary, the functional unit and the impact assessment method were heavily influenced by standards such as GBCA (2014) and EN15978:2011.

4.1.2 Inventory analysis

Inventory development was mainly focussed upon the creation of a transparent bill of quantities for each building considered. This involved a detailed review of architectural and structural drawings from which material quantities were developed. The online project data repository Aconex was used for this purpose as both buildings considered had complete data sets available.

As material quantities were developed, supplier locations were also collated in consultation with Australand. These locations, along with material masses were used to develop transport tasks employed within the inventory.

Further inventory development activities were also carried out such as the estimation of building operational energy loads, refurbishment activities and identification of building material fates at end of life.

As the inventory was developed it was documented using the spreadsheet package Excel (Microsoft) and an LCA model was created in Sima Pro (Pre Consultants). Sima Pro is a software package which is specifically designed to facilitate LCA by allowing users to create life cycle models based on material and energy reference flows. Sima Pro is useful as it allows the user to easily access existing life cycle inventories (LCIs) which convert foreground data, usually in the form of basic material flows such as kilograms of steel needed in a building, into elementary environmental exchanges associated with the production of that steel, such as emissions of carbon dioxide to the atmosphere. When complete the study inventory was expressed in terms of these elementary exchanges per functional unit provided.

The inventory is documented in Section 5.

4.1.3 Impact assessment

Impact assessment was undertaken using the Sima Pro software package using the methods described in Section 3.9. Sima Pro undertakes this task by aggregating the elementary flows developed for the inventory and multiplying each by a characterisation factor prescribed by the assessment method used. Elementary environmental exchanges that cause greater damage in a given impact category (ie. Climate change) attract larger factors, and lessor impact exchanges smaller factors.

After completing checks, such as a review of missing substances, the impact assessment forms the basic result of the study and is reported in Section 6.

4.1.4 Interpretation

The interpretation stage of the LCA was undertaken once the impact assessment was completed and attempts to relate outcomes to study goals and inventory elements. As a building LCA, this involved looking at the drivers of outcomes across life cycle stages and across building elements. Conclusions were also drawn as part of this stage, informed by the results, discussion and data uncertainties. Interpretation is reflected in Sections 8 and 9 of this report.

4.2 Comparing the outcomes to Forte

In addition to comparing the Study Building to the Reference Building, an objective of the study was to compare results to the Forte building reported in the LCA study by Durlinger, Crossin and Wong (2012). As the Forte study employed slightly different assumptions to those employed in this study, only partial comparisons could be drawn. Comparison was therefore limited to life cycle stages excluding the Use Stage (Product, Construction, End of Life, Beyond Building Life). The Use Stage of life could not be compared as modelling of this stage was not consistent between the studies.

4.3 Calculating Green Star points under the Innovation Challenge

The GBCA's Innovation Challenge – Materials Life Cycle Impacts (GBCA 2014) procedure was employed to calculate available Green Star points for the Study Building. The procedure involves assessing the percentage difference in life cycle impact between the Study Building and the Reference Building. The percentage difference in each impact category is totalled and divided by 20 to give a Green Star point score. The approach is demonstrated in Section 8.3.

5 Inventory

The following section describes the outcomes of the life cycle inventory analysis conducted for the Study Building and Reference Building. The inventory developed describes the reference flows (material and energy) required to provide a single functional unit from each building (1m^2 GDA).

The section is presented to accord with the building life cycle described in Section 3.

5.1 Product stage

5.1.1 Development of material quantities

A bill of quantities for each building was developed from a comprehensive set of design drawings for each building. Drawings were provided in electronic form and included architectural and structural drawings. All were considered to be at ‘construction’ release.

Drawings were reviewed manually in hard-copy form and quantities developed through drawing interpretation. This approach was employed as it enabled a consistent and transparent approach. Alternatives considered, such as employing construction cost estimates, tended to lack transparency or appeared to employ inconsistent approaches to the buildings considered.

From the drawing quantity estimate (net material mass) a gross material mass was developed which incorporated an allowance for material waste generated on site. Wastes expected were estimated based upon (Cochran & Townsend 2010) where possible (Table 9). For other materials, an estimate of 5% for linear materials, 5% for liquid materials and 10% for board materials were employed.

Table 9 Material waste estimates (compiled by Cochran and Townsend (2010) from DelPico (2004) and Thomas (1991))

Material	% Waste
Concrete	3
Brick and other clay products	4
Drywall and other calcined gypsum products	10
Wood products	5

From the drawing analysis a detailed material model was developed in the LCA modelling software Sima Pro using background life cycle inventories as described in Appendix A and Appendix B. Each element in the material model was assessed for uncertainty and representativeness using the processes described in Section 3.5.

A further check of material quantity estimates was undertaken by comparing independent estimates of material quantities developed by practitioners familiar with each building. These were compared to the estimates developed from the drawings and the implications of differences investigated (refer Section 7).

5.1.2 Building material quantities before fit-out.

A summary of gross building material quantities is shown in Table 10. Gross material masses include wastes that would be generated on site though cutting and other losses. The Reference Building (5,912 m^2 GDA) is larger than the Study Building (3,895 m^2 GDA) so requires more material to construct, however when results are normalised for area is still shown to be significantly heavier than the Study Building (1,653 kg/m2 GDA versus 618 kg/m^2 GDA).

Table 10 Gross material mass (includes allowance for waste on site), before fitout.

	Study Building		Reference Building	
Item	**kg**	**kg/m2 GDA**	**kg**	**kg/m2 GDA**
Concrete	1,367,845	351	8,768,470	1,483
Wood framing	233,240	60	-	-
Cement board	225,145	58	-	-
Plasterboard	205,285	53	278,583	47
Concrete blocks	130,537	34	36,192	6
Steel	115,605	30	388,342	66
Aggregates and sands	77,868	20	246,963	42
Windows	25,563	7	31,902	5
Other materials	27,830	7	21,421	4
Total Building	**2,408,919**	**618**	**9,771,872**	**1,653**
Total includes waste	*98,667*	*25*	*289,957*	*49*

The difference in mass between the buildings is predominantly driven by the use of concrete in both buildings. The Reference Building employs concrete in all aspects of its structure (sub-structure, core, floors, walls and roof) whereas the Study Building employs concrete as a sub-structure material only.

The major contributors to building mass for both buildings include concrete, wood, cement board, plasterboard, concrete blocks steel, aggregates and windows. Other materials comprise 1% or less of building mass before fitout.

5.1.3 Material production

The Product Stage described by Figure 10 incorporates the production of each material employed in the building. For each material described in the LCA model of each building (Appendix B) a production inventory must either be selected from a background (already existing) database or developed from scratch. As many inventories are employed in a building LCA it is only possible to document a few of the most important ones. The following section therefore addresses the key materials emerging from the analysis in Section 5.1.2. The model documentation in Appendix B provides a complete list of background inventories and their corresponding sources.

As discussed in Section 3.5, the inventory employs a range of background inventories. Wherever possible, life cycle inventories in this study have been taken from the AusLCI Database developed by the Australian Life Cycle Assessment Society (ALCAS), and distributed in Sima Pro format by Life Cycle Strategies. The AusLCI dataset supports two classes of data: 1) original data sets prepared in accordance with the AusLCI project which are based on inventory data collected from Australian processes in accordance with the AusLCI protocol, and 2) shadow data sets which are based on EcoInvent data which typically refer to European production processes. Shadow inventories have been modified where possible to utilise Australian sources of energy and fossil fuel.

As background inventories have been derived from a range of sources, the following section undertakes to assess the significant inventory elements by comparing their impacts to alternative benchmark data sets.

5.1.3.1 Concrete

Concrete is employed by both buildings at a range of different strengths. The bulk of material (approximately 80% for the Reference Building and 100% for the Study Building) is poured on site from local batching plants (within 2.5km travel distance). The Reference Building also incorporates precast concrete panels which are locally produced.

Concrete employed across both buildings is produced at strengths ranging from 32 MPa to 60 MPa. The higher strengths tend to be employed in specific load bearing panel products. In the Study Building 84% of concrete is between 32 MPa to 40 MPa strength and in the Reference Building 75% of concrete is produced at 40 MPa.

Concrete production within the LCA model employs inventories developed for the concrete mixes reported in Durlinger, Crossin and Wong (2012) for 32, 40 and 50 MPa strengths (Table 11). Mixes were modified from Durlinger, Crossin and Wong (2012) to replace blast furnace slag (cement substitute) with Portland cement. Background production inventories were selected from the AUPLCI database. An inventory for 60 MPa strength was not available, so 50 MPa was used as a proxy.

Table 11 Concrete mixtures employed (1 m3 concrete).

	32 Mpa	**40 MPa**	**50 MPa**
Cement, Portland	310	390	524
Gravel/aggregates	1,050	1,080	1,100
Sand	860	790	650
Water	170	175	180

To check the completeness of results, the inventories were impact assessed (Section 3.9) and compared to concrete inventories published in the BPIC database (Table 12). The datasets published by BPIC list basic material flows into and out of cement and concrete facilities, so were manually connected to further background inventories (for example, the production of electricity in Victoria, Australia). It was noted through this process that the inventories did not appear to deal with raw factor materials such as limestone and the movements thereof.

The comparison shows the inventories developed to be comparable to the BPIC models, however has notably higher impacts in the areas of ozone depletion and photochemical oxidation. This could be due to missing transport stages in the BPIC inventory.

Table 12 Concrete inventories compared for 1m3 concrete.

		32MPa		40 MPa		50 MPa
		This study	BPIC	This study	BPIC	This study
Climate change	kg CO2 eq	361.0	375.6	430.1	460.4	543.4
Ozone depletion	mg CFC-11 eq	11.1	2.1	11.7	2.5	12.4
Acidification	kg SO2 eq	0.7	0.6	0.8	0.8	1.0
Eutrophication	kg PO43- eq	0.2	0.2	0.2	0.2	0.2
Photochemical oxidation	g C2H4 eq	28.5	12.7	30.4	14.9	33.0
Abiotic depletion	kg Sb eq	1.7	1.1	1.9	1.3	2.4

Other studies were also considered. Hammond and Jones (2008) consider a wide range of studies of concrete and state global warming impacts for 2,400 kg (1 m3) of concrete as 381 kg CO_2e in floor, columns and load bearing structures. They also state impacts of 501 kg CO_2e in high strength applications.

5.1.3.2 Wood

Wood products are exclusively employed in the Study Building in a range of applications. Most wood is used in lineal form where it is used as a framing material for internal/external walls and floors. With the exception of the basement (undercroft) of the building walls are produced offsite at framing and truss manufacturers and assembled onsite (Figure 13).

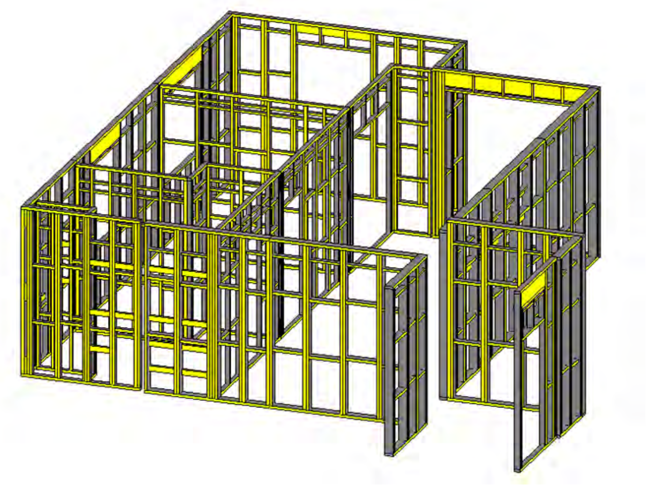


Figure 13 Framing example for Study Building.

A unique aspect of the Study Building is that it also employs offsite manufacture for flooring modules, ‘cassettes’, which are fabricated off site and hoisted into position. Wood is used as a part of the composite joist structure in each cassette.

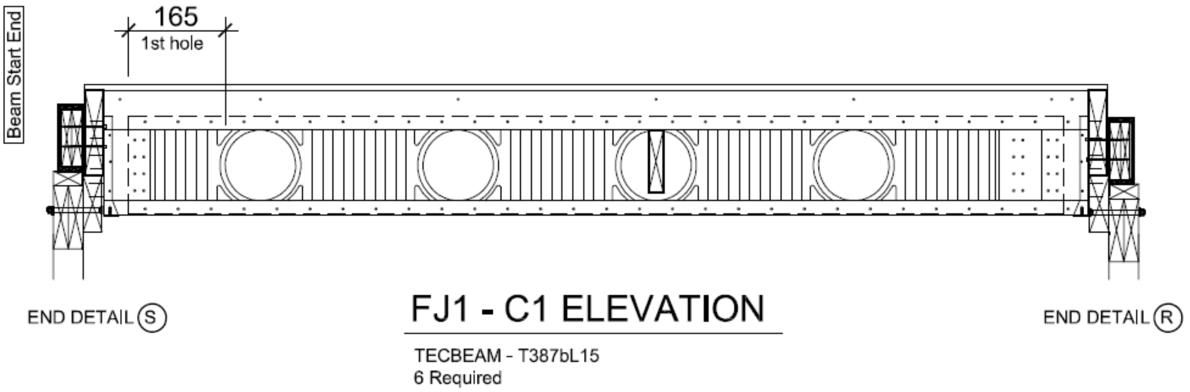


Figure 14 Floor cassette shown in elevation.

Each floor cassette employed in the system is made up of a number of composite beam joists (steel web, Laminate Veneer Lumber (LVL) flanges) and LVL blocks which support a fastened cement board panel (magnesium oxide cement board).

Wood product types employed in the building are shown in Table 13. For each wood type a AusLCI inventory was used to model production impacts of each timber product. For LVL, no inventory was available so GluLam was employed instead.

Table 13 Wood product types employed in the Study Building.

Wood type	**% of total**
Softwood (Pine)	54%
Hardwood (kiln dried)	9%
LVL	34%
Plywood	3%

To test completeness of the inventories developed each was compared to an equivalent or similar inventory in the BPIC database. As for concrete, timber inventories were created from BPIC data by connecting material flows to appropriate background inventories in the AusLCI. When impact assessed, the results (Table 14) show a remarkable correlation in most categories.

The one exception seen was for the AusLCI hardwood product inventory which was higher in a number of areas, particularly photochemical oxidation. A review of the inventory found that this discrepancy was due carbon monoxide emissions associated with burning of material in forestry operations: 73 kg of carbon monoxide emitted for AusLCI versus 3kg for BPIC (for 1m3 hardwood).

A review of sources found the AusLCI to be based on a recently published paper by England et al. (2013), and the BPIC data based on an earlier unpublished study by CSIRO. Both studies represent credible sources and both appear to have similar system boundaries. Although a reason for the difference is unknown, it is possible that the CSIRO study did not include emissions associated with forest residue burning or forest fuel reduction burning. This is a significant source of uncertainty in the study.

Table 14 Timber inventories compared for 1m3 of timber product.

		Softwood			Hardwood		LVL		Plywood
		AusLCI	BPIC	AusLCI (Europe Prod)	AusLCI	BPIC	AusLCI (glulam)	BPIC	BPIC
		This study		This study	This study		This study		This study
Climate change	kg CO2 eq	157.8	265.3	172.4	408.3	490.4	394.1	466.7	282.2
Ozone depletion	mg CFC-11 eq	7.8	4.3	11.7	17.7	16.5	14.5	30.0	6.3
Acidification	kg SO2 eq	1.0	1.1	1.2	2.4	1.2	1.9	1.5	0.9
Eutrophication	kg PO43- eq	0.3	0.3	0.3	0.6	0.3	0.5	0.5	0.3
Photochemical oxidation	g C2H4 eq	211.1	299.1	103.4	1999.2	293.0	317.3	411.4	355.2
Abiotic depletion	kg Sb eq	1.0	1.2	1.2	1.9	2.1	2.7	3.3	1.9

Climate change impacts reported for wood products were somewhat lower than those seen in other studies. Assuming 550 kg/m3 density for softwood and 850 kg/m3 for hardwood, Hammond and Jones (2008) states impacts of 253 kg CO_2e and 391 kg CO_2e respectively.

5.1.3.3 Cement board

The Study Building employs two types of cement board products in its floor, ceiling and wall systems. Magnesium oxide cement board is used as the top surface of the floor system and in the party walls of the building (Figure 15). The other cement panel, calcium silicate cement board, is used in the ceiling systems of the building. The panels are employed because of their favourable acoustic and fire resistance properties.

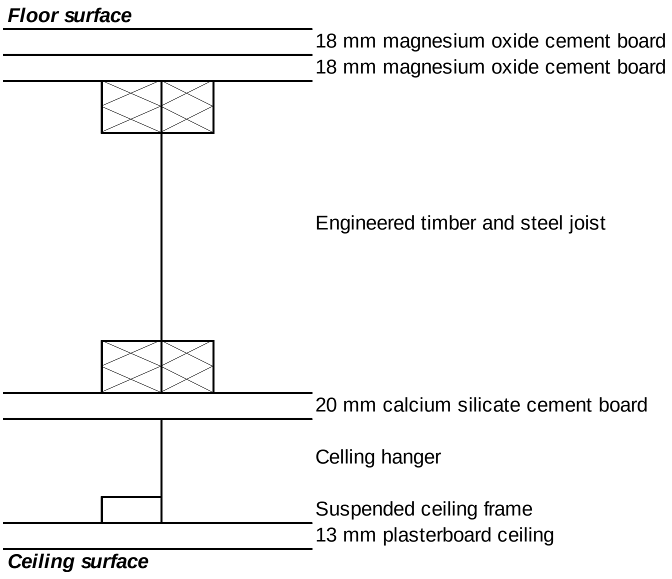


Figure 15 Section through Study Building floor system.

<u>Magnesium oxide cement board</u>

The magnesium oxide cement board (Systempanel™) employed in the building is produced by Promat and sourced from a production facility in China. As no constituent production data was available beyond the Material Safety Data Sheet (MSDS) an inventory for production was developed from scratch.

The board MSDS states the material constituents as: Glass fibre, perlite, Sorel cement, water and wood (Promat 2013). Unfortunately, the MSDS does not break the material ratios down however it is possible to infer useful information from this data.

The key material used in the board is Sorel type cement. Sorel cement is different to typical Portland cement as it employs magnesium oxide and magnesium chloride. The manufacture of magnesium oxide typically takes place in a kiln where magnesium carbonate is converted to magnesium oxide at temperatures several hundred degrees below that required in the Portland cement production process. Some authors argue this leads to a lower greenhouse gas footprint as less energy is required (Hasanbeigi, Price & Lin 2012), however others state the opposite to be true (Duxson & Provis 2008). In general there seems to be significant potential to reduce the greenhouse impact of magnesium oxide based cements in future, however current practices seem to offer limited greenhouse gas improvements over existing Portland cements.

A review of European production processes for magnesium oxide correlates with this view. JRC-IPTS (2013) states that in the production of 1 tonne of magnesium oxide, approximately 1 tonne of CO_2 is emitted directly and that the indirect emissions associated with energy required to support the reaction contribute a further 0.4 to 1.3 tonnes of CO_2. This result also compares well with the magnesium oxide production inventory in the AusLCI database, which results in a climate change impact of 1.1 kg CO_2e when assessed using the study impact assessment method.

As constituent material quantities are not disclosed for the board, it was necessary to employ the material breakdown of a competitor product that is similar in nature: Titanboard™. Titanboard™ is also a magnesium oxide based board which appears to have a very similar material makeup to magnesium oxide cement board used in the Study Building, based on its MSDS disclosure (Titanwall 2006) which includes material proportions (Table 15).

Table 15 Titanboard™ and Systempanel MSDS™ disclosures compared.

Titanboard™		Systempanel™	
Material	Proportion	Material	Proportion
Magnesium oxide	65%	Sorel cement	Not stated
Magnesium chloride	25%		
Fibreglass non-woven mesh	<10%	Glass fibre	Not stated
Talc	<5%	Perlite	Not stated
Other	<5%	Water/wood	Not stated

For each constituent material described in the Titanboard™ MSDS, a background inventory was selected from the AusLCI or developed from scratch.

The magnesium oxide production inventory was based on a European magnesium oxide production process from the AusLCI database. The process modelled involves the calcination of magnesium carbonate under heat. The European production model has been modified to replace heat from oil and gas with heat from hard coal, as would be expected in China.

Magnesium chloride used in the magnesium oxide cement board was modelled in two different ways. The first method assumed magnesium chloride was produced from salt from sea or lake water, which was reduced in solar evaporation ponds to achieve a brine solution with a magnesium chloride concentration of 33% by weight (8.5% magnesium). Remaining water was assumed to be evaporated by heat generated by a coal burning furnace. The process information was derived from Tripp (2009).

The second method was based on magnesium chloride production from available carnallite (extracted from dry lakes / dry sea beds). Primary energy required to dry carnallite to form magnesium metal is reported as 55.5 MJ/kg magnesium produced (Ehrenberger 2013). As magnesium prior to electrolysis is in magnesium chloride form, it can be conservatively assumed that 3.9 kg of magnesium chloride is produced by the energy stated (possibly more). It is assumed that the heat required to do this is provided by a coal fired furnace, which equates to 14.1 MJ/kg magnesium chloride produced.

The remaining material elements were modelled using production inventories from the AusLCI to create two models for magnesium oxide cement board. When impact assessed the results are shown in Table 17. The higher impact model (magnesium chloride from carnallite) was selected as most conservatively reflecting the board production process. The results were also compared to fibre cement sheet. The results show magnesium oxide cement board as having similar impacts to fibre cement as reported in AusLCI in most indicators. Hammond and Jones (2008) report a higher greenhouse gas emission for fibre cement of 2110 kg per tonne of material, putting the magnesium oxide cement board at below this figure.

Calcium silicate cement board

By way of contrast to the Systempanel™, Promat were able to provide an Environmental Product Disclosure (EPD) for the calcium silicate cement board (Promatect 100™). The EPD was completed according to the Dutch standard NEN8006:2004 and includes an assessment of impacts across the following indicators: abiotic depletion, global warming, depletion of the ozone layer, human toxicity and ecotoxicity. The EDP was useful for all indicators in this study.

Table 16 Impacts from production and transport of 4.45kg of Promatect 100™ board (Promat 2008).

Indicator	Unit	Production	Transport	Total
Abiotic depletion	kg antimony eq.	0.0165	2.33E-04	0.016733
Global warming	kg CO2 eq.	1.91	0.0392	1.9492
Depletion of the ozone layer	kg CFC-11 eq.	9.97E-08	2.74E-08	0.000
Human ecotoxicity	kg 1,4 dichlorobenzene eq.	0.081	0.00362	0.08462
Ecotoxicity aquatic[1]	kg 1,4 dichlorobenzene eq.	67.6	1.5	69.1
Ecotoxicity terrestrial	kg 1,4 dichlorobenzene eq.	0.0014	4.13E-05	0.0014413
Smog	kg 1,4 dichlorobenzene eq.	6.71E-04	4.09E-05	0.0007119
Acidification	kg SO2 eq.	0.00422	2.36E-04	0.004456
Eutrophication	kg PO4-	3.82E-04	5.68E-05	0.0004388

[1] average between fresh water and marine

To create a production model for calcium silicate cement board, elementary flows based on equivalent units, sufficient to generate the outcomes reported in the EPD under impact assessment, were employed. The resulting outcome under impact assessment when compared to fibre cement sheet is shown in Table 17.

Table 17 Cement board inventories compared for 1 tonne of material.

		Fibre cement sheet AusLCI	Magnesium oxide cement board (MgCl2 from brine)	Magnesium oxide cement board (MgCl2 from carnallite)	Calcium silicate cement board
				This study	This study
Climate change	kg CO2 eq	1439.7	1167.3	1434.2	438.2
Ozone depletion	mg CFC-11 eq	54.0	19.8	20.5	28.5
Acidification	kg SO2 eq	2.9	5.1	7.0	1.2
Eutrophication	kg PO43- eq	0.8	0.9	1.4	0.1
Photochemical oxidation	g C2H4 eq	150.5	282.0	366.0	205.8
Abiotic depletion	kg Sb eq	7.0	3.5	5.6	3.8

Hammond and Jones (2008) report calcium silicate boards as having greenhouse gas emissions of 130 kg CO_2e per tonne of material, which is lower than the calcium silicate cement board inventory would suggest.

5.1.3.4 Plasterboard

Both the Study Building and the Reference Building employ a significant quantity of plasterboard. The inventory employed for plasterboard comes from the AusLCI database as it correlates with publicly reported production inventories for plasterboard in Australia (GBMA 2009). The BPIC inventory appears to contain an error as it is reported as being derived from the same sources as GBMA (2009) and does not correlate with Hammond and Jones (2008) which reports typical greenhouse gas emissions of 380 kg CO_2e per tonne.

Table 18 Plasterboard inventories compared for 1 tonne of material.

		AusLCI	BPIC	GBMA report
		This study		
Climate change	kg CO2 eq	418.7	2362.5	424.2
Ozone depletion	mg CFC-11 eq	26.3	14.3	13.0
Acidification	kg SO2 eq	1.0	4.5	1.3
Eutrophication	kg PO43- eq	0.2	1.1	0.2
Photochemical oxidation	g C2H4 eq	0.0	0.1	0.1
Abiotic depletion	kg Sb eq	2.9	16.6	Not stated

5.1.3.5 Concrete blocks

Concrete blocks are employed in ground floor wall structures in both buildings. The Study Building also employs concrete blocks in the central core of the building (filled with concrete in this application).

Concrete block production within the LCA model employs an inventory from the AusLCI database. As a comparison, a model was developed from the BPIC inventory for concrete block production. The AusLCI inventory compares reasonably well to the BPIC inventory however is more greenhouse intensive than that reported by Hammond and Jones (2008) who report between 61 and 98 kg CO_2e per kg of blocks.

Table 19 Concrete block inventories compared for 1 tonne of material.

		AusLCI	BPIC
		This study	
Climate change	kg CO2 eq	138.4	122.1
Ozone depletion	mg CFC-11 eq	3.7	1.1
Acidification	kg SO2 eq	0.3	0.7
Eutrophication	kg PO43- eq	0.1	0.2
Photochemical oxidation	g C2H4 eq	0.0	0.0
Abiotic depletion	kg Sb eq	0.4	0.5

5.1.3.6 Steel

Steel is used in the construction of both buildings across a range of applications. More than half the steel used in both buildings is used to reinforce concrete structures in both a mesh and bar format. The remaining steel is used predominantly in galvanised framing (formed sections) to support walls and suspended ceilings, in roofing material (Study Building only) and in a limited number of structural applications (less than 6% of applications).

Steel used in both buildings is sourced locally. To model production two inventories have been employed, one for the production of reinforcing steel and one for galvanised sheet products. Steel employed in Australia is sourced from two production systems. The first, the Blast Furnace - Basic Oxygen Steelmaking (BF-BOS) route, produces steel from iron ore and other factors largely extracted from the environment. The second pathway produces steel from largely recovered waste steel materials in an Electric Arc Furnace (EAF). Steel produced via the BF-BOS route tends to be more environmentally impactful than steel produced via the EAF pathway making steel impact estimation particularly sensitive to the mix of steels being used.

For reinforcing steel, an inventory was selected from the AusLCI database. When compared to a reinforcing steel inventory developed from the BPIC database, most steel production impacts were found to be higher than the BPIC inventory. The AusLCI inventory was also found produce larger climate change impacts than other benchmarks such as (Strezov & Herbertson 2007) who estimate greenhouse gas emissions for reinforcing steel at 1,120 kg CO_2e per tonne (Table 20).

Table 20 Steel inventories compared (1 tonne steel).

		Reinforcing		Galvanised
		AusLCI	BPIC	AusLCI
		This study		This study
Climate change	kg CO2 eq	1612.9	1174.7	3502.0
Ozone depletion	mg CFC-11 eq	25.7	11.2	58.1
Acidification	kg SO2 eq	4.6	2.1	11.6
Eutrophication	kg PO43- eq	1.2	0.4	2.2
Photochemical oxidation	g C2H4 eq	0.8	0.4	2.5
Abiotic depletion	kg Sb eq	11.8	7.1	22.8

A comparative inventory for sheet products was not considered (BPIC do not publish such an inventory) however a comparison was drawn to Strezov and Herbertson (2007) who report greenhouse gas emissions of 3,600 kg CO_2e per tonne sheet steel product.

A key challenge when interpreting the BPIC inventory is the source of constituent materials such as iron ore, and what processing these materials might have had.

5.1.3.7 Aggregates and sands

Aggregates and sands, although employed in large quantities, tend to have lower impacts in the indicators considered as they require smaller amounts of energy to produce, on a mass basis. Both inventories for aggregates and sands were selected from the AusLCI inventory.

5.1.3.8 Windows

Windows were modelled in the same way for both buildings. Window impact is assumed to be related to the glass employed in the window and the framing material. Glass quantities for each building were estimated based on the glazed area of each building. Framing requirements were estimated by considering the length of frame employed in each window, which was calculated from each building's glazing drawings.

The production inventory for each window was therefore based upon a production inventory associated with plate glass, and a production inventory associated aluminium framing and sealing. The window frame model was based on an inventory for window frame manufacture in the AusLCI database. The inventory includes aluminium production and extrusion necessary to produce a frame, along with ancillary elements such as seals and guides. A generic frame mass of 2 kg/m is assumed based on the analysis of a typical window cross section. Plate glass was based on a production inventory for coated flat glass from the AusLCI database. Window thickness is assumed to be 10.38mm throughout both buildings.

Both inventories are based on a European production environment and have been regionalised by replacing background European energy inventories for Australian energy inventories. A comparison of the impact assessed inventories for a typical window is shown in Table 21, versus an inventory created from the BPIC database. The AusLCI inventory has been selected because it can be adjusted to suit the windows under consideration, rather than representing a generic window type. For example, ratios of frame to window area can be changed, as can the window frame section (these are not possible with the BPIC inventory).

Table 21 Window inventories compared for a 2.1m high x 1m wide window (2.1m^2).

		AusLCI	BPIC
		This study	
Climate change	kg CO2 eq	265.7	373.5
Ozone depletion	mg CFC-11 eq	7.7	11.1
Acidification	kg SO2 eq	1.0	1.2
Eutrophication	kg PO43- eq	0.1	0.2
Photochemical oxidation	g C2H4 eq	0.0	0.1
Abiotic depletion	kg Sb eq	1.7	2.2

5.1.3.9 Other materials

Other materials employed in the LCA models are documented for the Study Building in Table 51, Table 52 of Appendix A and for the Reference Building in Table 64, Table 65 of Appendix B. Other materials make up 1% or less of building mass before fit-out.

5.1.4 Building fit-out

In addition to the structural elements of the building, an estimate of building fitout requirements was also developed. Fitout was assumed to be undertaken in the same fashion for both buildings, it therefore does not act to differentiate building impacts.

The estimate was developed by looking at the materials needed to fit out a 70 m^2 apartment and balcony area and its share of common area. The estimate developed is shown Table 22 and Table 23, and shows fitout materials to weigh approximately 33 kg/m^2 GDA for both buildings.

For the Study Building, fitout materials account for 129 t of additional materials, contributing to a gross material mass of 2,381 t for the completed building. Fit-out materials therefore make up 5% of gross material mass. For the Reference Building, fit-out materials account for 198 t of additional materials, contributing to a gross material mass of 9,970 t for the completed building. Fit-out in this case makes up 2% of gross material mass.

Table 22 Estimate for apartment living space fitout per m^2 GDA.

2 BR Apt								
Basic Areas	**Gross Qty**	**Unit**	**Gross Qty per GDA**	**Unit**	**Process name**	**Process source**	**Notes**
Reference Area (GDA)	70	m2	1.00	m2			
Timber floor	28	m2	0.40	m2			
Tiled foor	10	m2	0.14	m2			
Carpeted floor	32	m2	0.46	m2			
Tiled wall	22	m2	0.31	m2			
Key Materials							
Carpet	48	kg	0.69	kg	Nylon 6, at plant/RER U/AusSD U	AusLCI	1.5kg per m2
Synthetic underlay	32	kg	0.46	kg	Polyurethane, flexible foam, at plant/RER U/AusSD U	AusLCI	1kg per m2
Ceramic tile	384	kg	5.49	kg	Ceramic tiles, at regional storage/CH U/AusSD U	AusLCI	12 kg per m2
Timber floor	372.4	kg	5.32	kg	Sawn timber, hardwood, planed, kiln dried, u=10%, at plant/RER U/AusSD U	AusLCI	19 mm hardwood
PB Low Cabinets	110	kg	1.57	kg	Particle board, indoor use, at plant/RER U/AusSD U	AusLCI	30 kg per 60cm cabinet
PB High Cabinets	120	kg	1.71	kg	Particle board, indoor use, at plant/RER U/AusSD U	AusLCI	20 kg per 60cm cabinet
Glass	600	kg	8.57	kg	Flat glass, uncoated, at plant/RER U/AusSD U	AusLCI	Mirrors installed
PB Skirts	100	kg	1.43	kg	Particle board, indoor use, at plant/RER U/AusSD U	AusLCI	0.002m2 profile
Wiring - copper	5.6	kg	0.08	kg	Copper, at regional storage/RER U/AusSD U	AusLCI	6mm2 conductor (5.6kg/100)
Wiring - PVC sheath	17.4	kg	0.25	kg	Polyvinylchloride, at regional storage/RER U/AusSD U	AusLCI	23kg/100m total cable
PVC waste pipe	34	kg	0.49	kg	Polyvinylchloride, at regional storage/RER U/AusSD U	AusLCI	1.7 kg/m
PE pressure pipe	12	kg	0.17	kg	Polyethylene, HDPE, granulate, at plant/RER U/AusSD U	AusLCI	0.4 kg/m
Oven - Steel	20	kg	0.29	kg	New inventory employing background inventories from AUPLCI	New, as pe	Steel
AC Split - steel	28.5	kg	0.41	kg	New inventory employing background inventories from AUPLCI	New, as pe	57 kg AC system - estimate. 50% mass is steel
AC Split - aluminium	22.8	kg	0.33	kg	Aluminium, primary, at plant/RER U/AusSD U	AusLCI	40% of mass is aluminium castings
AC Split - ABS plastic	5.7	kg	0.08	kg	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER U/AusSD U	AusLCI	10% of mass is plastic.
PB Doors	158.4	kg	2.26	kg	Particle board, indoor use, at plant/RER U/AusSD U	AusLCI	3 doors
Bathroom ceramics	200	kg	2.86	kg	Sanitary ceramics, at regional storage/CH U/AusSD U	AusLCI	Estimate for pan, cistern, sink
Paint	19.25	kg	0.28	kg	Acrylic varnish, 87.5% in H2O, at plant/RER U/AusSD U	AusLCI	Estimate 140m2 incl ceiling - 2 coats, 16m2/litre, dens 1.1kg
Total	2290.05		32.72	kg			

Table 23 Estimate for building common space fitout per m^2 GDA.

Common Area (90%GDA, 10% Common)							
Basic Areas	**Gross Qty**	**Unit**	**Gross Qty per GDA***	**Unit**			**Notes**
Reference Area	70	m2	0.11	m2			
Tiled foor	10	m2	0.02	m2			
Carpeted floor	60	m2	0.10	m2			
Key Materials							
Carpet	90	kg	0.14	kg	Nylon 6, at plant/RER U/AusSD U	AusLCI	1.5kg per m2
Synthetic underlay	60	kg	0.10	kg	Polyurethane, flexible foam, at plant/RER U/AusSD U	AusLCI	1kg per m2
Ceramic tile	120	kg	0.19	kg	Ceramic tiles, at regional storage/CH U/AusSD U	AusLCI	12 kg per m2
PB Skirts	100	kg	0.16	kg	Particle board, indoor use, at plant/RER U/AusSD U	AusLCI	0.002m2 profile
Wiring - copper	5.6	kg	0.01	kg	Copper, at regional storage/RER U/AusSD U	AusLCI	6mm2 conductor (5.6kg/100)
Wiring - PVC sheath	17.4	kg	0.03	kg	Polyvinylchloride, at regional storage/RER U/AusSD U	AusLCI	23kg/100m total cable
PVC waste pipe	34	kg	0.05	kg	Polyvinylchloride, at regional storage/RER U/AusSD U	AusLCI	1.7 kg/m
PE pressure pipe	12	kg	0.02	kg	Polyethylene, HDPE, granulate, at plant/RER U/AusSD U	AusLCI	0.4 kg/m
Paint	5.5	kg	0.08	kg	Acrylic varnish, 87.5% in H2O, at plant/RER U/AusSD U	AusLCI	Estimate 40m2 incl ceiling - 2 coats, 16m2/litre, dens 1.1kg
Total	444.5		0.78	kg			

5.2 Construction process

Estimation of materials and energy associated with the building construction process on site is notoriously difficult to undertake. In this case, it is recognised that the Reference Building incorporates a far larger mass of materials per m^2 GDA and must lift these materials to a higher level on-site. This would suggest more energy is used in the construction process on site, however there is no empirical evidence to back this up. Without good data to support on-site construction impacts, it was decided to exclude this from the study. Instead, construction impacts are limited to the inbound transport of materials and the disposal of waste generated on site.

5.2.1 Inbound transport

The inbound transport task for each building was estimated by considering the key constituent material masses and their points of production origin. Mass of material multiplied by transport distance was calculated to give a total transport task measured in tonne.kilometers (t.km). From the transport task, fuel use and other impacts were determined using existing background LCIs (documented in Appendix C).

A summary of the transport task for each building is shown in Table 24, based on a detailed transport model which is described in Appendix C. The table shows that although the study building has a smaller road transport task, due to its comparatively light weight, it does carry a significant ship transport burden. This burden relates directly to the importation of the magnesium oxide cement board and calcium silicate cement board products from China and Belgium respectively. As these products are relatively massive and travel a long distance, they contribute to a significant sipping burden. The Reference Building has a larger road based task due its large mass per m^2 GDA.

Table 24 Transport task estimate.

	Study Building		Reference Building	
Item	**t.km**	**t.km/m2 GDA**	**t.km**	**t.km/m2 GDA**
Road	184,369	47	486,155	82
Ship	4,180,621	1,073	-	-

Distances travelled (as opposed to transport task, discussed above), were longer for inbound materials associated with the Study Building. On average, materials travelled 85 km by road for the Study Building and 50 km by road for the Reference Building. For the Study Building, materials that were imported by sea travelled 9964 km by ship on average. This difference reflects the more diverse material requirement of the Study Building, versus the Reference Building which is largely produced from locally manufactured concrete.

5.2.2 Construction waste

As mentioned in Section 5.1.1, the building material quantities incorporate an allowance for waste due to cutting and over ordering. This material manifests as waste on site and must be disposed of. As shown in Table 10, the 99 t of waste are generated on site for the Study Building and 290 t of waste for the Reference Building. Disposal of this material is assumed to involve transport to either a reprocessing facility or to landfill, depending on whether the material is marked for recycling or not.

Recycling rates assumed for the waste materials generated are taken from (Durlinger, Crossin & Wong 2012) which are in turn based on practices appropriate to Victoria, Australia (Table 25).

Table 25 Waste treatment assumptions for both buildings (Durlinger, Crossin & Wong 2012)

Material type	Recovery rate	Landfill rate
Masonary, including concrete	64%	36%
Wood products	40%	60%
Plastics	15%	85%
Organics (including wood)	13%	87%
Other (including glass)	1%	99%
Paper and board	0%	100%

Background inventories associated with waste treatments are from the AusLCI database. System expansion is applied in all inventories to address benefits from recycling or waste treatment. Avoided products generated within each inventory are listed in Table 26 and are consistent with Durlinger, Crossin and Wong (2012). Additionally, wood and organic products are credited with a small benefit from landfill treatment due to electricity generation from gasses generated as they decompose.

The intent of these inventories is to recognise that many construction wastes are reprocessed into useful commodities (such as scrap aluminium into aluminium ingot), and that the net benefit needs to be accounted for in the LCA. This is discussed further in Section 5.5.

Table 26 Avoided products due to waste treatment of materials.

Material type	Recovery rate	Landfill rate
Metals	82%	18%
Masonary, including concrete	64%	36%
Wood products	40%	60%
Plastics	15%	85%
Organics (including wood)	13%	87%
Other (including glass)*	0%	100%
Paper and board	0%	100%

* Durlinger et. al. state 1% recycling for 'other'.

5.3 Use stage

The use stage of the building life cycle includes processes relating to building operation and maintenance. Building operation is limited to the heating and cooling of the building, lighting of the building and the provision of hot water. Building maintenance incorporates the replacement or refurbishment of building sub-systems on a regular basis.

5.3.1 Building Operation

Building operational requirements were estimated using the GBCA's Green Star – Multi Unit Residential v1 – Greenhouse Gas Emissions Calculator. The calculator estimates total annual greenhouse gas emissions for multi-unit buildings based on a range of inputs. The inputs used in the calculator and the resultant annual energy requirements for each building are shown in Table 27. Greenhouse gas emission outputs from the calculator were not used as they are determined from background inventories from the AusLCI and AUPLCI database.

Heating and cooling for all apartments is provided by electric, reverse cycle unitary systems, typically installed as a head unit within the apartment and a heat-exchanger mounted in a balcony area. The systems employed use the R410a refrigerant, which has a high climate change impact if released to the atmosphere. This study assumes that refrigerants employed are contained within the heating and cooling systems over the life of the building and safely recovered at the end of building life.

Excluding refrigerant leakage from the building comparison is not expected to impact the study comparative findings as both buildings use similar heating and cooling systems. A rough calculation of climate change impacts due to refrigerant leakage would increase total heating and cooling impacts for both buildings by approximately 5%, based on AIRAH (2012).

Table 27 Summary of inputs used in the GBCA's GHG calculator and the resultant energy requirements.

Item	Unit	Study Building	Reference Building	Source
Area-weighted average 'area-adjusted' thermal energy requirement				
Heating	MJ/m2.year	50	65	Calculated from NatHERS rating sheets for each apartment
Cooling (sens+ latent)	MJ/m2.year	31	18	Calculated from NatHERS rating sheets for each apartment
TOTAL	MJ/m2.year	81	83	
Heating cooling system efficiency				
Heating COP - average	NA	3.81	3.75	Calculated from reverse cycle AC system specifications. All heating cooling powered by electricity.
Cooling EER - average	NA	3.65	3.66	Calculated from reverse cycle AC system specifications. All heating cooling powered by electricity.
Heating cooling system calculated energy use				
Electricity	kWh/year	21,538	33,165	
Hot water service energy				
Hot water demand	litres/year	2,708,688	4,136,020	Estimate generated by the calculator from inputs regarding appliance water efficencies.
Energy from electricity	kWh/year	1,859	2,838	Estimated from energy use modelling in Biddyut and Andrews (2013) which reports 4,699 kWh/yr to run a gas heated ring main delivering 6,847 litres/year for a 257 apartment building in Melbourne. Includes ring main supply pump.
Energy from gas	MJ/year	869,573	1,327,791	Estimated from energy use modelling in Biddyut and Andrews (2013) which reports 2,198 GJ/yr to run a gas heated ring main delivering 6,847 litres/year for a 257 apartment building in Melbourne.
Lighting				
Dwellings	kWh/year	45,301	67,907	GBCA benchmark assumed of 12.7 kWh/m2/yr. Lighting density known to be better then BCA minimums.
Foyers	kWh/year	17,554	25,134	GBCA benchmark assumed of 36.8 kWh/m2/yr. Lighting density known to be better then BCA minimums.
Indoor carpark	kWh/year	37,151	66,468	GBCA benchmark assumed of 39.4 kWh/m2/yr. Lighting density known to be better then BCA minimums.
Outdoor carpark	kWh/year	None	18,971	GBCA benchmark assumed of 19.7 kWh/m2/yr. Lighting density known to be better then BCA minimums.
Total energy requirements from calculator				
Electricity	kWh/year	123,403	214,483	
Natural gas	MJ/year	869,573	1,327,791	
Total Energy requirements from calculator per m2 GDA				
Electricity	kWh/year	**32**	**36**	
Natural gas	MJ/year	**223**	**225**	
Total water requirements from calculator				
Water	litres/year	6,392,647	9,761,232	
Total Water requirements from calculator per m2 GDA				
Water	litres/year	**1,641.1**	**1,651.1**	

To convert annual energy requirements into inventories of elementary flows, background inventories are employed from the AusLCI for electricity supply in Victoria and the AUPLCI for natural gas supply in Victoria. The impact assessed inventories are shown in Table 28 compared to published full fuel cycle greenhouse gas emissions (DoE 2014). The study electricity inventory compares well with (DoE 2014), however the natural gas inventory is more greenhouse gas intensive.

Table 28 Study energy inventories compared to (DoE 2014).

		Electricity	Nat. Gas	Electricity	Nat. Gas
		AusLCI	AUPLCI	DoE(2014)	DoE(2014)
		1 kWh	1 GJ	1 kWh	1 GJ
Climate change	kg CO2 eq	1.3	64.3	1.3	55.2
Ozone depletion	mg CFC-11 eq	0.0	0.6		
Acidification	g SO2 eq	1.7	253.5		
Eutrophication	g PO43- eq	0.4	65.5		
Photochemical oxidation	mg C2H4 eq	16.4	3470.2		
Abiotic depletion	g Sb eq	9.6	520.5		

As building operation is assessed over a 60 year period, the study makes the assumption that impacts associated with electricity supply will remain constant over this period. Given that climate change impacts associated with electricity supply have fallen 7% since 1990 in Victoria (DCCEE 2012), this assumption may overstate operational impacts somewhat.

5.3.2 Building maintenance and refurbishment

In addition to the energy and water required to operate the building, assumptions have been made with respect to ongoing maintenance and refurbishment. These assumptions are extremely uncertain but help to describe a complete picture of the building life cycle.

Table 29 describes the periodic maintenance assumptions for both buildings. The period noted in years describes the period of time before the maintenance or refurbishment activity is undertaken. For example, for a 60 year building life span, the 'Minor refurbishment' (shown in Table 29) will be undertaken 5 times.

Table 29 Maintenance and refurbishment periods for both buildings.

Activity	Period (years)	Description
Building maintenance		
Wash windows	1/4	2 litres water, 50g ammonia, 50g isopropanol per m2 window area
Vacuum floors	1/52	0.01 kWh per m2 floor area
Minor apartment refurbishment		
Paint interior	10	As per construction quantity
Minor common area refurbishment		
Paint interior	10	As per construction quantity
Paint exterior	10	As per construction quantity
Replace carpets	10	As per construction quantity
Major apartment refurbishment		
Replace kitchen cabinets	20	As per construction quantity
Replace carpets - dwelling	20	As per construction quantity
Replace AC system	20	As per construction quantity
Replace timber floor - dwelling	20	As per construction quantity
Replace tiling in the dwelling	20	As per construction quantity

5.4 End of life

At the end of the building life the building is assumed to be disassembled and its component materials set to waste treatment in the same fashion as for construction waste (Section 5.2.2). As for the construction process, it is unclear what on-site energy would be required to dismantle each building so this is excluded from the study. This exclusion would be expected to have a minor impact on study results.

5.5 Beyond building life cycle

The buildings considered have environmental effects beyond their immediate life cycles. These effects are largely driven by beneficial outcomes associated with waste treatment (both construction waste and at the end of the building's life).

When waste materials such as aluminium are disposed of, a proportion is typically reprocessed into a useful commodity, like aluminium ingot. Reprocessing itself usually involves an environmental burden, however the activity usually generates a net benefit once these burdens are considered compared to virgin materials. In this study the benefit due to recycling is attributed to the building life cycle as shown in Equation 1.

Equation 1 Determination of the benefit due to recycling.

R = Reprocessing burden needed to produce a commodity (including collection and transport)

V = Burden associated with producing the commodity from resources derived from the environment (often referred to as the 'avoided product')

B = Benefit due to recycling (negative means favourable)

$$B = R - V$$

In this study, the reprocessing burden (R) is directly accounted for within the respective life cycle stage where it occurs. For example, if aluminium is disposed of at the ‘End of life’ stage it will be accounted for as a burden within that stage. Avoided burdens (-V) due to the reprocessing of aluminium are accounted for in the ‘Beyond building life cycle’ stage.

A further impact that occurs beyond the building life cycle is the generation of electricity from landfill gas. In this study, the avoided burden associated with drawing this electricity from the Victorian electricity is included in the ‘Beyond building life cycle’ stage.

5.6 Inventory adjustments to achieve better functional equivalency

As a comparative LCA, the study adopts the assumption that both the Study Building and the Reference Building provide identical functionality per unit of GDA. By making this assumption it is possible to compare how much material each building uses and what its life cycle impacts are. Unfortunately, when comparing buildings, the assumption rarely holds true, as actual buildings tend to differ in many ways. In this study, the Study Building provides a different degree of service to its occupants than the reference building. Where possible, this section identifies adjustments to the building inventory that provide for a fairer comparison of the two buildings base on the services they provide.

Building areas of interest are compared in Table 30, illustrating the similarity of the buildings. Three areas of difference are apparent, although the differences are small. The Study Building has 3% more windows per m^2 GDA and 6% less exterior wall per m^2 GDA versus the Reference Building. The Study Building also has 2% less balcony space versus the Reference Building. Although adjustment for these differences is possible, the minor nature of the change needed would be more likely to confuse rather than enhance findings. For this reason, adjustments are tested as a sensitivity study only (Section 7). The final difference exists between the enclosed car parking areas provided by both buildings. The Reference Building provides 5% more car parking than the Study Building per m^2 GDA, and the provision of this arguably comes at a material cost in terms of concrete and steel needed. Adjustment in this area is warranted.

Table 30 Building areas compared.

				Per m2 GDA	
	Unit	**Study**	**Reference**	**Study**	**Reference**
GFA	m2	5,315	8,282	1.4	1.4
Enclosed carpark	m2	943	1,687	0.2	0.3
GDA	m2	**3,895**	**5,912**	1.0	1.0
Conditioned floor area	m2	3,030	4,963	0.8	0.8
Exterior wall area (excl windows)	m2	1,603	3,008	0.4	0.5
Interior wall area	m2	3,507	6,323	0.9	1.1
Exterior wall area (incl windows)	m2	2,322	3,915	0.6	0.7
Window area	m2	719	907	0.2	0.2
Balcony area	m2	328	565	0.1	0.1
Exterior walls as % of GDA	na	60%	66%		
Balcony as % of GDA	na	8%	10%		
Window as % of GDA	na	18%	15%		
Carpark as % of GDA	na	24%	29%		

5.6.1 Adjustment for undercover car parking

To adjust for undercover car parking the size of the plan area of the Reference Building car park was reduced to achieve the same car park as a percentage of GDA as the Study Building (reduced from 29% to 24%). As the perimeter of the Reference Building carpark is independent of the dwellings which are built on top of it, the adjustment process is straight forward, involving a reduction in size of the foundation slab and carpark roof. As the adjustment is small, wall areas are assumed to remain the same. The adjustment levied is shown in Table 31.

Table 31 Reference Building quantity adjustment for carpark.

	Reference Building				
	Quantity				
	Unit	Drawing	Adjustment	Final Adjusted	
Carpark area as %GDA		29%		24%	
Substructure					
Concrete 40 Mpa	tonnes	1,702.0	- 145.9	1,556.1	
0.2 mm PE membrane	tonnes	0.3	- 0.1	0.3	
Gravel bed 0.8m	tonnes	247.0	- 43.2	203.8	
Steel - reinf.	tonnes	29.8	- 3.2	26.6	
Floor system					
Concrete 40 Mpa	tonnes	4,390.1	- 303.2	4,086.9	
Steel - reinf.	tonnes	142.1	- 5.8	136.2	
Form deck	tonnes	87.7	- 1.5	86.3	
Gal steel frame	tonnes	32.9	-	32.9	
Plasterboard 13mm	tonnes	79.5	-	79.5	
Lighting energy					
Indoor carpark	kWh/yr	66,467.8	- 9,970.2	56,497.6	
Outdoor carpark	kWh/yr	18,971.1	- 18,971.1	-	
Total Building					**% change**
Material mass	tonnes	9,771.9	- 502.9	9,269.0	-5%
Material mass	kg/m2 GDA	1,652.9	- 85.1	1,567.8	-5%
Electricity use	kWh/yr	214,483.0	- 28,941.3	185,541.7	-13%
Electricity use	kWh/m2 GDA/yr	36	-5	31	-13%

In reducing the carpark size of the Reference Building, it would be expected that lighting loads associated with this aspect would also reduce. Further, the Reference Building incorporates some lighting for outdoor parking which is not provided for by the Study Building, so this burden is also removed.

Table 32 Operational energy and water requirements after adjustments.

	Unit	Study	Reference (drawing)	Reference (adjusted)
Electricity	kWh/m2 GDA/yr	**32**	36	**31**
Natural gas	MJ/m2 GDA/yr	**223**	225	**225**
Water	Litres/m2 GDA/yr	**1,641**	1,651	**1,651**

After adjustment both buildings perform very similarly from an operational energy perspective (Table 32). In many respects, this outcome is unsurprising as both have been designed to perform at a similar NatHERS star rating and after adjustment, both provide very similar service levels per m^2 GDA.

5.7 Overall data quality assessment

The quality of data in the inventory has been assessed using two approaches. First the uncertainty of the quantity data for materials or energy specified in the inventory has been assessed using the Pedigree Matrix described in Section 3.5. The assessment approach utilises the Pedigree Matrix to generate total uncertainties for quantities in the inventory based on the structured assessment of the data. Second, a subjective assessment of inventory appropriateness is undertaken. This second assessment seeks to indicate how well an inventory employed suits the study purpose. The assessment of key inventory elements is shown in Table 33.

Although pockets of poor data exist within the study, data constancy is generally maintained. Overall, when combined with the data quality management techniques described in Section 3.5, data quality is sufficient to address study aims.

Table 33 Data quality assessment matrix.

		Quantity Uncertainty Assessment		Inventory Appropriateness Assessment				
		Typical Pedigree Matrix score for foreground quantity in LCA model	Total uncertainty	Representativeness	Consistency with other study inventories	Completeness	Precision	Geographic correlation
Product Stage	Concrete	3,1,1,1,1,na	1.11	Good	Good	Good	Good	Good Cement - Australia Electricity - Australia Other processes - Europe
	Wood framing	3,1,1,1,1,na	1.11	Good	Good	Good	Good	Good Sawlogs - Australia Electricity - Australia Other processes - Europe
	Cement board	3,1,1,1,1,na	1.11	Good	Good	Moderate	Poor	Poor Calcium Silicate - Europe Magnesium Oxide - Europe
	Plasterboard	3,1,1,1,1,na	1.11	Moderate	Good	Good	Good	Moderate Production process - Europe Electricity - Australia
	Concrete blocks	3,1,1,1,1,na	1.11	Moderate	Good	Good	Good	Good Cement - Australia Electricity - Australia Other processes - Europe
	Steel	3,1,1,1,1,na	1.11	Good	Good	Good	Good	Moderate Production process - Europe Electricity - Australia Gas - Australia
	Aggregates and sands	3,1,1,1,1,na	1.11	Moderate	Good	Good	Good	Good Australia
	Windows	3,1,1,1,1,na	1.11	Good	Good	Good	Good	Moderate Production process - Europe Electricity - Australia
	Fitout materials	4,4,1,1,1,n	1.24	Poor	Good	Moderate	Poor	Moderate Mix of materials. Generally: Production process - Europe Electricity - Australia
	Other materials	3,1,1,1,1,na	1.11	Moderate	Good	Good	Good	Moderate Mix of materials. Generally: Production process - Europe Electricity - Australia
Construction Process	Construction waste	5,3,2,5,4,na	1.8	Moderate	Moderate	Moderate	Moderate	Moderate Mix of materials. Generally: Production process - Europe Electricity - Australia
	Inbound transport	3,2,1,1,1,na	1.12	Good	Good	Good	Good	Good Road - Australia Ocean - Europe
Use Stage	Electricity use	2,1,1,1,1,na	1.07	Good	Good	Good	Good	Good Australia
	Natural gas use	2,1,1,1,1,na	1.07	Good	Good	Good	Good	Good Australia
	Water use	2,1,1,1,1,na	1.07	Good	Good	Good	Good	Good Australia
	Building maintenance and refurbishment	4,4,1,1,1,na	1.24	Moderate	Good	Poor	Poor	Moderate Mix of materials. Generally: Production process - Europe Electricity - Australia
End of Life	Waste treatments	Undefined	Undefined	Moderate	Good	Moderate	Moderate	Moderate Landfill - Europe Recycling - Australia
Beyond Building Life Cycle	Avoided products	Undefined	Undefined	Moderate	Good	Moderate	Poor	Moderate Recovery rate - Australia Process avoided - Mix (as described above)

5.8 Resultant elementary flows

The result of the LCA model is an aggregate of elementary flows to and from the environment. The inventory of elementary flows can be impact assessed using characterisation factors (listed in Appendix D) to determine the impacts associated with each building. Table 34 describes those elementary flows which most significantly influence the impact assessment. Although many hundreds of substances are considered in the analysis, the flows shown are the most significant, each contributing greater than 1% to any one or more of the indicators assessed.

Table 34 Elementary flows which contribute greater than 1% to any impact category for 1 functional unit (1m^2 GDA provided for 60 years).

Elementary flow	Compartment	Unit	Study Building	Reference Building
Emissions to the environment				
Carbon dioxide	Air	kg	3,802.49	3,953.11
Carbon monoxide	Air	kg	5.63	5.88
Hexane	Air	kg	0.01	0.01
Hydrogen chloride	Air	kg	1.21	1.21
Methane	Air	kg	4.85	5.08
Methane, biogenic	Air	kg	4.62	1.92
Methane, Halons	Air	kg	0.000003	0.000003
Methane, CFCs	Air	kg	0.000002	0.000002
Nitrogen oxides	Air	kg	13.08	13.45
COD	Water	kg	4.86	4.35
Nitrogen, total	Water	kg	0.18	0.18
Phosphate	Water	kg	0.33	0.32
Phosphorus	Water	kg	0.05	0.05
Sulfur dioxide	Water	kg	0.98	0.74
Resources extracted from the environment				
Coal, hard	In ground	kg	73.06	82.13
Coal, brown	In ground	kg	2,812.76	2,823.26
Natural gas	In ground	kg	345.88	360.67
Oil, crude	In ground	kg	43.10	56.73

Further to the assessment of elementary flows, a non-assessed substance check was undertaken for elementary flows not captured by the impact assessment method (Sima Pro facilitates this task). These flows were manually reviewed for each impact category to see if obvious assessable flows were being missed. In cases where flows were missed the impact assessment method was updated to capture the missing flows. The exercise does not guarantee that all assessable flows are captured but it reduces the risk of error.

6 Results

In accordance with the LCA methodology, the elementary flows (main flows shown in Table 34) were assessed using the impact assessment method described in Section 3.9. The resulting impacts by impact category are shown in Table 35.

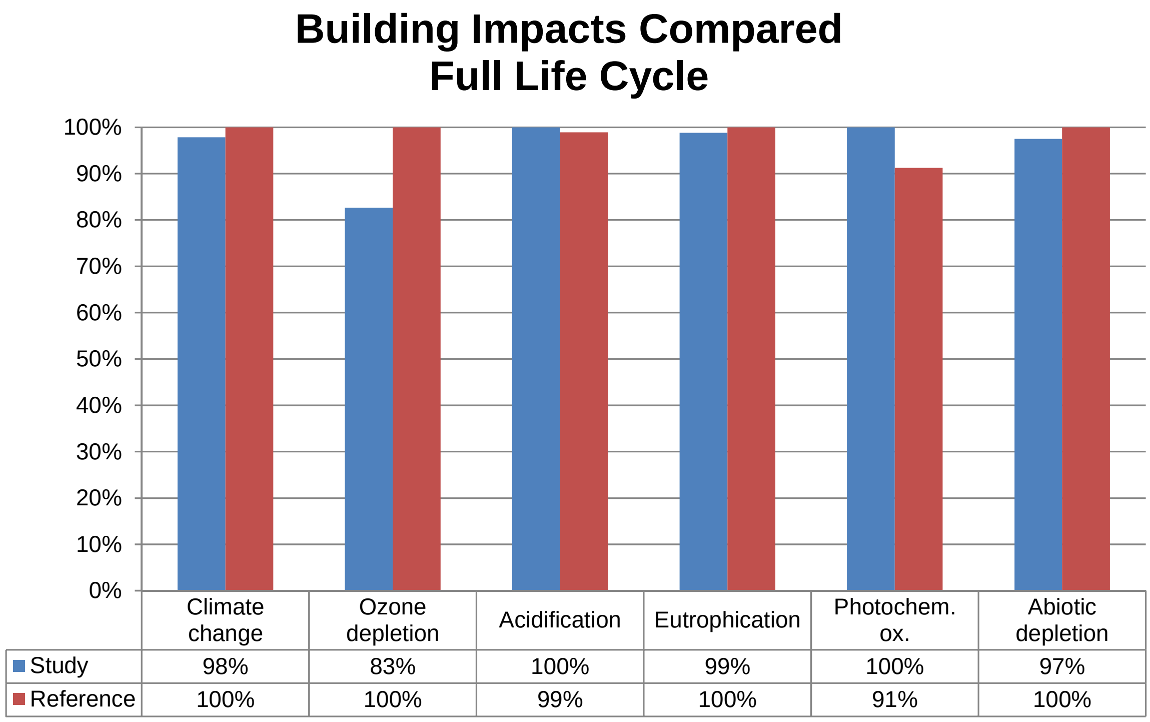
Table 35 Impact assessment results for 1 functional unit (1m^2 GDA provided for 60 years)

		Product stage	Construction process				Use stage (60 years)			End of life	Beyond building life cycle	Total
	Unit	Materials (net of waste)	Production of waste materials	Disposal of waste materials	Inbound transport	Excavation and disposal of earth	Operation (heating, cooling, ligting, water use)	Maintenance	Refurbishment	Building disposal	Avoided products	Total
Study Building												
Climate change	kg CO2 eq	340.5	13.3	4.5	17.6	7.6	3,517.1	48.6	114.9	93.5	- 94.9	4,062.8
Ozone depletion	mg CFC-11 eq	9.2	0.4	0.1	1.4	1.5	11.2	0.1	2.3	1.2	- 1.0	26.5
Acidification	kg SO2 eq	1.2	0.0	0.0	0.3	0.0	7.1	0.1	0.4	0.1	- 0.3	8.9
Eutrophication	kg PO43- eq	0.3	0.0	0.0	0.0	0.0	2.0	0.0	0.1	0.0	- 0.1	2.4
Photochem. ox.	g C2H4 eq	143.1	6.4	1.1	9.4	1.7	97.0	1.8	49.2	22.9	- 52.8	279.8
Abiotic depletion	kg Sb eq	2.0	0.1	0.0	0.1	0.1	26.1	0.4	0.6	0.2	- 0.6	28.9
Reference Building												
Climate change	kg CO2 eq	506.8	5.5	1.8	9.3	13.0	3,499.7	48.0	115.0	51.6	- 98.2	4,152.4
Ozone depletion	mg CFC-11 eq	12.6	0.2	0.0	1.1	2.5	11.3	0.1	2.3	2.9	- 1.0	32.0
Acidification	kg SO2 eq	1.3	0.0	0.0	0.0	0.1	7.1	0.1	0.4	0.1	- 0.3	8.8
Eutrophication	kg PO43- eq	0.3	0.0	0.0	0.0	0.0	2.0	0.0	0.1	0.0	- 0.0	2.4
Photochem. ox.	g C2H4 eq	144.5	2.5	0.4	1.9	3.0	97.1	1.6	49.2	8.9	- 53.7	255.4
Abiotic depletion	kg Sb eq	2.9	0.0	0.0	0.1	0.1	25.9	0.4	0.6	0.3	- 0.7	29.6
Reference Building versus Study Building (positive favourable)												
Climate change	kg CO2 eq	✓ 166.3	✗ - 7.8	✗ - 2.8	✗ - 8.3	✓ 5.4	✗ - 17.4	✗ - 0.7	○ 0.0	✗ - 41.9	✗ - 3.3	✓ 89.6
Ozone depletion	mg CFC-11 eq	✓ 3.4	○ - 0.2	○ - 0.0	○ - 0.3	✓ 1.0	○ 0.1	○ - 0.0	○ 0.0	✓ 1.7	○ - 0.0	✓ 5.6
Acidification	kg SO2 eq	○ 0.2	○ - 0.0	○ - 0.0	○ - 0.2	○ 0.0	○ - 0.0	○ - 0.0	○ 0.0	○ 0.0	○ - 0.0	○ - 0.1
Eutrophication	kg PO43- eq	○ 0.0	○ - 0.0	○ - 0.0	○ - 0.0	○ 0.0	○ 0.0	○ - 0.0	○ 0.0	○ - 0.0	○ 0.0	○ 0.0
Photochem. ox.	g C2H4 eq	✓ 1.4	✗ - 3.9	✗ - 0.7	✗ - 7.5	✓ 1.2	○ 0.1	○ - 0.2	○ 0.0	✗ - 14.0	✗ - 0.9	✗ - 24.4
Abiotic depletion	kg Sb eq	✓ 0.9	○ - 0.0	○ - 0.0	○ - 0.1	○ 0.1	○ - 0.1	○ - 0.0	○ 0.0	○ 0.1	○ - 0.1	✓ 0.7

Table 35 shows the outcomes for each building by impact category and by life cycle stage. Results add cumulatively from left to right across the life cycle and the ‘Total’ column reflects impacts for the entire life cycle. At the base of the table, the Reference Building is compared to the Study Building. Positive values in the section reflect favourable outcomes for the Study Building (impacts are lower than the Reference Building), negative values the opposite.

To help guide analysis, the comparison table has been marked with icons that highlight points of difference. The green ‘tick’ represents results where the Study Building is favourable by more than 0.5 of a unit. The red ‘cross’ represents results where the Study Building is unfavourable by more than 0.5 of a unit, and the yellow ‘circle’ represents items falling in between the two.

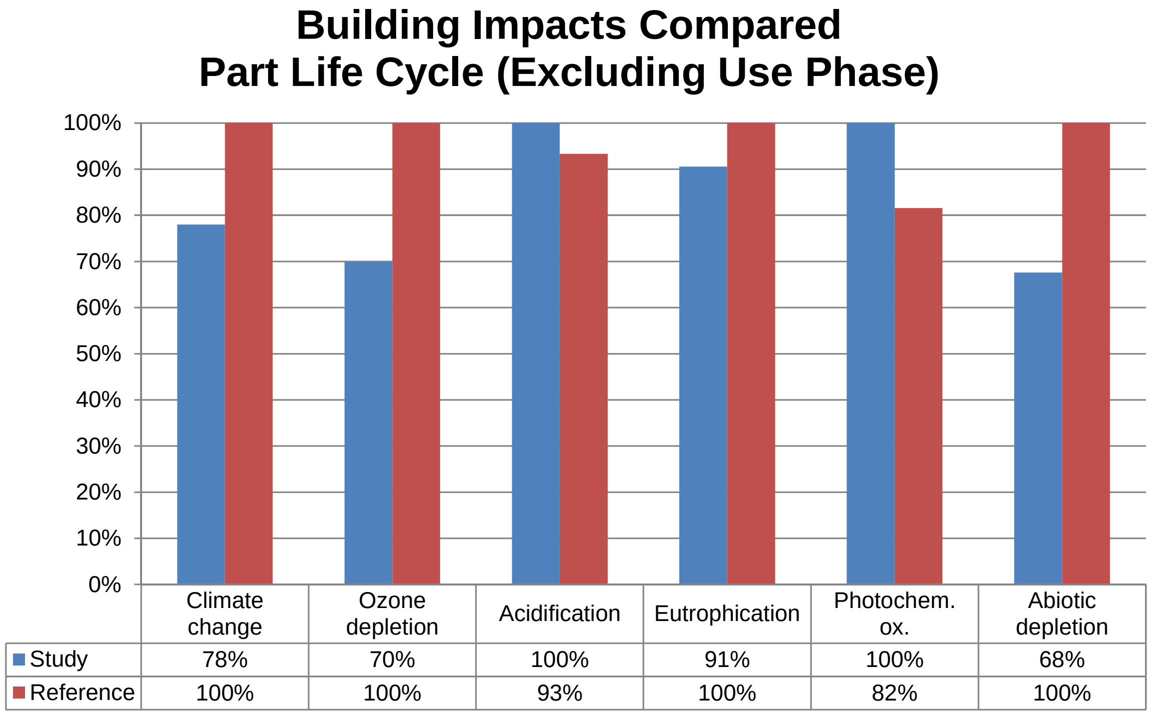
Results are also presented in a relative fashion in Figure 16 and Figure 17. In these diagrams, the building with the largest impact in a given impact category is allocated 100% and building with the smaller impact result is presented as a percentage of the larger impact. For example, the Reference Building has a larger impact for ozone depletion over the life cycle so is allocated 100% in the impact category in Figure 16. The Study Building impact is 83% of the Reference Building impact (Study Building/Reference Building*100%) so is shown as 83%.



	Climate change	Ozone depletion	Acidification	Eutrophication	Photochem. ox.	Abiotic depletion
🟦 Study	98%	83%	100%	99%	100%	97%
🟥 Reference	100%	100%	99%	100%	91%	100%

Figure 16 Building impacts compared - full life cycle.

Figure 16 illustrates the relative differences of buildings in each impact category across the full life cycle. Figure 17 illustrates relative differences over a partial life cycle which excludes the Use Stage of building life. It is included as it more clearly shows the difference between the buildings due to material selection and the construction approach adopted.



	Climate change	Ozone depletion	Acidification	Eutrophication	Photochem. ox.	Abiotic depletion
🟦 Study	78%	70%	100%	91%	100%	68%
🟥 Reference	100%	100%	93%	100%	82%	100%

Figure 17 Building impacts compared - partial life cycle (excluding Use Phase).

The following Section 7, considers the validity of these results, tests possible areas of uncertainty and compares the results to other studies. This is then followed by a discussion of the outcomes and their interpretation, Section 8.

7 Validation

The results shown in Table 35 are based on a wide range of assumptions, many of which are described in Section 5. With so many points considered and so many calculations undertaken it is likely that untested results could be misinterpreted. The following section aims to address some areas of uncertainty that could impact the results shown and assess the implications.

7.1 Uncertainty in data quantities

The DQA described in Section 5.7 provides a subjective assessment of data points used in the LCA which can help guide further analysis. A challenge when interpreting the DQA is deciding how the assessment might impact upon results and how might conclusions be tempered accordingly.

A useful way to address a component of the data quality problem is to employ uncertainty analysis that takes into account the range of data possibilities in the model and aggregates these in a plausible way. In this study an uncertainty analysis has been undertaken which employs Monte Carlo simulation to simulate 1000 random calculations of the difference between the Reference Building impacts and the Study Building impacts. As an output, the analysis technique provides a range of possible outcomes based upon the uncertainty information embedded in the model.

Table 36 Uncertainty analysis of the difference between the Reference Building and the Study Building by impact category.

		n=1000, 76% of all data contain uncertainty information			
Impact Category	**Unit**	**5 percentile**	**Reference Building less Study Building (nominal)**	**95 percentile**	**Assessment**
Climate change	kg CO2 eq	0.82	89.56	148.00	Conclusive
Ozone depletion	mg CFC-11 eq	1.07	5.55	10.60	Conclusive
Acidification	kg SO2 eq	-0.42	-0.10	0.19	Uncertain
Eutrophication	kg PO43- eq	-0.05	0.03	0.11	Uncertain
Photochem. ox.	g C2H4 eq	-55.10	-24.43	34.30	Uncertain
Abiotic depletion	kg Sb eq	0.08	0.75	1.19	Conclusive

The results of the uncertainty analysis for this study are shown in Table 36 for a 90% confidence interval. In other words, when simulated 1000 times, the impact outcome is likely to land within the values shown in 5th percentile and 95th percentile columns of Table 36. The results in the table highlight situations where we can be reasonably confident in the outcome and where conclusions could change. The results shown here suggest that the acidification, eutrophication and photochemical oxidation impact categories are uncertain. The other indicators appear conclusive and are favourable for the Study Building.

Photochemical oxidation is a good example of how results vary under simulation and how this affects what conclusions can be drawn from the results. Figure 18 shows a histogram of simulation outcomes for the difference between buildings in the photochemical oxidation impact category. Red bars are those where the Reference Building has lower impacts than the Study Building and green bars are those where the Study Building has lower impacts. Although the average simulation outcome (shown as a vertical dotted line) shows the Reference Building to have lower impacts, the 90% confidence interval (shown as solid vertical red lines) incorporates outcomes where the reverse is true (green bars). This result suggests that known data uncertainty makes drawing a definitive conclusion more difficult. This is in contrast to the climate change impact category, where all results favour the Study Building within the confidence interval (Figure 19).

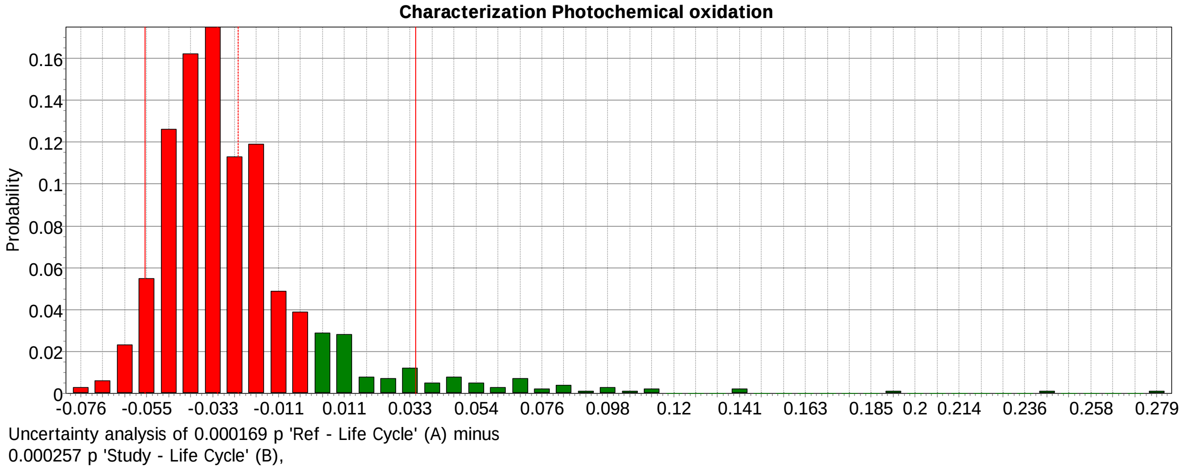


Figure 18 Histogram of differential results for photochemical oxidation.

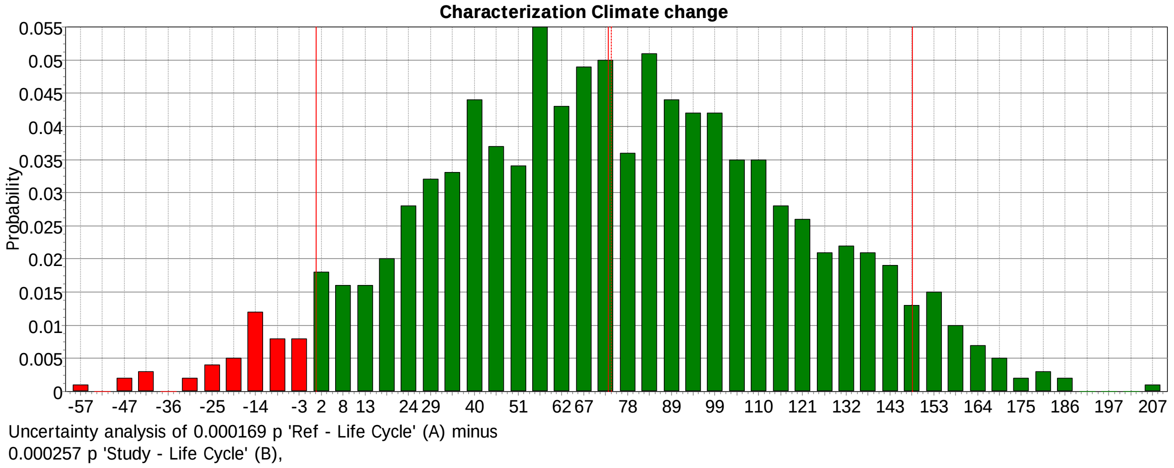


Figure 19 Histogram of differential results for climate change.

For those impact categories that achieved less than a 90% confidence interval, the interval was iteratively narrowed in 10% intervals until a consistent differential conclusion was recorded. This process allowed a confidence interval to be determined for which the directional conclusion was valid. These are shown recorded in the right hand column of Table 37. Directional conclusions for acidification and eutrophication were found to be highly uncertain as directional conclusions were valid in less than 40% of simulation outcomes. Photochemical oxidation, on the other hand, was directionally consistent in 80% of simulation outcomes.

Table 37 Impact assessment results for 1 functional unit (1m2 GDA provided for 60 years), incorporating results from uncertainty analysis.

Impact Category	Unit	Study Building	Reference Building	Difference (Reference less Study)	Confidence in differential finding under uncertainty analysis*
Climate change	kg CO2 eq	4,062.8	4,152.4	89.6	90%
Ozone depletion	mg CFC-11 eq	26.5	32.0	5.6	90%
Acidification	kg SO2 eq	8.9	8.8	Inconclusive	40%
Eutrophication	kg PO43- eq	2.4	2.4	Inconclusive	30%
Photochem. ox.	g C2H4 eq	279.8	255.4	- 24.4	80%
Abiotic depletion	kg Sb eq	28.9	29.6	0.7	90%

* Interval over which the directional finding is consistent over 1000 simulations. Rounded to nearest 10%

Overall, the uncertainty analysis technique employed was useful as it provided a way of measuring the impacts of uncertainty on study outcomes. It did, however, have limitations. It did not address uncertainty associated with the selection of background inventories, the appropriateness of model structure or the omission of data elements. Results shown therefore understate total uncertainty in study findings.

7.2 Accuracy of building material quantities.

A challenge with all building LCA's is developing an accurate and consistent bill of quantities for the buildings being assessed. As detailed bill of quantity data, beyond the quantity surveyor (QS) estimates shown below, was not available for the buildings considered, quantities have been developed by a single analyst from drawings provided by the client. This approach maximises consistency, completeness and transparency but may adversely impact overall quantity accuracy.

Although uncertainty in measured data is partially addressed by the technique described in Section 7.1, it is worthwhile comparing material quantities to other sources. Table 38 and Table 39 compare material quantities to high-level estimates provided by building practitioners within the client organisation.

Table 38 Study Building material quantities compared to practitioner estimates.

	QS Estimate		Density		QS Estimate	This Study	Variance	Correlation
	Qty	Unit	amt	unit	mass (kg)	mass (kg)	Mass (kg)	
Softwood*	350	m3	550	kg/m3	192,500	202,287	9,787	Good
Hardwood*	42	m3	850	kg/m3	35,700	30,953	- 4,747	Good
Concrete	660	m3	2400	kg/m3	1,584,000	1,367,845	- 216,155	Good
Bricks	16000	p	6	kg/unit	96,000	130,537	34,537	Good
Kooltherm	2300	m2	1.92	kg/m2	4,416	2,838	- 1,578	Poor
Alum. cladding	150	m2	11.2	kg/m2	1,680	3,078	1,398	Poor
Steel - Reinf	65000	kg	1	kg/kg	65,000	45,293	- 19,707	Poor
Steel - Struc	12000	kg	1	kg/kg	12,000	5,309	- 6,691	Poor
Steel - Roof	5000	kg	1	kg/kg	5,000	4,568	- 432	Good
Cement boards	7000	m2	18	kg/m2	126,000	225,145	99,145	Moderate
Plaster	17000	m2	13	kg/m2	221,000	205,285	- 15,715	Good
Window area	744	m2	30	kg/m2	22,320	25,563	3,243	Good
Other	0	NA	NA	NA	-	160,218	160,218	Poor
*Updated data from truss/frame manufacturer				Total	2,365,616	2,408,919	43,303	

Table 39 Reference Building material quantities compared to practitioner estimates.

	QS Estimate		Density		QS Estimate	This Study	Variance	Correlation
	Qty	Unit	amt	unit	mass (kg)	mass (kg)	Mass (kg)	
Softwood	26	m3	550	kg/m3	14,300	-	- 14,300	Poor
Hardwood	0	m3	850	kg/m3	-	-	-	NA
Concrete	2742	m3	2400	kg/m3	6,580,800	8,768,470	2,187,670	Moderate
Bricks	585	p	16	kg/unit	9,360	36,192	26,832	Poor
Kooltherm	0	m2	1.92	kg/m2	-	-	-	NA
Alum. cladding	0	m2	11.2	kg/m2	-	-	-	NA
Steel - Reinf*	123000	kg	1	kg/kg	123,000	197,390	74,390	Moderate
Steel - Struc	0	kg	1	kg/kg	-	-	-	NA
Steel - Roof	0	kg	1	kg/kg	-	-	-	NA
Cement boards	0	m2	18	kg/m2	-	-	-	NA
Plaster	28441	m2	13	kg/m2	369,733	278,583	- 91,150	Moderate
Window area	1724	m2	30	kg/m2	51,720	31,902	- 19,818	Poor
Other	0	NA	NA	NA	-	459,335	459,335	Poor
*QS excludes wall panels and lost formwork					7,148,913	9,771,872	2,622,959	

For the Study Building, which has been completed, Table 38 shows some variation between material quantities but overall a reasonable correlation between drawing take-offs and the QS estimate developed. The outcome serves to support the drawings based approach which enabled far greater material detail to be built into the LCA model, such as building sub-system information. The drawings based approach also served to provide a high degree of transparency in building material quantity estimates (refer Appendix A and Appendix B).

The Reference Building, shown in Table 39 does not correlate to the same degree. In general estimates from drawings are considerably greater than those developed by the practitioner. Although the exact reason for this is unknown, reasons for the variation could be due to the nature of the project and it's stage of development. At time of writing the reference building had not been completed so uncertainty regarding building content would be higher. In general, the practitioner estimate developed was based upon building subcontractor quotation information which included a mix of panelised and formed on site concrete elements. Extracting material volumes from this information is likely to have been challenging.

To build confidence in the drawings based approach results were also compared to other studies John et al. (2009) and Durlinger, Crossin and Wong (2012) as shown Table 40. The results suggest that the drawings based estimates are consistent with other studies. The Reference Building, in particular, appears to be at the lower end of the mass spectrum for concrete and steel buildings.

Table 40 Building quantities compared to other studies.

				Building type from John, Nebel, Perez & Buchanan (2009)*		Building type from Durlinger et al (2013)**	
	Unit	Study Building	Reference Building	Concrete and steel office building	Timber frame office building	Forte - apartment building (cross laminated timber)	Reference building - apartment building (reinforced concrete)
Material mass per m2 GFA	kg/m2 GFA	453	1,180	1,359	487	1367	2609
Material mass per m2 GDA	*kg/m2 GDA*	*618*	*1,653*				

* Calculated from table 6.1 divided by GFA of 4247m2.

** Calculated from table 5.4 and 5.8 divided by GFA of 1755 m2

In the absence of a detailed bill of quantities for both buildings, it was decided that the drawings based estimates provided the best consistency between the building studied and the most transparent approach. The results also correlate well with other studies. This said, it is acknowledged that material quantities represent a significant source of uncertainty in building LCA reports. For this reason, transparency is regarded as the only effective countermeasure to this perennial problem, further justifying the approach adopted.

7.3 Window to floor ratios

The results presented in Table 35 suggest a conclusion regarding the light-weight approach taken to construct the Study Building and the heavy-weight approach taken to construct the Reference Building. It is assumed that the cause of the outcome is due to these construction choices, however what if another factor is at play?

One area of difference between the two buildings is the ratio of window areas to floor areas (refer Table 30). The Study Building has more windows per unit of floor area than the Reference Building (0.18 window to floor ratio and 0.15 respectively). This could increase the amount of material in walls in the Reference Building or affect its performance in some other way.

To test this concern, the Reference Building model was adjusted to increase the window area by 17% and reduce the wall area by 5%, sufficient to provide a window to GDA area ration of 0.18, identical to the Study Building (wall area is reduced by 157 m^2, the amount the window area is increased).

Table 41 Results change when Reference Building window to floor ratio is increased from 0.15 to 0.18.

			Window to floor = 0.15	**Window to floor = 0.18**
Category Indicator	**Unit**	**Study Building**	**Reference Building**	**Reference Building (adjusted for window ratio)**
Climate change	kg CO2 eq	4,062.8	4,152.4	4,151.3
Ozone depletion	mg CFC-11 eq	26.5	32.0	32.0
Acidification	kg SO2 eq	8.9	8.8	8.8
Eutrophication	kg PO43- eq	2.4	2.4	2.4
Photochem. ox.	g C2H4 eq	279.8	255.4	255.2
Abiotic depletion	kg Sb eq	28.9	29.6	29.6

Results of the analysis (Table 41) showed very little change in outcomes for the Reference Building outcomes and none of the study conclusions were changed.

As a further check, the Reference Building thermal performance was modelled using a simplified model to see if equivalent thermal load could be achieved with the larger windows. The simplified model included four apartments, one at the centre of each face of the building at level three. Each apartment was assessed using FirstRate™ software and the ratings compared to the reported NatHERS assessment. Further modelling was then undertaken to assess any adverse impact on the star rating and finally interventions were modelled to determine what would be required achieve the replicated star rating. In all, the process determined what material implications associated with increasing window size in the Reference Building, and found them to be minimal (Table 42).

Table 42 Thermal modelling undertaken to assess material impacts of increasing window size in the Reference Building.

		NatHERS star ratings (unit = stars)				
Apartment on level 3	**Facing direction**	**Reported assessment**	**Replicated assessment**	**After increase in window area**	**After increase in window area, with intervention**	**Intervention needed to achieve replicated rating**
1	E	7.2	**7**	6.9	**7**	Increase 24.9 m2 exterior wall insulation from 88mm to 110mm
2	N	7.8	**7.7**	7.6	**7.7**	Increase 21.1 m2 exterior wall insulation from 88mm to 110mm
3	S	7.3	**7.1**	6.9	**7.1**	Increase 21.1 m2 exterior wall insulation from 88mm to 110mm, and Increase 66.9 m2 exterior wall insulation from 66mm to 110mm
4	W	6.6	**5.7**	5.3	**5.8**	Increase 62.2 m2 exterior wall insulation from 88mm to 110mm, and replace windows with single glazed low-e glass = 11.54m2

7.4 Carbon monoxide emissions from wood production

A potential problem noticed when assessing the impacts of the hardwood background inventory in Section 5.1.3.2, was that the AusLCI inventory employed has considerably increased carbon monoxide emissions versus the BPIC inventory, likely due to differences in the allocation of emissions due to fuel reduction burns and forest residue burning. To test if this difference might change study conclusions, the Study Building was modelled using the BPIC inventory.

Table 43 Study Building impacts when hardwood inventory employs the BPIC dataset.

Impact category	**Unit**	**Study Building**	**Study Building using BPIC hardwood inventory**	**Reference Building**
Climate change	kg CO2 eq	4,062.8	4,056.8	4,152.4
Ozone depletion	mg CFC-11 eq	26.5	26.5	32.0
Acidification	kg SO2 eq	8.9	8.9	8.8
Eutrophication	kg PO43- eq	2.4	2.4	2.4
Photochem. ox.	g C2H4 eq	279.8	268.0	255.4
Abiotic depletion	kg Sb eq	28.9	28.9	29.6

The results shown in Table 43 show that the Study Building impacts do reduce in a number of categories, but not to the point that would change study outcomes. Although it would be worthwhile clarifying which inventory is the better source, the implications in in terms if this study are mute.

7.5 Building life

A key area of uncertainty in the study pertains to building life. Estimating how along a building will last for is particularly difficult as many factors impact on longevity, many derived from market forces, rather than building elements. To assess the impact building life might have on study findings the life was varied for both the Study Building and the Reference Building and the results calculated. In undertaking the calculation operational energy requirements were varied, as were building maintenance and refurbishment schedules.

The results of the assessment are shown in Table 44. The results demonstrate the significant impact building life has on each individual building impact, but also that the difference between the buildings remains surprisingly robust. This results shows that across all impact categories, lifetime assumptions have little impact on study conclusions. This finding is most likely due to the similarity in operating assumptions between both buildings.

Table 44 Impact of changes in building life on study conclusions.

			Baseline				
Category Indicator	**Unit**	**50 years**	**60 years**	**70 years**	**80 years**	**90 years**	**100 years**
Study Building							
Climate change	kg CO2 eq	3,444.6	4,062.8	4,681.1	5,299.3	5,917.6	6,535.8
Ozone depletion	mg CFC-11 eq	24.0	26.5	28.9	31.3	33.7	36.1
Acidification	kg SO2 eq	7.6	8.9	10.2	11.4	12.7	14.0
Eutrophication	kg PO43- eq	2.0	2.4	2.8	3.1	3.5	3.8
Photochem. ox.	g C2H4 eq	254.2	279.8	305.4	331.1	356.7	382.3
Abiotic depletion	kg Sb eq	24.3	28.9	33.4	37.9	42.5	47.0
Reference Building							
Climate change	kg CO2 eq	3,537.1	4,152.4	4,767.6	5,382.8	5,998.1	6,613.3
Ozone depletion	mg CFC-11 eq	29.6	32.0	34.4	36.8	39.3	41.7
Acidification	kg SO2 eq	7.5	8.8	10.1	11.3	12.6	13.9
Eutrophication	kg PO43- eq	2.1	2.4	2.8	3.1	3.5	3.9
Photochem. ox.	g C2H4 eq	229.8	255.4	281.0	306.6	332.2	357.8
Abiotic depletion	kg Sb eq	25.1	29.6	34.1	38.6	43.1	47.7
Reference Building versus Study Building (positive favourable)							
Climate change	kg CO2 eq	92.58	89.56	86.55	83.54	80.52	77.51
Ozone depletion	mg CFC-11 eq	5.55	5.55	5.56	5.57	5.57	5.58
Acidification	kg SO2 eq	- 0.10	- 0.10	- 0.10	- 0.10	- 0.10	- 0.10
Eutrophication	kg PO43- eq	0.03	0.03	0.03	0.03	0.03	0.03
Photochem. ox.	g C2H4 eq	- 24.41	- 24.43	- 24.45	- 24.46	- 24.48	- 24.50
Abiotic depletion	kg Sb eq	0.77	0.75	0.73	0.70	0.68	0.66

7.6 Results comparison to other studies

A further check of findings involved the comparison of study results to other similar studies. As LCA is a diverse method, comparison to other studies is complicated by the range of assumptions and objectives that studies incorporate. In general, it was found that climate change impacts tended to be common other studies, so a reasonable point for comparison. It was also found that impacts associated with the Product Stage and Construction Process were usually consistently reported, however full life cycle information was more difficult to compare, mainly due to differences in operating modelling approaches.

The study findings were compared to four alternative studies: Kaethner and Burridge (2012), Durlinger, Crossin and Wong (2012), Carre (2011) and John et al. (2009). The comparison was drawn based on the climate change impact for the Product Stage and Construction Process per m^2 gross floor area (GFA). Comparisons per m^2 GDA were not easily drawn as some buildings were office buildings, and GDA is defined in different ways. The results of the comparison are shown in Table 45.

Table 45 Comparison of Product Stage and Construction Process to other studies.

	Product Stage + Construction Process		Kaethner & Burridge (2012)	Durlinger, Crossin & Wong(2012)		Carre (2011)	John, Nebel, Perez & Buchanan (2009)			
	kg CO2e/m2 GDA	kg CO2e/m2 GFA	kg CO2e/m2 GFA	kg CO2e/m2 GFA	kg CO2e/m2 GFA	kg CO2e/m2 GFA	kg CO2e/m2 GFA	kg CO2e/m2 GFA	kg CO2e/m2 GFA	kg CO2e/m2 GFA
Calculation notes			1	2	3	4	5			
Building types			Concrete and steel framed schools, hospitals and offices.	Cross Laminated Timber apartment building (Forte) with concrete retail podium. 2431 m2 area incl. 197 m2 retail space.	Concrete and steel frame apartment building. 2431 m2 area incl. 197 m2 retail space.	3 bedroom single storey home. Brick veneer, timber frame on a concrete slab. 202m2 GFA incl. garage.	Office building, concrete structure, 4247 m2.	Office building, steel structure, 4247 m2.	Office building, timber structure (typical timber use), 4247 m2.	Office building, timber structure (maximum timber use), 4247 m2.
Study geography	Melbourne		United Kingdom	Melbourne		Melbourne	Christchurch, NZ			
Study Building	*383*	**281**	300 to 520	327	404	131	371	380	229	133
Reference Building	*490*	**350**								

Calculation Notes:

1. Compiled from table 5, Range embodied CO2(t).
2. Figure compiled by adding reported construction and material impacts of 649 t CO2e and 146 t CO2e to give 795 t CO2e, and dividing this by the GFA of 2431 m2. Quoted figure excludes carbon sequestration. Forte GFA calculated by dividing cumulative energy demand from table 6.1 by (50 years x cumulative energy demand from table 7.1) of Durlinger, Crossin and Wong (2012).
3. Figure compiled by adding reported construction and material impacts of 931 t CO2e and 52 t CO2e to give 983 t CO2e, and dividing this by reported gross floor area of 2431 m2. From fig 7-3 on p.56. Quoted figure excludes carbon sequestration.
4. Figure compiled from figure 20. 26,528 kg CO2e total construction impact for building b divided by 202 m2 floor space.
5. Figures compiled from the 'Initial Embodied' column of table 6.7, which is divided by a GFA of 4247m2.

The results show the study outcomes to be in the same range as other studies. Kaethner and Burridge (2012) provides a good reference against which the Reference Building outcomes can be compared, as does the concrete apartment building from Durlinger, Crossin and Wong (2012) and the concrete office of John et al. (2009). The Study Building is probably most comparable to the timber structure office building of John et al. (2009), but Carre (2011) and the Forte building of Durlinger, Crossin and Wong (2012) provide interesting reference points.

From the comparison it is clear the study outcomes are in the same range as the other studies considered. Importantly, where a similar comparison is undertaken for an office building, as in John et al. (2009), the results are also comparatively consistent.

7.7 Comparing buildings using alternate area definitions

A possible source of bias in the study is associated with the selection of the functional unit (Section 3.4), as the unit of area is not prescribed in GBCA (2014) and therefore is open to interpretation. In this study building impacts are reported per unit of GDA which includes apartment interior space and the balcony space. This measure was selected as it was felt to best reflect the building's primary function, however it is acknowledged that arguable alternative measures do exist, as discussed in Section 3.4. This sensitivity study tests the impact of this selection on study conclusions.

Alternative definitions of building area were tested as follows:

1) Enclosed apartment area – Area within each apartment, excluding balconies.
2) Gross floor area excluding carpark[4] – total area provided on each floor of the building including: lifts, corridors, foyers, stairwells, apartment interiors, and apartment balconies.

The Study Building and Reference Building impacts were then recalculated using the above area definitions, which were compared to the study definition of GDA (the BASE CASE).

---

[4] Carpark area was excluded in this definition as it has already been adjusted for in Section 5.6.1.

Table 46 Life cycle (60 years) impact assessment results under alternative definitions of building area.

Category Indicator	Unit	Study Building	Reference Building	Difference (Reference less Study)
Results per functional unit (1 m^2 GDA) - BASE CASE				
Climate change	kg CO2 eq	4,062.8	4,152.4	89.6
Ozone depletion	mg CFC-11 eq	26.5	32.0	5.6
Acidification	kg SO2 eq	8.9	8.8	- 0.1
Eutrophication	kg PO43- eq	2.4	2.4	0.0
Photochem. ox.	g C2H4 eq	279.8	255.4	- 24.4
Abiotic depletion	kg Sb eq	28.9	29.6	0.7
Results per 1 m^2 enclosed apartment area, excluding balcony				
Climate change	kg CO2 eq	4,436.5	4,591.15	154.7
Ozone depletion	mg CFC-11 eq	28.9	35.39	6.5
Acidification	kg SO2 eq	9.7	9.72	0.0
Eutrophication	kg PO43- eq	2.6	2.69	0.1
Photochem. ox.	g C2H4 eq	305.6	282.38	- 23.2
Abiotic depletion	kg Sb eq	31.5	32.75	1.2
Results per 1 m^2 GFA (excluding carpark)				
Climate change	kg CO2 eq	3,619.7	3,722.35	102.6
Ozone depletion	mg CFC-11 eq	23.6	28.69	5.1
Acidification	kg SO2 eq	7.9	7.88	- 0.0
Eutrophication	kg PO43- eq	2.1	2.18	0.0
Photochem. ox.	g C2H4 eq	249.3	228.94	- 20.4
Abiotic depletion	kg Sb eq	25.7	26.56	0.8

Table 46 shows that the alternative definitions of floor area considered tend to advantage the Study Building relative to the Reference Building, with the BASE CASE representing the most conservative approach. The result also illustrates how the selection of functional unit can materially impact results. Standards such as GBCA (2014) may be better served if the functional unit is prescribed, rather than being left open to selection.

8 Discussion

8.1 Potential environmental impacts and their causes

Before looking into the results presented in Section 6, the first observation is how light the Study Building is in relation to the Reference Building. At 618 kg per m^2 GDA the Study Building is one third the weight of the Reference Building (Table 10). This reduced mass carries with it inherent advantages from an environmental standpoint, provided material production intensities are managed. Lower mass should lead to lower transport impacts, and lower construction impacts (excluding on-site activities) and in part this is found to be true. As is true for any innovative approach, further optimisation will likely be possible as techniques are improved and supply chains optimised.

8.1.1 Overall findings

The results shown in Figure 16 show the Study Building to have lower environmental impacts versus the Reference building in the categories of climate change, ozone depletion, eutrophication and abiotic depletion. The Reference Building is shown to have lower impacts in the categories of acidification and photochemical oxidation. Uncertainty analysis with respect to these outcomes was undertaken for a 90% confidence interval (Section 7.1) which showed reasonable confidence in the outcomes for climate change, ozone depletion and abiotic depletion. The other categories of acidification, eutrophication and photochemical oxidation were found to be more uncertain, as directional[5] findings were seen to change within the 90% confidence interval.

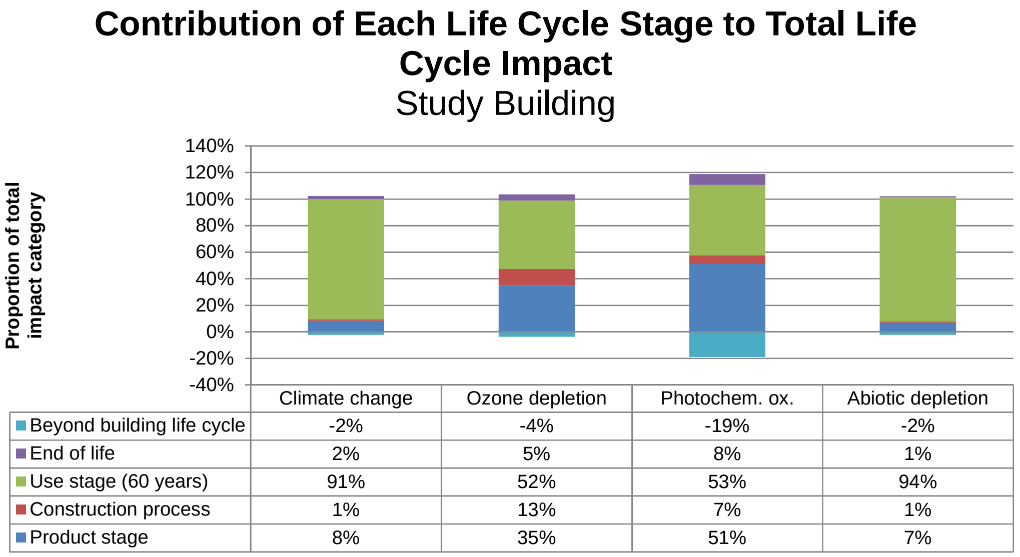
Interpretation of the differential findings for category indicators that were not consistent within a 90% interval is problematic, especially for those where the differences seen are particularly small. Eutrophication and acidification impact categories were both found to lie within less than 1% each other for both buildings making differences hard to substantiate. For this reason it was decided to consider the comparative findings for these indicators as ‘inconclusive’. Photochemical oxidation, however, was found to show a larger difference (9%, refer Figure 16) between the buildings considered, so although differential findings do not support a 90% confidence level, the quantum of the difference is worthy of further discussion and is likely to be significant. Results when uncertainty analysis is considered are best summarised by Table 37.

8.1.2 Drivers of life cycle impacts

The stages of building life which cause the bulk of life cycle impacts vary between impact categories. Figure 20 and Figure 21 show how each life cycle stage contributes to the total life cycle impact for each impact category for the Study Building and Reference Building respectively. The figures show that the Use Stage of life causes 88-94% of climate change and abiotic depletion impacts, and 43-58% of ozone depletion and photochemical oxidation impacts. Both ozone depletion and photochemical oxidation are more strongly influenced by the Product life cycle stage (materials). Negative contributions, shown in the Beyond Building Life Cycle stage reflect environmental credits due to the recovery and recycling of building materials at the end of life.

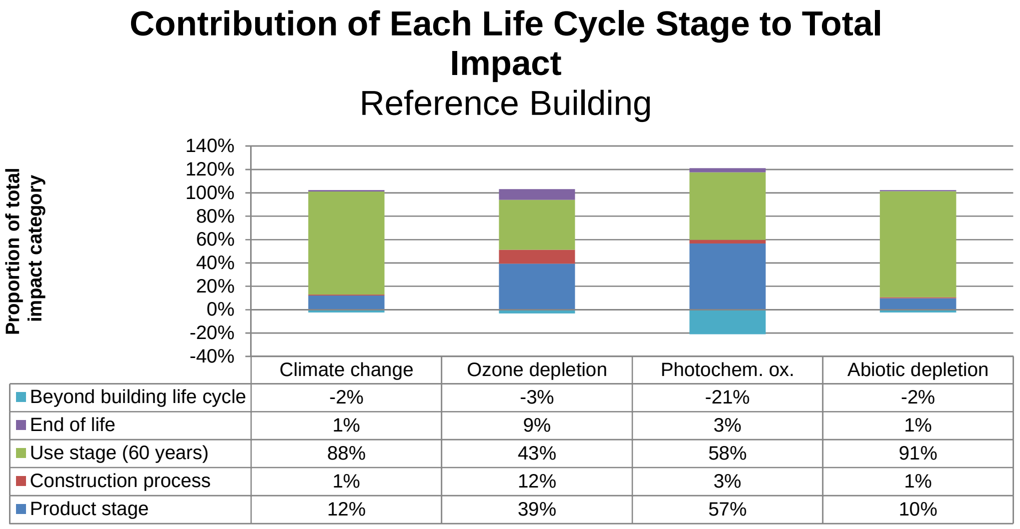
---

[5] Across 1000 model simulations, findings sometimes showed the Study Building as preferable and sometimes showed the Reference Building as preferable. The conclusion drawn from this is that underlying data quality is not sufficient to state with building is preferable to a 90% confidence level.



	Climate change	Ozone depletion	Photochem. ox.	Abiotic depletion
■ Beyond building life cycle	-2%	-4%	-19%	-2%
■ End of life	2%	5%	8%	1%
■ Use stage (60 years)	91%	52%	53%	94%
■ Construction process	1%	13%	7%	1%
■ Product stage	8%	35%	51%	7%

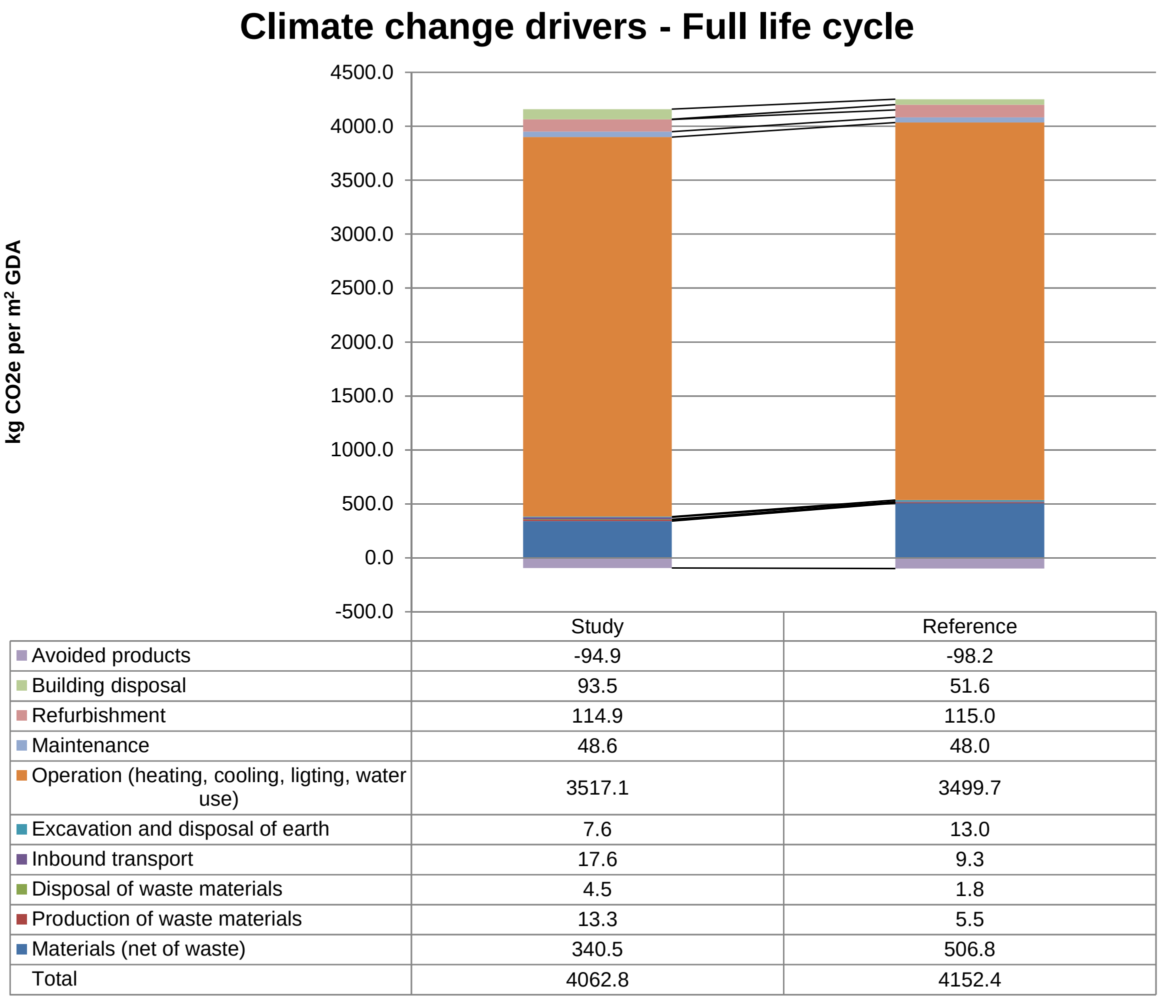
Figure 20 Contribution of life cycle stages to total life cycle impact - Study Building. Excludes inconclusive impact categories (acidification and eutrophication).



	Climate change	Ozone depletion	Photochem. ox.	Abiotic depletion
■ Beyond building life cycle	-2%	-3%	-21%	-2%
■ End of life	1%	9%	3%	1%
■ Use stage (60 years)	88%	43%	58%	91%
■ Construction process	1%	12%	3%	1%
■ Product stage	12%	39%	57%	10%

Figure 21 Contribution of life cycle stages to total life cycle impact - Reference Building. Excludes inconclusive impact categories (acidification and eutrophication).

Table 35 shows in detail how each life cycle stage (and sub-stage) contributes to the total life cycle outcome for each category indicator. Figure 22 illustrates the results from Table 35 graphically for the climate change category. The diagram makes clear the dominance of building operation within the Use Stage of building life accounting for a minimum of 88% of the building life cycle impact for climate change. The diagram also illustrates that although dominant, the Use Stage does not differentiate the buildings, instead it is building materials (within the Product Stage) which cause the difference. This is because both buildings are designed to achieve very similar operational requirements with respect to the use of energy. For example both are designed to achieve 7 star NatHERS ratings.



	Study	Reference
🟪 Avoided products	-94.9	-98.2
🟩 Building disposal	93.5	51.6
🟥 Refurbishment	114.9	115.0
🟦 Maintenance	48.6	48.0
🟧 Operation (heating, cooling, ligting, water use)	3517.1	3499.7
🟦 Excavation and disposal of earth	7.6	13.0
🟪 Inbound transport	17.6	9.3
🟩 Disposal of waste materials	4.5	1.8
🟥 Production of waste materials	13.3	5.5
🟦 Materials (net of waste)	340.5	506.8
Total	4062.8	4152.4

Figure 22 Drivers of climate change impacts.

It is worthwhile briefly considering the operational impacts which are similar for both buildings. Table 47 describes a breakdown of the operational impacts for the Study Building which shows that lighting is the main driver of impacts. Although operation does not differentiate the buildings, the table shows how small differential changes in this area could generate substantial differences between the buildings.

Table 47 Impact of operations for the Study Building (1m^2 GDA for 60 years).

Impact Category	Unit	Total	Heating and cooling	Hot water	Lighting	Water use
Climate change	kg CO2 eq	3,517.1	439.7	899.2	2,041.8	136.4
Ozone depletion	mg CFC-11 eq	11.2	0.2	8.1	0.8	2.2
Acidification	kg SO2 eq	7.1	0.6	3.4	2.6	0.5
Eutrophication	kg PO43- eq	2.0	0.1	0.9	0.6	0.4
Photochem. ox.	g C2H4 eq	97.0	5.4	46.9	25.2	19.4
Abiotic depletion	kg Sb eq	26.1	3.2	7.2	14.8	0.8

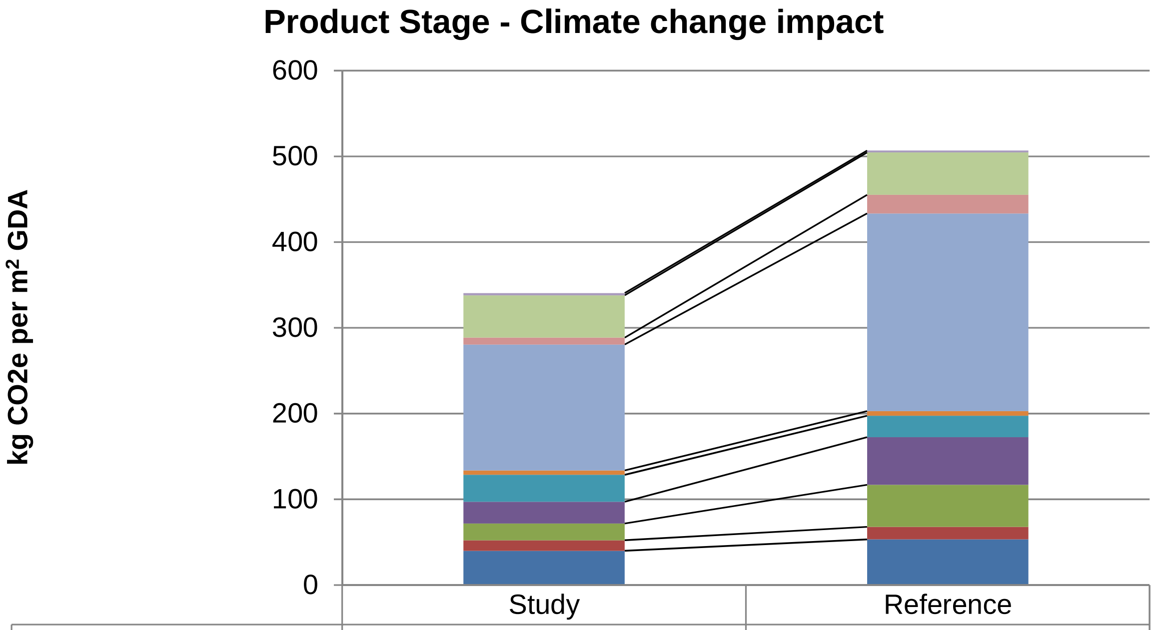
Table 47 also shows how the traditional cause of building operational impacts, heating and cooling, is not as significant as hot water and lighting. The outcome is likely to be due to the 7 Star NatHERS rating of the apartment buildings and the universal use of relatively efficient reverse cycle air conditioning units (COP's of 3.6 or greater. Refer Section 5.3.1), and fairly standard assumptions for lighting and hot water use. Although operational energy use is unlikely to differentiate these buildings, metering of actual energy use could help refine these energy use estimates.

Looking more closely at building materials in the Product Stage, Figure 23 illustrates how the Study Building achieves lower impacts versus the Reference Building from a climate change standpoint. Overall, the Study Building generates 67% of the climate change impacts of Reference Building at the

Product Stage. Given the Study Building represents one third of the mass of the Reference Building, some of the material intensities (impacts per kg) are higher than those of the Reference Building, however the overall outcome is a significantly reduced impact building.

For both buildings, the floor system represents the largest contributor to climate change impacts (43 to 45%). In the Study Building, impacts within the floor system are mainly caused by the use of the magnesium oxide boards in the cassette system which are employed in two 18mm layers on each floor (equating to 40kg per m^2). In the Reference Building, floor system impacts are driven mainly by the post tensioned concrete slabs.

Further environmental advantage is achieved by the Study Building across other building systems such as external and internal walls which are light weight versus solid 150mm concrete panels in the Reference Building. External walls used in the Study Building were produced using a light weight timber frame clad in rendered phenolic foam panels, versus the Reference Building which employed 150mm precast concrete panels for the same purpose.



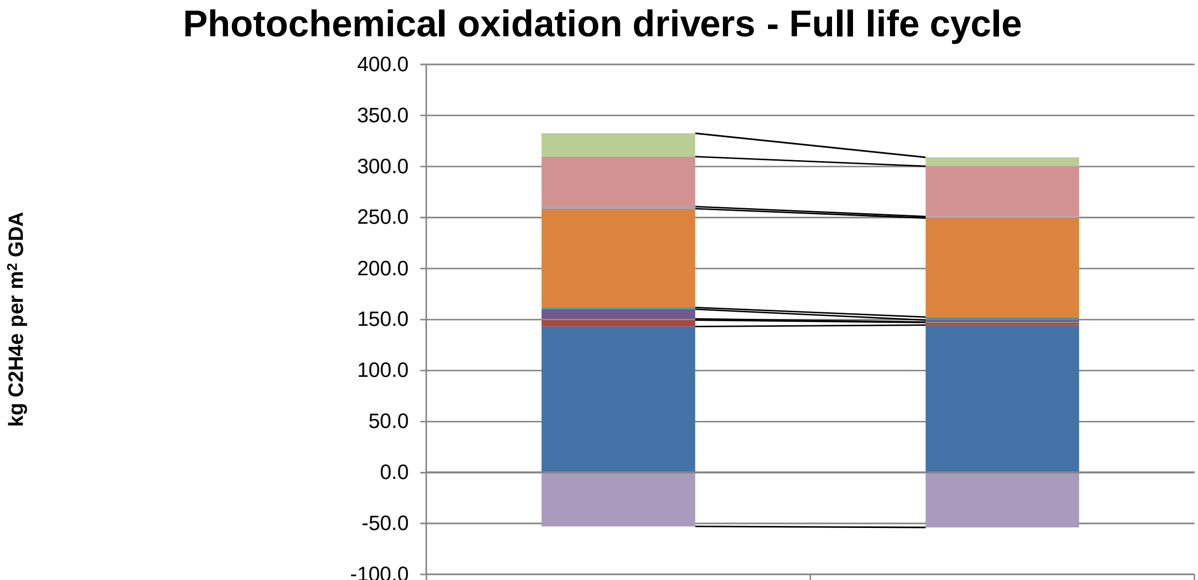
	Study	Reference
🟪 Common fitout	3	3
🟩 Apartment fitout	49	49
🟥 Roof system	8	22
🟦 Floor system	147	230
🟧 Columns, beams, lintels	5	5
🟦 Windows	31	25
🟪 External walls	25	56
🟩 Internal walls	20	49
🟥 Core	12	15
🟦 Substructure	40	53
Total	340	507

Figure 23 Climate change impact of building materials.

Beyond climate change, ozone depletion and abiotic depletion were found to behave in a similar fashion. Major drivers of difference were due to materials impacts in the Product Stage and so relate to the reduced quantities of materials employed in the Study Building, which generate net benefits as they are not offset by increased manufacturing intensity.

The exception to the advantage exhibited by the Study Building is in the Photochemical Oxidation impact category where the Reference Building achieves impacts 91% of those of the Study Building. Figure 24 shows the drivers of photochemical oxidation in both buildings and identifies Building Disposal and Inbound Transport as key points of difference. Photochemical oxidant impacts are shown to be higher for the Study Building during the Building Disposal process due to the emission of methane as timber is expected to degrade in landfill. The impact is further exacerbated by the expected lower recovery rate for timber during building demolition meaning a larger portion is expected to end up in landfill, versus the Reference Building materials like concrete and steel which are recycled at higher rates (refer Table 25).

Photochemical oxidant impacts for the Study Building are also driven by Construction Processes such as Inbound Transport (Figure 24). Inbound Transport impacts for the Study Building are caused by sulphur dioxide emissions from fuel combustion in ships needed to import the cement board materials used in the floor system (from Europe and China), in contrast to the Reference Building for which little international shipping is employed.



	Study	Reference
■ Avoided products	-52.8	-53.7
■ Building disposal	22.9	8.9
■ Refurbishment	49.2	49.2
■ Maintenance	1.8	1.6
■ Operation (heating, cooling, ligting, water use)	97.0	97.1
■ Excavation and disposal of earth	1.7	3.0
■ Inbound transport	9.4	1.9
■ Disposal of waste materials	1.1	0.4
■ Production of waste materials	6.4	2.5
■ Materials (net of waste)	143.1	144.5
Total	279.8	255.4

Figure 24 Drivers of photochemical oxidation impacts.

In concluding the review of impacts it is worthwhile mentioning the analysis undertaken to confirm study findings. A conservative approach to analysis has been undertaken that has involved the implementation of data quality strategies outlined in Section 3.5 and validation activities presented in Section 7. Areas of uncertainty, beyond those addressed by Monte Carlo analysis described in Section 7.1 have included cross referencing material inventories throughout the inventory analysis, consideration of material quantity accuracy, the testing of key issues such as window to floor ratios, hardwood production emissions, building life and building area definition. Results have also been compared to other similar studies.

8.2 Comparing impacts to the Forte building

A secondary objective of the study was to compare findings, where possible to those reported for the Forte building as described in Durlinger, Crossin and Wong (2012). The approach adopted in Durlinger, Crossin and Wong (2012) is reasonably consistent with that adopted in this study for the Product Stage and Construction Process stages of the building life cycle. Beyond these stages, Durlinger, Crossin and Wong (2012) adopt a quite different methodology for modelling operational and end of life impacts making comparison difficult[6].

Table 48 gives an overview of how the buildings compare. Firstly, Forte is a far smaller building than the Study Building incorporating only 23 apartments versus the 57 in the Study Building. It also has a far smaller GFA of 2,431 m^2 which equates to 46% of the Study Building and is far taller at twice the height. Forte's function varies from that of the Study Building, as it incorporates a retail space on the ground floor and it does not include a carpark. These differences make drawing a clean comparison difficult as the buildings are quite different in many respects.

Table 48 Study Building compared to Forte.

Item	Unit	Study Building	Forte	Data Manipulation
Gross Floor Area	m2	5315	2431	Forte GFA calculated by dividing cumulative energy demand from table 6.1 by (50 years x cumulative energy demand from table 7.1) of Durlinger, Crossin and Wong (2012).
Number of apartments		57	23	
Number of floors		5 + carpark	9 + retail podium	
Location		Parkville, Victoria	Docklands, Victoria	
Construction type		Light-weight timber frame on concrete and screw-pile foundations. Exterior walls of rendered phenolic foam panels. Floor system employing engineered timber joists installed in 'cassette' modules. Filled concrete block lift and stair core. The building incorporates a basement carpark.	"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." (Durlinger, Crossin & Wong (2012), p5)	
Building mass	kg/m2 GFA	453	987	Forte calculated from table 5.4 and 5.8 divided by GFA of 2431 m2
Climate change impact for Product Stage, Construction Process Stage, End of Life and Beyond Building Life stage of building life (excluding carbon sequestration, excluding fitout)	kg CO2e/m2 GFA	300	452	Forte figure compiled by adding reported construction and material impacts of 649 t CO2e and 146 t CO2e to give 795 t CO2e from fig 7-3, and dividing this by reported gross floor area of 2431 m2. The Study Building is adjusted to present results per unit GFA and to exclude fitout, which is not assessed in Forte.
Climate change impact for Product Stage, Construction Process Stage, End of Life and Beyond Building Life stage of building life (including carbon sequestration, excluding fitout)	kg CO2e/m2 GFA	196	185	Forte as above but also including a credit of 354 t CO2e from fig 7-3 due to carbon storage at disposal. Study Building adjusted to include carbon storage in landfill. Degradable organic carbon fraction of wood in the Study Building reduced from from 0.5 to 0.25 to make consistent with Durlinger et al.(2012).

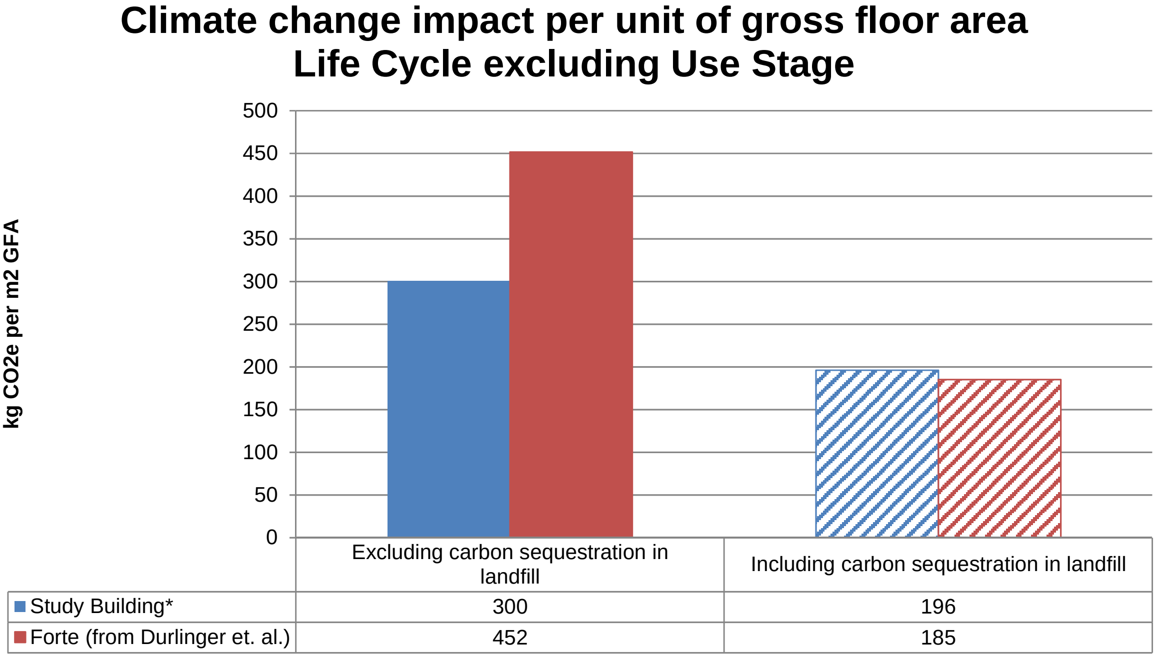
With building functional differences in mind, it is clear that the Study Building is lighter than Forte, which employs a heavy timber structure, incorporating solid cross laminated timber panels (approximately 150mm thick). The Study Building is 46% of the Forte weight.

Comparison of the Study Building to Forte was possible for all life cycle stages except the Use Stage, due to differences in the way this stage was modelled. Only the climate change impact category was compared due to differences in the way other impact categories were disclosed in the reports. Comparison was undertaken on a Gross Floor Area (basis) as GDA was not calculated by Durlinger, Crossin and Wong (2012).

Although demonstrably different buildings, climate change impacts associated with the building life cycle, excluding the Use Stage, were calculated for the Study Building versus Forte on a GFA basis. The comparison was done under the two assumptions used in Durlinger, Crossin and Wong (2012), the first excludes the storage of carbon in landfill (consistent with the approach adopted in this study) and the second includes the storage of carbon in landfill (Figure 25).

---

[6] Durlinger, Crossin and Wong (2012) used Apache Sim to model the Forte podium space and Accurate (NatHERS) for the apartment spaces. They did not model hot water, and used a mix of HVAC efficiency assumptions. In all, it was considered too difficult to draw a fair comparison between the buildings during the Use Stage.



	Excluding carbon sequestration in landfill	Including carbon sequestration in landfill
🟦 Study Building*	300	196
🟥 Forte (from Durlinger et. al.)	452	185

* Study building adjusted to exclude fit-out as per Durlinger et. al. (2012)

Figure 25 Climate change impacts of Study Building compared to Forte (as reported in Durlinger et. al. (2012)). Calculations detailed in Section 8.2.

The results shown in Figure 25 demonstrate the significant affect the sequestration assumption, mentioned above has on the climate change impact for the Forte building as it contains a large mass of wood materials. If these materials store carbon in landfill in the long term, then this results in a substantial reduction in life cycle climate change impacts of the Forte building due to its large wood mass.

Under the assumption that no carbon is permanently stored in landfill at the end of the building life, then the Study Building has 66% of the climate change impacts of the Forte building. The main reason for the improved outcome for the Study Building in this instance is due to the significantly lighter weight of the Study Building, weighing approximately 46% of the mass of Forte per unit of GFA provided. If, however, carbon is stored in landfill at the end of building life then Forte would have a climate change impact of 94% that of the Study Building. As mentioned above, the reason for this is the large amount of carbon stored in the building materials disposed of to landfill, which partially offsets manufacturing impacts associated with the larger material mass.

There are sound arguments supporting the inclusion of carbon sequestration in wood products in use and in landfill, however such sequestration is not formally recognised in IPCC guidelines for national greenhouse gas inventories (IPCC 2006) used for reporting under the Kyoto Protocol. As there is no consensus around the treatment of biogenic carbon between methods available in LCA (Levasseur et al. 2013), the approach taken is decided differently from report to report making comparisons between reports difficult, as is the case here. In the base analysis undertaken in this study, the decision to assess flows of biogenic carbon in a manner consistent with the IPCC approach (i.e. treat them as neutral) stems from the authors interpretation of the GBCA requirement to assess climate change impacts using the approach employed in the IPCC’s forth assessment report (GBCA 2014). The methods adopted in Durlinger, Crossin and Wong (2012) were not aimed at GBCA compliance so adopted an IPCC approach and a storage approach, recognising the lack of agreement in the area. The inconsistency of the approaches taken in the two studies means that comparison between the Study Building and Forte cannot be simply drawn and requires some interpretation.

In Figure 25 the ‘excluding sequestration’ approach includes climate impacts associated with cultivating, processing and disposing of wood products, however it also assumes that carbon stored in the products themselves or in landfill remains part of a natural cycle so neither causes nor mitigates climate change impacts. Under the IPCC guidelines for national greenhouse gas inventories this would be considered the ‘default’ accounting approach. From a building design perspective the accounting approach rewards the efficient use of wood materials in construction as reduced material use tends to reduce impacts.

The ‘including sequestration’ approach shown in Figure 25 considers the cultivating, processing and disposing processes, described above, plus the growth of carbon stock stored in wood products or landfill facilities. The approach considers that a large amount of carbon in wood products is likely to be stored for extended periods of time in use and in landfill so is therefore removed from the natural carbon cycle. From a building design perspective this accounting approach encourages the use of massive wood elements which will store carbon. The approach can represent a paradigm shift because increased use of material can lead to reduced climate change impacts in a building.

In comparing these two buildings it is recognised that they have adopted quite different strategies to achieving their climate change goals. The Study Building has sought to reduce impacts by using all materials as efficiently as possible, whereas the Forte building, it is assumed, has employed an approach that sought to store carbon in the long term. Both approaches reflect rational design responses in an area where consensus around the ‘right’ approach is yet to coalesce. It is outside the scope of this study to determine which design approach is better however some conclusions can still be drawn from the result.

The Study Building achieves a significantly reduced climate change impact under the base study assumptions and a result that is roughly equivalent to Forte (within the accuracy range of the two studies) under a sequestration scenario. The result shows that in this case the light weight approach of the Study Building achieves climate change impacts comparable to Forte or better, depending on which carbon accounting approach is adopted.

The above comparison provides further evidence that the light weight approach adopted in the Study Building provides significant climate change advantages versus other construction techniques, however it is unlikely to represent a ‘final word’ on the matter. Both the CLT approach employed in Forte and the light weight approach used in the Study Building are relatively new to Australia so it is likely that both will continue to improve from a climate change perspective as more is learned about each system.

8.3 Materials Life Cycle Impacts – Innovation Challenge

Finally, in completing the study it was intended that the GBCA’s Green Star Innovation Challenge – Materials Life Cycle Impacts be completed to determine what additional points could be earned by the Study Building if it were under a Green Star program. The stated aim of the GBCA’s Materials Life Cycle Impacts innovation challenge is to:

> “Assess and reduce the environmental impacts of building materials for the whole building over its entire life cycle.” (GBCA 2014, p. 3)

It is believed that this LCA report would qualify under the program (although this has not been tested) as key pre-requisites such as the definition of the functional unit in terms of GDA, the use of EN15978 and ISO14044 to guide system boundaries and reporting, respectively, have been adopted. A calculation of the points earned by the Study Building of a total of six available is shown in Table 49.

Table 49 Calculation of Green Star points associated with the Innovation Challenge using the methodology outlined in (GBCA 2014). The column excluding shown excluding the Use Stage (shown in italics), is a theoretical calculation only, and not part of the Innovation Challenge approach.

		Full life cycle			***Excluding Use***		
Impact category	**Unit**	**Study Building**	**Reference Building**	**Percentage change ((Ref-Study)/Ref)**	***Study Building***	***Reference Building***	***Percentage change ((Ref-Study)/Ref)***
Climate change	kg CO2 eq	4062.8	4152.4	2.2%	*382.1*	*489.7*	*22.0%*
Ozone depletion	mg CFC-11 eq	26.5	32.0	17.3%	*12.8*	*18.3*	*30.1%*
Acidification	kg SO2 eq	8.9	8.8	-1.1%	*1.3*	*1.2*	*-7.1%*
Eutrophication	kg PO43- eq	2.4	2.4	1.2%	*0.3*	*0.3*	*9.5%*
Photochem. ox.	g C2H4 eq	279.8	255.4	-9.6%	*131.9*	*107.6*	*-22.6%*
Abiotic depletion	kg Sb eq	28.9	29.6	2.5%	*1.8*	*2.7*	*32.4%*
Total percentage reduction				**12.6%**			***64.2%***
Divide by 20							
Total points generated (rounded)				0.6			*3.2*
plus 1 point for completing an LCA				1.0			*1.0*
Total points achieved				**1.6**			***4.2***

The results shown in Table 49 show that the building would achieve a minor credit of 1.6 points. This result is disappointing given the significant material impact reductions achieved by the building (67% of the climate change impacts of the Reference Building at the Product Stage, for example). By taking an ‘all inclusive’ look at the building, as prescribed by EN15978 upon which the GBCA method is based, the credit has little to do with materials selected in the building and far more to do with operational impacts. Although not an area of focus in this study, reductions in operational performance are likely to dominate this credit, in which case it should probably be altered or renamed. Given Green Star already addresses operational performance in other ways, this would appear to be a ‘double-count’.

An alternative approach to measuring life cycle materials impacts might be to exclude the Use Stage of building life. This could work if operational performance is suitably recognised elsewhere in Green Star. A recalculated result excluding the Use Stage is shown in italics at the right of Table 49. In this case the Study Building would achieve a total of 4.2 of 6 points available. This results appears to better reflect the stated intent of (GBCA 2014).

It was also noted through this exercise that the points earned by the Study Building were highly influenced by the choice of Reference Building. In this study an actual Reference Building (rather than a theoretical building) was selected which achieved a similar operational performance to the Study Building in order to illustrate the differences in the buildings due to materials, as is the stated intent of the materials LCA credit. Under the rules of the materials LCA credit a building could have been selected that performed at a ‘Deemed to Satisfy’ level for energy efficiency (6 Stars rather than 7 Stars), which would have increased the points earned by the Study Building, without any change to materials selections. Clearly this is not the intent of the credit, yet it is allowable under the current rules.

9 Conclusion

The study set out to address the aim of comparing the potential life cycle impacts of two multi-storey residential apartment buildings using the LCA methodology and has done so. The Study Building assessed employed a light weight timber structure, whereas the Reference Building employed a more traditional reinforced concrete structure. Both buildings provide similar functionality and both are being constructed at the same location.

Table 50 Impact assessment results for 1 functional unit ($1m^2$ GDA provided for 60 years), incorporating results from uncertainty analysis.

Impact Category	Unit	Study Building	Reference Building	Difference (Reference less Study)	Confidence in differential finding under uncertainty analysis*
Climate change	kg CO2 eq	4,062.8	4,152.4	89.6	90%
Ozone depletion	mg CFC-11 eq	26.5	32.0	5.6	90%
Acidification	kg SO2 eq	8.9	8.8	Inconclusive	40%
Eutrophication	kg PO43- eq	2.4	2.4	Inconclusive	30%
Photochem. ox.	g C2H4 eq	279.8	255.4	- 24.4	80%
Abiotic depletion	kg Sb eq	28.9	29.6	0.7	90%

* Interval over which the directional finding is consistent over 1000 simulations. Rounded to nearest 10%

Results (Table 35) showed that the Study Building, which incorporates a light weight timber structure, generated reduced environmental impacts in three out of five impact categories considered (climate change, ozone depletion, abiotic depletion) versus the Reference Building. In one category, photochemical oxidation, the Study Building was shown to be more impactful than the Reference Building. Two impact categories, eutrophication and acidification are found to be inconclusive (Table 37).

When tested under uncertainty analysis, a confidence greater than 90% was achieved for directional findings in the impact categories of climate change, ozone depletion and abiotic depletion. Confidence in directional outcomes for impact categories of acidification, eutrophication and photochemical oxidation were found to be less than 90% due to uncertainty in underlying data. Although confidence in photochemical oxidation was shown to be less than 90%, the differential result is still reported as it is felt to be of significance (as opposed to acidification and eutrophication differences which were too uncertain to draw conclusions from).

The environmental advantage of the Study Building was found to stem from its light weight design which uses one third of the materials of the Reference Building to achieve the same function. When considered in the absence of the building Use Stage, the Study Building achieved 78% of the climate change impacts of Reference Building, 70% of the ozone depletion and 68% of the abiotic depletion. The Reference Building was found to have 82% of the photochemical oxidation impacts, excluding the Use Stage (Figure 17).

The study also addressed the secondary objective of comparing findings to those published for the Forte building, described in Durlinger, Crossin and Wong (2012). Although demonstrably different buildings, climate change impacts associated with materials were shown to be lower in the Study Building versus Forte on a GFA basis (Figure 25).

The main reason for the improved outcome for the Study Building was due to the significantly lighter weight of the Study Building, weighing 33% of the mass of Forte per unit of GFA provided. Full building life cycles could not be compared due to methodological differences in the way operational impacts were estimated.

An additional objective of the study was to assess the number of Green Star points that could be earned under the GBCA's Green Star Innovation Challenge – Materials Life Cycle Impacts. Green Star innovation points available were shown to be minimal (1.6 of a total of 6 available), as the scheme is highly influenced by building operational impacts, rather than the material innovation exhibited by the Study Building (Table 49). As an exercise, points were recalculated for a partial life cycle that excluded the Use Stage showing the Study Building would earn 4.2 of 6 points available if this approach were to be adopted. The exercised showed that exclusion of the Use Stage may represent a more targeted way of rewarding material innovation, in keeping with the GBCA’s stated objective for the materials LCA credit.

In conclusion, the study achieved a unique outcome in comparing two real residential apartment buildings using the LCA methodology. In a city like Melbourne, where residential apartment buildings are being constructed at an ever increasing rate, the study will hopefully serve to inform better environmental decision making across a range of aspects.

9.1 Limitations of findings

LCA is a powerful methodology for objectively assessing the environmental impacts of buildings, however the approach has its limitations. Although significant effort (refer Section 3.5 and Section 7) has been made to verify the study outcomes, some key limitations to findings remain:

a) Uncertainty analysis shows that and comparative conclusions cannot be drawn for acidification and eutrophication indicators assessed.
b) Some uncertainty remains with respect to the photochemical oxidation findings drawn. Confidence in this indicator is less the other indicators assessed.
c) Although not a driver of difference in this study, the estimation of building operational energy use is notoriously difficult. Energy use estimates informing Use Stage outcomes represent a significant source of uncertainty in both buildings. The mix of fuel sources used to generate electricity, for example, is constantly changing (refer Section 5.3.1) making long term predictions of environmental impact difficult.
d) Impacts associated with End of Life and Beyond Building Life Stages involve predictions of material degradation behaviour in landfill and recycling rates. As these processes occur over extended periods some considerable time in the future, prediction of their impacts is difficult at best. An advantage of the EN15978 standard, used in this study to guide system boundaries, is that it prescribes a standard approach to this issue.

10 References

AIRAH 2012, *Methods of Calculating Total Equivalent Warming Impact*, The Australian Institute of Refrigeration, Air Conditioning and Heating, Australia.

Carre, A 2011, *A Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design*, FWPA, Melbourne.

Cochran, KM & Townsend, TG 2010, 'Estimating construction and demolition debris generation using a materials flow analysis approach', *Waste Management*, vol. 30, pp. 2247–54.

DCCEE 2012, *National Greenhouse Accounts (NGA) Factors - July 2012*, Dept. Climate Change and Energy Efficiency, Canberra.

DoE 2014, *National Greenhouse Accounts Factors - Australian National Greenhouse Accounts*, Department of the Environment, Canberra.

Durlinger, B, Crossin, E & Wong, J 2012, *Life Cycle Assessment of Cross Laminated Timber Building*, Forest and Wood Products Australia, Melbourne.

Duxson, P & Provis, J 2008, 'Low CO2 Concrete: Are We Making Any Progress?', *BEDP Environmental Design Guide*, vol. Pro 24, no. November 2008, pp. 1-7.

Ehrenberger, S 2013, *Life Cycle Assessment of Magnesium Components in Vehicle Construction*, German Aerospace Centre e.V. - Institute of Vehicle Concepts, Stuttgart.

EN 15978 2011, *EN 15978:2011 Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method*, European Committee for Standardisation, Brussels.

England, JR, May, B, Raison, RJ & Paul, KI 2013, 'Cradle-to-gate inventory of wood production from Australian softwood plantations and native hardwood forests: Carbon sequestration and greenhouse gas emissions', *Forest Ecology and Management*, no. 302, pp. 295-307.

European Standards 2011, *EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method*.

Frischknecht, R & Jungbluth, N 2004, *Ecoinvent Report No. 1 - Overview and Methodology*, Swiss Centre for Life Cycle Inventories, Dübendorf.

GBCA 2014, *Materials Life Cycle Impacts*, Green Building Council of Australia, viewed 15 August 2014, <http://www.gbca.org.au/uploads/78/34894/Materials_Life_Cycle%20Impacts_FINAL_JUNE2014.pdf>.

GBMA 2009, *Sustainability in the Australian and New Zealand Gypsum Board Industry*, Gypsum Board Manufacturers of Australia.

Hammond, G & Jones, C 2008, *Inventory of Carbon and Energy (ICE) - Version 1.6a*, University of Bath, Bath.

Hasanbeigi, A, Price, L & Lin, E 2012, *Emerging Energy-efficiency and CO2 Emission-reduction Technologies for Cement and Concrete Production*, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley.

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

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

ISO 14044 2006, *ISO 14044:2006 Environmental Management - Life Cycle Assessment - Requirements and Guidelines*, International Organisation for Standardisation, Geneva.

John, S, Nebel, B, Perez, N & Buchanan, A 2009, *Environmental Impacts of Multi-Storey Buildings Using Different Construction Materials - A report written under contract to the New Zealand Ministry of Agriculture and Forestry.*, Department of Civil and Natural Resources Engineering University of Canterbury, Christchurch, New Zealand.

JRC-IPTS 2013, *Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide*, European Commission - Joint Research Centre - Institute for Prospective Technological Studies.

Kaethner, SC & Burridge, JA 2012, 'Embodied CO2 of Structural Frames', viewed 20/1/2014, <http://www.concretecentre.com/sustainability/energy_efficiency/embodied_co2/embodied_co2_of_frames.aspx>.

Levasseur, A, Lesage, P, Margni, M & Samson, R 2013, 'Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment', *Journal of Industrial Ecology*, vol. 17, no. 1, pp. 117-28.

Promat 2008, *EPD for Promatect 100*, Promat International NV, Belgium.

Promat 2013, *MSDS - SystemFloor*, Promat Australia, Mile End, South Australia.

Strezov, L & Herbertson, J 2007, *A Life Cycle Perspective on Steel Building Materials*, Report to the Australian Steel Institute, Sydney.

Titanwall 2006, *MSDS - Titanboard*, Titanwall Inc., Alberta, Canada.

Tripp, TG 2009, 'Production of Magnesium from Great Salt Lake, Utah USA', *Natural Resources and Environmental Issues*, vol. 15, no. 10.

Appendix A Study Building material quantities and background inventories employed.

A.1 Life cycle inventories employed in construction model.

Table 51 Life cycle inventories employed in Study Building construction model – Part 1.

Item	Process Name	Process Source	Measured Qty	Unit	Assumptions	Drawing Qty (t)	Cons waste %	Cons waste (t)	Gross Qty (t)
Substructure							**3%**	*ave waste*	
Concrete 32 Mpa	New inventory based on Durlinger et. al. (2013)	New	299	m3	Replace flyash with Portland cement. Density 2400kg/m3	716.9	3%	21.5	738.4
0.2 mm PE membrane	Polyethylene, HDPE, granulate, at plant/RER U/AusSD U	AusLCI	900	m2	Includes extrusion energy.0.2 mm membrane, density 910kg/m3	0.2	5%	0.0	0.2
Sand bed - 50 mm	Sand, at mine/CH U/AusSD U	AusLCI	45	m3	Density 1680kg/m3	75.6	3%	2.3	77.9
Steel - reinf.	Reinforcing steel, at plant/RER U/AusSD U	AusLCI	30	t	None	30.1	0%	0.0	30.1
Core							**3%**	*ave waste*	
Blocks (16kg)	Concrete block, at plant/DE U/AusSD U	AusLCI	5750	p	Assume concrete is major production impact. 16 kg each	92.0	4%	3.7	95.7
Concrete - 40 Mpa	New inventory based on Durlinger et. al. (2013)	New	62	m3	Replace flyash with Portland cement. Density 2400kg/m3	148.4	3%	4.5	152.8
Concrete - 50 Mpa	New inventory based on Durlinger et. al. (2013)	New	14	m3	Replace flyash with Portland cement. Density 2400kg/m3	32.8	3%	1.0	33.8
Steel - reinf.	Reinforcing steel, at plant/RER U/AusSD U	AusLCI	1	t	None	1.1	0%	0.0	1.1
Internal walls							**7%**	*ave waste*	
Framing timber (local)	Sawn timber, softwood, raw, kiln dried, u=10%, at plant/RER U/AusSD U	AusLCI	91	m3	65% local sourced sofwood. Density 550 kg/m3	50.1	5%	2.5	52.6
Framing timber (import)	Sawnwood, softwood, raw, kiln dried, 10% water on dry mass basis {RER}| production | Alloc Def, U	AusLCI	49	m3	35% Europe sourced sofwood. Density 550 kg/m3	27.0	5%	1.3	28.3
Plywood 7mm	Plywood, indoor use, at plant/RER U/AusSD U	AusLCI	13	m3	Density 550 kg/m3	7.0	5%	0.4	7.4
Plasterboard 13mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	3744	m2	Area density = 11 kg/m2	41.2	10%	4.1	45.3
Plasterboard 16mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	3270	m2	Area density = 13 kg/m2	42.5	10%	4.3	46.8
Glasswool 75mm	Glass wool mat, at plant/CH U/AusSD U	AusLCI	1635	m2	Area density = 15 kg/m3	1.8	5%	0.1	1.9
External walls							**6%**	*ave waste*	
Framing timber (local)	Sawn timber, softwood, raw, kiln dried, u=10%, at plant/RER U/AusSD U	AusLCI	39	m3	65% local sourced sofwood. Density 550 kg/m3	21.4	5%	1.1	22.5
Framing timber (import)	Sawnwood, softwood, raw, kiln dried, 10% water on dry mass basis {RER}| production | Alloc Def, U	AusLCI	21	m3	35% Europe sourced sofwood. Density 550 kg/m3	11.5	5%	0.6	12.1
Plasterboard 13mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	1335	m2	Area density = 11 kg/m2	14.7	10%	1.5	16.2
Plasterboard 16mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	2196	m2	Area density = 13 kg/m2	28.5	10%	2.9	31.4
Glasswool 75mm	Glass wool mat, at plant/CH U/AusSD U	AusLCI	1603	m2	Area density = 15 kg/m3	1.8	5%	0.1	1.9
Gal steel frame	New inventory employing background inventories from AUPLCI	New	5	t	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	4.9	0%	0.0	4.9
Brick230x76	Concrete block, at plant/DE U/AusSD U	AusLCI	5586	p	6 kg per brick	33.5	4%	1.3	34.9
Mortar	Cement mortar, at plant/CH U/AusSD U	AusLCI	6	t	None	5.6	3%	0.2	5.8
Render	Cover coat, mineral, at plant/CH U/AusSD U	AUPLCI	114	m2	10.2kg/m2 (AcraTex) - 6mm thick	1.2	5%	0.1	1.2
Sarking	Model based on AusLCI background inventories.	New	114	m2	Mix of HDPE, aluminium and kraft paper(90%).Area density = 350g/m2	0.0	5%	0.0	0.0
MgO cement sht. 18mm	New	New	229	m2	65% MgO, 25% MgCl. Dens 20kg/m2	4.5	10%	0.5	5.0
Phenolic foam panel	New	New	107	m3	Density = 24 kg/m3	2.6	10%	0.3	2.8
Base coat - Acrylic	Adhesive mortar, at plant/CH U/AusSD U	AusLCI	8	t	Assume similar to acrylic render. 4mm thick	8.4	5%	0.4	8.8
Fibreglass mesh	Glass fibre, at plant/RER U/Adapted/AU U	AUPLCI	208	kg	None	0.2	5%	0.0	0.2
Texture coat	Acrylic varnish, 87.5% in H2O, at plant/RER U/AusSD U	AusLCI	1575	l	Assume similar to acrylic paint. 1.33 kg per litre	2.1	5%	0.1	2.2
Aluminium cladding 6mm	Inventory based on aluminium hydroxide and aluminium prodcution. Uses AusLCI bacground inventories.	New	275	m2	11% rolled aluminium sheet. 89% aluminium hydroxide. Area density = 11.2 kg/m2	3.1	0%	0.0	3.1

Table 52 Life cycle inventories employed in Study Building construction model – Part 2.

Item	Process Name	Process Source	Measured Qty	Unit	Assumptions	Drawing Qty (t)	Cons waste %	Cons waste (t)	Gross Qty (t)
Window system							**0%**	*ave waste*	
Frame	Window frame, aluminium, U=1.6 W/m2K, at plant/RER U/AusSD U	AusLCI	2763	m	44mm thickness frame, 50.7kg per m2 (80% Aluminium)	6.2	0%	0.0	6.2
Glass	Flat glass, coated, at plant/RER U/AusSD U	AusLCI	719	m2	10.38mm glass, 27 kg/m2	19.4	0%	0.0	19.4
Columns, beams and lintels							**4%**	*ave waste*	
Structural steel	Rolled steel, strucutral, at regional store /AU U	AUPLCI	5	t	None	5.3	0%	0.0	5.3
Kiln dried hardwood	Sawn timber, hardwood, planed, kiln dried, u=10%, at plant/RER U/AusSD U	AusLCI	22	m3	Density = 850 kg/m3	18.6	5%	0.9	19.6
Floor System (Slabs, Floor cassettes, Ceiling)							**5%**	*ave waste*	
Concrete 40 Mpa	New inventory based on Durlinger et. al. (2013)	New	177	m3	Replace flyash with Portland cement. Density 2400kg/m3	424.3	3%	12.7	437.0
Form deck (10.5kg/m2)	New inventory employing background inventories from AUPLCI	New	9.5	t	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	9.5	0%	0.0	9.5
Steel - reinf.	Reinforcing steel, at plant/RER U/AusSD U	AusLCI	14	t	None	14.1	0%	0.0	14.1
Gal steel frame	New inventory employing background inventories from AUPLCI	New	46	t	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	45.6	0%	0.0	45.6
LVL	Glued laminated timber, indoor use, at plant/RER U/AusSD U	AUPLCI	126	m3	Density 600 kg/m3	75.7	5%	3.8	79.5
MgO cement sht. 18mm	New	New	7072	m2	65% MgO, 25% MgCl. Dens 20kg/m2	140.0	10%	14.0	154.0
Calcium silicate sht. 20mm	New	New	3536	m2	Density = 850 kg/m3	60.1	10%	6.0	66.1
Glasswool 75mm	Glass wool mat, at plant/CH U/AusSD U	AusLCI	3536	m2	Area density = 15 kg/m3	4.0	5%	0.2	4.2
Plasterboard 13mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	3536	m2	Area density = 11 kg/m2	38.9	10%	3.9	42.8
Roof system							**7%**	*ave waste*	
Kiln dried hardwood	Sawn timber, hardwood, planed, kiln dried, u=10%, at plant/RER U/AusSD U	AusLCI	13	m3	Density = 850 kg/m3	10.8	5%	0.5	11.4
Naiplates	New inventory employing background inventories from AUPLCI	New	450	kg	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	0.5	0%	0.0	0.5
Roofing sheet (5.7kg/m2)	New inventory employing background inventories from AUPLCI	New	4.6	t	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	4.6	0%	0.0	4.6
Glasswool 75mm	Glass wool mat, at plant/CH U/AusSD U	AusLCI	800	m2	Area density = 15 kg/m3	0.9	5%	0.0	0.9
Sarking	Model based on AusLCI background inventories.	New	800	m2	Mix of HDPE, aluminium and kraft paper(90%).Area density = 350g/m2	0.3	5%	0.0	0.3
Plasterboard 16mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	1600	m2	Area density = 13 kg/m2	20.8	10%	2.1	22.9
					Total	2310.3		98.7	2408.9
								4%	

A.2 Materials estimate development

Table 53 Study - substructure quantity estimate.

Substructure (Slab, Pile Caps, Piles, Lift/Stair base)				
Item			**Net Qty**	**Unit**
Slab				
Concrete - 40 MPa				
thickness	0.15	m		
area*	900.0	m2		
		Total	135.0	m3
Steel - reinf bar				
Reinf. 80 kg/m3	10800.0	kg		
		Total	10800.0	kg
Sand bed				
thickness	0.05	m		
area	900.0	m2		
		Total	45.0	m3
Membrane - PE				
area	900.0	m2		
		Total	900.0	m2
Piles and Pile caps				
Concrete - 40 MPa				
SF1 - edge footing				
section	0.8	m3/lm		
qty	90	m		
tot vol	72	m3		
PC2 - pile cap				
vol	1.8	m3/cap		
qty	5			
tot vol	9	m3		
PC3 - pile cap				
vol	1.7	m3/cap		
qty	4			
tot vol	6.8	m3		
PC4 - pile cap				
vol	4.8	m3/cap		
qty	6			
tot vol	28.8	m3		
PC5 - pile cap				
vol	11.5	m3/cap		
qty	3			
tot vol	34.5	m3		
		Total	151	m3
Steel - reinf bar				
Reinf. 20kg/m3	3022.0	kg		
		Total	3022.0	kg
Steel - screw piles				
length	4	m		
diam	0.2	m		
thick	0.01	m		
qty	81			
vol	2.03575204	m3		
density	7850	kg/m3		
		Total	15980.65351	
Concrete - 40 MPa				
area	21	m2		
thickness	0.6	m		
		Total	12.6	m3
Steel - reinf bar				
Reinf. 20kg/m3	252.0	kg		
		Total	252.0	kg
TOTAL - Substructure (Slab, Pile Caps, Piles, Lift/Stair base)				
Concrete - 32 MPa		Total	299	m3
Membrane - PE		Total	900	m2
Sand bed 50 mm		Total	45	m3
Steel - reinf.		Total	30055	kg

Table 54 Study - core, walls and windows quantity estimate.

Core (Enclosure, Stairs)				
Item			**Net Qty**	**Unit**
Walls (block Connex200, 16kg per block)				
length	23	m		
height	20	m		
area	460	m2		
blocks (16kg)			5750	p
Concrete - 40 MPa			62	m3
Concrete - 50 MPa				
Stairs				
landings				
area	2.88	m2		
thick	0.2	m		
vol	0.576	m3		
stair				
area	2.64	m2		
thick	0.3	m		
vol	0.792	m3		
number	10			
tot vol	13.68			
		Total	14	m3
Steel - reinf bar				
Reinf. 80 kg/m3	1094.4	kg		
		Total	1094	kg
TOTAL - Core (Enclosure, Stairs)				
Blocks (16kg)		Total	5750	p
Concrete - 40 MPa		Total	62	m3
Concrete - 50 MPa		Total	14	m3
Steel - reinf.		Total	1094	kg
Internal Walls (Panels, Frames, Linings, Insulation)				
Item			**Net Qty**	**Unit**
Framing timber		Total	140	m3
Plywood 7mm		Total	13	m3
Plasterboard 13mm		Total	3744	m2
Plasterboard 16mm		Total	3270	m2
Glasswool 75mm		Total	1635	m2
External Walls (Panels, Linings, Insulation)				
Item			**Net Qty**	**Unit**
Framing timber		Total	60	m3
Plasterboard 13mm		Total	1335	m2
Plasterboard 16mm		Total	2196	m2
Glasswool 75mm		Total	1603	m2
Gal steel frame		Total	4941	kg
Brick230x76		Total	5586	p
Mortar		Total	5586	kg
Render		Total	114	m2
Sarking		Total	114	m2
MgO cement sht. 18mm		Total	229	m2
Phenolic foam panel		Total	107	m3
Base coat		Total	8400	kg
Fibreglass mesh		Total	208	kg
Texture coat		Total	1575	l
Aluminium cladding 6mm		Total	275	m2
Window System (Glass, Frames, Seals)				
Item			**Net Qty**	**Unit**
Aluminium frame		Total	2763	m
Glass 10.38mm		Total	719	m2

Table 55 Study - columns, beams lintels quantity estimate.

Columns, beams, lintels				
Item			**Net Qty**	**Unit**
Structural steel				
Columns				
height	2.6	m		
section	90x90x6	mm		
vol	0.005616	m3		
density	7850	kg/m3		
mass	44.0856	kg		
qty	56			
mass	2468.7936	kg		
		Total	2468.7936	kg
Beams				
250PFC	80	m		
		Total	2840	kg
Hardwood				
Lintels				
KDH 2/240x45	0.0216	m3/m		
Lintels Qty	53	m per floor		
Bracing, reinforcing	150	m per floor		
floors	5			
		Total	22	m3
TOTAL - Columns				
Structural steel		Total	5309	kg
KDH		Total	22	m3

Table 56 Study - floor and roof system quantity estimate.

Floor System (Slabs, Floor cassettes, Ceiling)				
Item			**Net Qty**	**Unit**
Suspendend slab				
Concrete 40 Mpa				
length	30	m		
width	30	m		
thicknes	0.2	m		
core area	16	m2		
vol	176.8	m3		
Form deck (10.5kg/m2)	9450	kg		
Steel reinf				
Reinf. 80 kg/m3	14144	kg		
Cassette - 4F C19				
Area	6.157	m2		
TecBeam				
Flange d	0.381	m		
Flange t	0.0012	m		
holes	6			
hole d	0.214	m		
Flange area	1.031966434	m2		
Flange vol	0.00123836	m3		
density	7850	kg/m3		
Flange mass	9.721123811	kg/m3		
Web vol	0.038366625	m3		
5 beams				
Flange steel	48.60561905	kg		
LVL Web	0.191833125	m3		
Blocks				
150x58 LVL	0.016356	m3		
120x35 LVL	0.0114072	m3		
Total per floor				
Area p floor	884	m2		
Gal Steel	6978.620634	kg		
LVL	31.52885355	m3		
MgO cement sht. 36mm	884	m2		
Calcium silicate sht. 20m	884	m2		
Glasswool 75mm	884	m2		
Gal steel (5kg/m2)	4420	kg		
Plasterboard 13mm	884	m2		
Total building	4	floors		
TOTAL - Floor System				
Concrete 40 Mpa		Total	176.8	m3
Form deck (10.5kg/m2)		Total	9450.0	kg
Steel reinf		Total	14144.0	kg
Gal steel frame		Total	45594	kg
LVL		Total	126	m3
MgO cement sht. 18mm		Total	7072	m2
Calcium silicate sht. 20mm		Total	3536	m2
Glasswool 75mm		Total	3536	m2
Plasterboard 13mm		Total	3536	m2
Roof System (Deck, Ceiling)				
Item			**Net Qty**	**Unit**
Engineered timber purlin 900 C-C (1m)				
Flange	0.00405	m3		
Web	0.006075	m3		
Flange	0.00405	m3		
Naiplates	0.5	kg		
Truss lengths				
Area	800	m2		
Truss	900	m		
TOTAL - Roof System				
KDH		Total	12.8	m3
Naiplates		Total	450	kg
Roofing sheet (5.7kg/m2)		Total	4568	kg
Glasswool 75mm		Total	800	m2
Sarking		Total	800	m2
Plasterboard 16mm		Total	1600	m2

A.3 Wall material content estimate

Table 57 Study - wall system material quantity estimate by floor.

Layer	Measure	Assumptions	Unit	LGrd	Grd	1st	2nd	3rd	4th	Total
Internal Walls										
Internal Partition										
	Wall area	2.6m high	m2	-	374	374	374	374	374	1,872
1	Plasterboard	thick : 13 mm	m2	-	374	374	374	374	374	1,872
2	Frame - GW5	adens: 0.02m3/m2	m3	-	9	9	9	9	9	45
3	Plasterboard	thick : 13 mm	m2	-	374	374	374	374	374	1,872
Inter-tenancy										
	Wall area	3m high	m2	-	183	183	183	183	183	915
1	Plasterboard	thick : 16 mm	m2	-	183	183	183	183	183	915
2	Frame - GW3	adens: 0.07m3/m2	m3	-	14	14	14	14	14	68
3	Glasswool	thick: 70 mm	m2	-	183	183	183	183	183	915
4	Plywood	7mm	m3	-	1	1	1	1	1	6
5	Plywood	7mm	m3	-	1	1	1	1	1	6
6	Acoustic bats	thick: 70 mm	m2	-	183	183	183	183	183	915
7	Plasterboard	thick : 16 mm	m2	-	183	183	183	183	183	915
Corridor / Lobby										
	Wall area	3m high	m2	-	144	144	144	144	144	720
1	Plasterboard	thick : 16 mm	m2	-	144	144	144	144	144	720
2	Frame - GW2	adens: 0.04m3/m2	m3	-	5	5	5	5	5	27
3	Glasswool	thick: 75 mm	m2	-	144	144	144	144	144	720
4	Plasterboard	thick : 16 mm	m2	-	144	144	144	144	144	720
External Walls										
Brick veneer										
	Wall area	Various	m2	-	114	-	-	-	-	114
1	Plasterboard	thick: 16 mm	m2	-	114	-	-	-	-	114
2	Frame - GW2	adens: 0.03m3/m2	m3	-	4	-	-	-	-	4
3	Glasswool	thick: 75 mm	m2	-	114	-	-	-	-	114
4	Sarking		m2	-	114	-	-	-	-	114
5	Brick230x76	49 per m2	p	-	5,586	-	-	-	-	5,586
6	Mortar	49 kg/m2	kg	-	5,586	-	-	-	-	5,586
7	Render	thick: 13 mm	m2	-	114	-	-	-	-	114
Party Wall										
	Wall area	3.2m high	m2	0	58	58	58	28	27	229
1	Plasterboard	thick: 16 mm	m2	-	58	58	58	28	27	229
2	Frame - GW2	adens: 0.04m3/m2	m3	-	2	2	2	1	1	9
3	Glasswool	thick: 75 mm	m2	-	58	58	58	28	27	229
4	Plasterboard	thick: 16 mm	m2	-	58	58	58	28	27	229
5	Gal steel frame	adens: 3.3kg/m2	kg	-	192	192	192	94	89	761
6	MgO cement sht.	thick: 18 mm	m2	-	58	58	58	28	27	229
Kooltherm - W face										
	Wall area	3.2m high	m2	0	118	131	131	131	157	668
1	Plasterboard	thick: 13 mm	m2	-	118	131	131	131	157	668
2	Plasterboard	thick: 13 mm	m2	-	118	131	131	131	157	668
3	Frame - GW2	adens: 0.04m3/m2	m3	-	4	5	5	5	6	25
4	Glasswool	thick: 75 mm	m2	-	118	131	131	131	157	668
5	Plasterboard	thick: 16 mm	m2	-	118	131	131	131	157	668
6	Gal steel frame	adens: 3.3kg/m2	kg	-	392	434	434	434	521	2,215
7	Phenolic panel	thick: 90 mm	m3	-	11	12	12	12	14	60
8	Base coat	20kg/3m2	kg	-	789	872	872	872	1,046	4,451
9	Fibreglass mesh	165 gsm	kg	-	20	22	22	22	26	110
10	Texture coat	15l/12 m2	l	-	148	164	164	164	196	835
Kooltherm - N,S,E faces										
	Wall area	3.2m high	m2	0	74	106	106	136	170	592
1	Plasterboard	thick: 16 mm	m2	-	74	106	106	136	170	592
3	Frame - GW2	adens: 0.04m3/m2	m3	-	3	4	4	5	6	22
4	Glasswool	thick: 75 mm	m2	-	74	106	106	136	170	592
5	Plasterboard	thick: 16 mm	m2	-	74	106	106	136	170	592
6	Gal steel frame	adens: 3.3kg/m2	kg	-	245	352	352	451	565	1,965
7	Phenolic panel	thick: 80 mm	m3	-	6	8	8	11	14	47
8	Base coat	20kg/3m2	kg	-	493	707	707	907	1,136	3,949
9	Fibreglass mesh	165 gsm	kg	-	12	17	17	22	28	98
10	Texture coat	15l/12 m2	l	-	93	133	133	170	213	741
Decorative Façade										
1	Alum. clad.6mm	direct measure	m2	-	-	100	61	114	-	275

A.4 Wall type material content

Table 58 Study - wall quantity estimates per unit area for steel frame walls.

Steel partition wall frame		
Element	**Qty**	**unit**
Height	2.6	m
Length	3	m
Stud spacing	0.6	m
Total studs	6	p
Nogings per void	1	p
Plates	2	m
Channel mass per m	1.1	kg/m
Total length	24.6	m
Total mass	25.9	
Total mass per area	3.3	kg/m2
stud 90x38 - 1mm		

Table 59 Study - wall quantity estimates per unit area for wall type GW2.

GW2 - 2/140x45 MGP12		
Element	**Qty**	**unit**
Height	2.6	m
Length	3	m
Spacing	0.6	m
Total studs	6	
Double/single stud	2	
Total risers	12	
Nogings per void	3	
Total noggings	15	
Double/single wall	1	
Plates	2.0	
Timber x	0.140	m
Timber y	0.045	m
Total length	46.2	m
Total vol	0.3	m3
Total length per m2	5.9	m
Total vol per m2	0.04	m3

Table 60 Study - wall quantity estimates per unit area for wall type GW3.

GW3 - 2x2/140x45 MGP12		
Element	**Qty**	**unit**
Height	2.6	m
Length	3	m
Spacing	0.6	m
Total studs	6	
Double/single stud	2	
Total risers	12	
Nogings per void	3	
Total noggings	15	
Double/single wall	2	
Plates	2.0	
Timber x	0.140	m
Timber y	0.045	m
Total length	92.4	m
Total vol	0.6	m3
Total length per m2	11.8	m
Total vol per m2	0.07	m3

Table 61 Study - wall quantity estimates per unit area for wall type GW4.

GW4 - 2/140x45 MGP12		
Element	**Qty**	**unit**
Height	2.6	m
Length	3	m
Spacing	0.6	m
Total studs	6	
Double/single stud	2	
Total risers	12	
Nogings per void	3	
Total noggings	15	
Double/single wall	1	
Plates	2.0	
Timber x	0.140	m
Timber y	0.045	m
Total length	46.2	m
Total vol	0.3	m3
Total length per m2	5.9	m
Total vol per m2	0.04	m3

Table 62 Study - wall quantity estimates per unit area for wall type GW5.

GW5 - 2/90x45 MGP12		
Element	**Qty**	**unit**
Height	2.6	m
Length	3	m
Spacing	0.6	m
Total studs	6	
Double/single stud	2	
Total risers	12	
Nogings per void	3	
Total noggings	15	
Double/single wall	1	
Plates	2.0	
Timber x	0.090	m
Timber y	0.045	m
Total length	46.2	m
Total vol	0.2	m3
Total length per m2	5.9	m
Total vol per m2	0.02	m3

A.5 Window system area and circumference estimate

Table 63 Study - window system area and circumference estimate.

Window Type	**Area per window**	**Circ. per window**	**Qty**	**Area**	**Circ.**
unit	m2	m	p	m2	m
A	2.9	14	37	107.3	518
B	6	20	40	240	800
C	5	18	10	50	180
D	1.7	10	55	93.5	550
E	0.8	4	23	18.4	92
F	4.3	15	19	81.7	285
G	7.2	21	2	14.4	42
H	8.2	23	7	57.4	161
I	6.2	15	9	55.8	135
		Total		**719**	**2,763**
		Total per m2 GDA		**0.18**	**0.71**

Appendix B Reference Building material quantities and background inventories employed.

B.1 Life cycle inventories employed in construction model.

Table 64 Life cycle inventories employed in Reference Building construction model – Part 1.

Item	Process Name	Process Source	Measured Qty	Unit	Assumptions	Drawing Qty (t)	Cons waste %	Cons waste (t)	Gross Qty (t)
Substructure							**3%**	*ave waste*	
Concrete 40 Mpa	New inventory based on Durlinger et. al. (2013)	New	689	m3	Replace flyash with Portland cement. Density 2400kg/m3	1652.4	3%	49.6	1702.0
0.2 mm PE membrane	Polyethylene, HDPE, granulate, at plant/RER U/AusSD U	AusLCI	1784	m2	Includes extrusion. 0.2 mm membrane, density 910kg/m3	0.3	5%	0.0	0.3
Gravel bed 0.8m	Gravel, crushed, at mine/CH U/Adapted/AU U	AUPLCI	143	m3	Density 1680kg/m3	239.8	3%	7.2	247.0
Steel - reinf.	Reinforcing steel, at plant/RER U/AusSD U	AusLCI	30	t	None	29.8	0%	0.0	29.8
Core							**3%**	*ave waste*	
Concrete - 50 Mpa	New inventory based on Durlinger et. al. (2013)	New	143	m3	Replace flyash with Portland cement. Density 2400kg/m3	343.9	3%	10.3	354.2
Steel - reinf.	Reinforcing steel, at plant/RER U/AusSD U	AusLCI	5		None	5.4	0%	0.0	5.4
Internal walls							**4%**	*ave waste*	
Concrete 40 Mpa	New inventory based on Durlinger et. al. (2013)	New	252	m3	Replace flyash with Portland cement. Density 2400kg/m3	604.6	3%	18.1	622.7
Concrete 50 Mpa	New inventory based on Durlinger et. al. (2013)	New	5	m3	Replace flyash with Portland cement. Density 2400kg/m3	11.1	3%	0.3	11.5
Steel - reinf.	Reinforcing steel, at plant/RER U/AusSD U	AusLCI	8	t	None	8.1	0%	0.0	8.1
Plasterboard 13mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	8874	m2	Area density = 11 kg/m2	97.6	10%	9.8	107.4
Plasterboard 16mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	3689	m2	Area density = 13 kg/m2	48.0	10%	4.8	52.7
Glasswool 75mm	Glass wool mat, at plant/CH U/AusSD U	AusLCI	1844	m2	Area density = 15 kg/m3	2.1	5%	0.1	2.2
Gal steel frame	New inventory employing background inventories from AUPLCI	New	27	t	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	26.7	0%	0.0	26.7
Blocks (16kg)	Concrete block, at plant/DE U/AusSD U	AusLCI	2175	p	Assume concrete is major production impact. 16 kg each	34.8	4%	1.4	36.2
Mortar	Cement mortar, at plant/CH U/AusSD U	AusLCI	4	t	None	4.4	5%	0.2	4.6
External walls							**3%**	*ave waste*	
Concrete 40 Mpa	New inventory based on Durlinger et. al. (2013)	New	476	m3	Replace flyash with Portland cement. Density 2400kg/m3	1142.6	3%	34.3	1176.9
Concrete 60 Mpa	Use 50MPa model as proxy. New inventory based on Durlinger et. al. (2013)	New	15	m3	Density 2400kg/m3	36.2	3%	1.1	37.3
Steel - reinf.	Reinforcing steel, at plant/RER U/AusSD U	AusLCI	15	t	None	15.0	0%	0.0	15.0
Plasterboard 13mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	2410	m2	Area density = 11 kg/m2	26.5	10%	2.7	29.2
Glasswool 75mm	Glass wool mat, at plant/CH U/AusSD U	AusLCI	7995	m2	Area density = 15 kg/m3	9.0	5%	0.4	9.4
Gal steel frame	New inventory employing background inventories from AUPLCI	New	8	t	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	8.0	0%	0.0	8.0
Texture coat	Acrylic varnish, 87.5% in H2O, at plant/RER U/AusSD U	AusLCI	6772	l	Assume similar to acrylic paint. 1.33 kg per litre	9.0	5%	0.5	9.5

Table 65 Life cycle inventories employed in Reference Building construction model – Part 2.

Item	Process Name	Process Source	Measured Qty	Unit	Assumptions	Drawing Qty (t)	Cons waste %	Cons waste (t)	Gross Qty (t)
Window system							**0%**	*ave waste*	
Frame	Window frame, aluminium, U=1.6 W/m2K, at plant/RER U/AusSD U	AusLCI	3321	m	44mm thickness frame, 50.7kg per m2 (80% Aluminium)	7.4	0%	0.0	7.4
Glass	Flat glass, coated, at plant/RER U/AusSD U	AusLCI	907	m2	10.38mm glass, 27 kg/m2	24.5	0%	0.0	24.5
Columns, beams and lintels							**3%**	*ave waste*	
Concrete 40 Mpa	New inventory based on Durlinger et. al. (2013)	New	44	m3	Replace flyash with Portland cement. Density 2400kg/m3	106.5	3%	3.2	109.7
Steel - reinf.	Reinforcing steel, at plant/RER U/AusSD U	AusLCI	8	t	None	8.4	0%	0.0	8.4
Floor System (Slabs, Ceiling)							**3%**	*ave waste*	
Concrete 40 Mpa	New inventory based on Durlinger et. al. (2013)	New	1776	m3	Replace flyash with Portland cement. Density 2400kg/m3	4262.3	3%	127.9	4390.1
Steel - reinf.	Reinforcing steel, at plant/RER U/AusSD U	AusLCI	142	t	None	142.1	0%	0.0	142.1
Form deck (10.5kg/m2)	New inventory employing background inventories from AUPLCI	New	87.7	t	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	87.7	0%	0.0	87.7
Gal steel frame	New inventory employing background inventories from AUPLCI	New	33	t	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	32.9	0%	0.0	32.9
Plasterboard 13mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	6572	m2	Area density = 11 kg/m2	72.3	10%	7.2	79.5
Roof system							**3%**	*ave waste*	
Concrete 40 Mpa	New inventory based on Durlinger et. al. (2013)	New	145	m3	Replace flyash with Portland cement. Density 2400kg/m3	349.1	3%	10.5	359.5
Steel - reinf.	Reinforcing steel, at plant/RER U/AusSD U	AusLCI	12	t	None	11.6	0%	0.0	11.6
Gal steel frame	New inventory employing background inventories from AUPLCI	New	4	t	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	4.0	0%	0.0	4.0
Plasterboard 13mm	Gypsum plaster board, at plant/CH U/AusSD U	AusLCI	808	m2	Area density = 11 kg/m2	8.9	10%	0.9	9.8
Form deck (10.5kg/m2)	New inventory employing background inventories from AUPLCI	New	8.5	t	95% Steel sheet at regional store 5% Zincalume coating Coating and forming processes included.	8.5	0%	0.0	8.5
					Total	9481.5		290.4	9771.9
								3%	

B.2 Materials estimate development

Table 66 Reference - substructure quantity estimate

Item			**Qty**	**Unit**
Substructure (Slab, Pile Caps, Piles, Lift/Stair base)				
Item			**Qty**	**Unit**
Slab				
Concrete - 40 MPa				
thickness	0.2	m		
area*	1784.0	m2		
		Total	267.6	m3
Steel - reinf bar				
Reinf. 80 kg/m3	21408.0	kg		
		Total	21408.0	kg
Screenings bed				
thickness	0.1	m		
area	1784.0	m2		
		Total	142.7	m3
Membrane - PE				
area	1784.0	m2		
		Total	1784.0	m2
Piles and Pile caps				
Concrete - 40 MPa				
GB1 - edge footing				
section	0.8	m3/lm		
qty	100	m		
tot vol	80	m3		
PC1 - pile cap				
vol	2.4	m3/cap		
qty	50			
tot vol	120	m3		
Piles				
diam	0.6	m		
length	8	m		
qty	76			
tot vol	171.90795	m3		
		Total	372	m3
Steel - reinf bar				
Reinf. 20kg/m3	7438.2	kg		
		Total	7438.2	kg
Lift and Stair Base				
Concrete - 40 MPa				
area	49	m2		
thickness	1	m		
		Total	49	m3
Steel - reinf bar				
Reinf. 20kg/m3	980.0	kg		
		Total	980.0	kg
Excavation - Estimate				
cut 1.25	892	m2		
cut 1.75	892	m2		
		Total	2676	m3
TOTAL - Substructure (Slab, Pile Caps, Piles, Lift/Stair base)				
Excavation		Total	2676	m3
Concrete - 40 MPa		Total	689	m3
Membrane - PE		Total	1784	m2
Screenings bed		Total	143	m3
Steel - reinf.		Total	29826	kg

Table 67 Reference - core, walls and windows quantity estimate.

Core (Enclosure, Stairs)				
Item			**Qty**	**Unit**
Concrete - 50 MPa				
Concrete panel 180/50/SL92				
area box1	427.5	m2		
aperatures	53	m2		
thickness	0.18			
tot vol	67.41	m3		
Concrete panel 150/50/SL92				
area box2	378	m2		
aperatures	18	m2		
thickness	0.15			
tot vol	54	m3		
Stairs				
landings				
area	2.88	m2		
thick	0.2	m		
vol	0.576	m3		
stair				
area	2.64	m2		
thick	0.3	m		
vol	0.792	m3		
number	16			
tot vol	21.888			
		Total	143	m3
Steel - reinf bar				
SL92 (5kg/m2)	3672.5			
Reinf. 80 kg/m3	1751.04	kg		
		Total	5424	kg
TOTAL - Core (Enclosure, Stairs)				
Concrete - 50 MPa		Total	143	m3
Steel - reinf.		Total	5424	kg
Internal Walls (Panels, Frames, Linings, Insulation)				
Item			**Qty**	**Unit**
Concrete - 50 MPa		Total	252	m3
Concrete - 60 MPa		Total	5	m3
Steel reinforcement		Total	8127	kg
Plasterboard 13mm		Total	8874	m2
Plasterboard 16mm		Total	3689	m2
Glasswool 75mm		Total	1844	m2
Gal steel frame		Total	26669	kg
Blocks (16kg)		Total	2175	p
Mortar		Total	4350	kg
External Walls (Panels, Linings, Insulation)				
Item			**Qty**	**Unit**
Concrete - 50 MPa		Total	476	m3
Concrete - 60 MPa		Total	15	m3
Steel reinforcement		Total	15,038	kg
Plasterboard 13mm		Total	2,410	m2
Plasterboard 16mm		Total	-	m2
Glasswool 75mm		Total	7,995	m2
Gal steel frame		Total	7,995	kg
Blocks (16kg)		Total	-	p
Mortar		Total	-	kg
Texture coat		Total	6,772	l
Window System (Glass, Frames, Seals)				
Item			**Qty**	**Unit**
Aluminium frame		Total	3321	m
Glass 10.38mm		Total	907	m2

Table 68 Reference – columns quantity estimate.

Columns				
Item			**Qty**	**Unit**
Concrete - 40 MPa				
length	1	m		
width	0.3	m		
height	2.9	m		
qty	51			
		Total	44.37	m3
Steel - reinf bar				
Reinf. 190 kg/m3	8430.3	kg		
		Total	8430	kg
TOTAL - Columns				
Concrete - 40 MPa		Total	44	m3
Steel - reinf bar		Total	8430	kg

Table 69 Reference – floor system quantity estimate – part 1.

Floor System (Slabs, Thickening, Ceiling)				
Item			**Qty**	**Unit**
Suspended slab (Ground)				
Concrete - 40 MPa				
Slab (surface)				
Area*	1784	m2		
thickness	0.18	m		
		Total	321.12	m3
Slab (thickening)				
Area*	300	m2		
thickness	0.07	m		
		Total	21	m3
Beams 250				
Width*	2.4	m		
thickness	0.07	m		
length	15	m		
		Total	3	m3
Beams 400				
Width*	2.4	m		
thickness	0.22	m		
length	131	m		
		Total	69	m3
Beams 650				
Width*	2.4	m		
thickness	0.47	m		
length	65	m		
		Total	73	m3
Form deck (10.5kg/m2)			18732	kg
Steel reinf.				
Reinf. 80 kg/m3	38970.24	*kg*		
		Total	38970	kg
Suspended slab (Level 1)				
Concrete - 40 MPa				
Slab (surface)				
Area**	1133	m2		
thickness	0.18	m		
		Total	203.94	m3
Slab (thickening)				
Area	136	m2		
thickness	0.12	m		
		Total	16.32	m3
Beams 700				
Width	5.3	m		
thickness	0.52	m		
length	9	m		
		Total	25	m3
Beams 600				
Width	2.4	m		
thickness	0.47	m		
length	31	m		
		Total	35	m3
Beams 800				
Width	1.2	m		
thickness	0.62	m		
length	40	m		
		Total	30	m3
Form deck (10.5kg/m2)			11896.5	kg
Steel reinf.				
Reinf. 80 kg/m3	24783.36	kg		
		Total	24783	kg
Ceiling to floor below				
Plasterboard 13mm		Total	1133	m2
Gal steel (5kg/m2)		Total	5665	kg
Suspended slab (Level 2)				
Concrete - 40 MPa				
Slab (surface)				
Area**	1133	m2		
thickness	0.18	m		
		Total	203.94	m3
Form deck (10.5kg/m2)			11896.5	kg
Steel reinf.				
Reinf. 80 kg/m3	16315.2	kg		
		Total	16315	kg
Ceiling to floor below				
Plasterboard 13mm		Total	1133	m2
Gal steel (5kg/m2)		Total	5665	kg

Table 70 Reference – floor system quantity estimate – part 2.

Floor System - continued				
Item			**Qty**	**Unit**
Suspended slab (Level 3)				
Concrete - 40 MPa				
Slab (surface)				
Area**	941	m2		
thickness	0.18	m		
		Total	169.38	m3
Form deck (10.5kg/m2)			9880.5	kg
Steel reinf.				
Reinf. 80 kg/m3	13550.4	kg		
		Total	13550	kg
Ceiling to floor below				
Plasterboard 13mm		Total	941	m2
Gal steel (5kg/m2)		Total	4705	kg
Suspended slab (Level 4)				
Concrete - 40 MPa				
Slab (surface)				
Area**	941	m2		
thickness	0.18	m		
		Total	169.38	m3
Form deck (10.5kg/m2)			9880.5	kg
Steel reinf.				
Reinf. 80 kg/m3	13550.4	kg		
		Total	13550	kg
Ceiling to floor below				
Plasterboard 13mm		Total	941	m2
Gal steel (5kg/m2)		Total	4705	kg
Suspended slab (Level 5)				
Concrete - 40 MPa				
Slab (surface)				
Area**	808	m2		
thickness	0.18	m		
		Total	145.44	m3
Form deck (10.5kg/m2)			8484	kg
Steel reinf.				
Reinf. 80 kg/m3	11635.2	kg		
		Total	11635	kg
Ceiling to floor below				
Plasterboard 13mm		Total	808	m2
Gal steel (5kg/m2)		Total	4040	kg
Suspended slab (Level 6)				
Concrete - 40 MPa				
Slab (surface)				
Area**	808	m2		
thickness	0.18	m		
		Total	145.44	m3
Form deck (10.5kg/m2)			8484	kg
Steel reinf.				
Reinf. 80 kg/m3	11635.2	kg		
		Total	11635	kg
Ceiling to floor below				
Plasterboard 13mm		Total	808	m2
Gal steel (5kg/m2)		Total	4040	kg
Suspended slab (Level 7)				
Concrete - 40 MPa				
Slab (surface)				
Area**	808	m2		
thickness	0.18	m		
		Total	145.44	m3
Form deck (10.5kg/m2)			8484	kg
Steel reinf.				
Reinf. 80 kg/m3	11635.2	kg		
		Total	11635	kg
Ceiling to floor below				
Plasterboard 13mm		Total	808	m2
Gal steel (5kg/m2)		Total	4040	kg
TOTAL - Floor System				
Concrete - 40 MPa		Total	1776	m3
Steel reinf.		Total	142075	kg
Form deck (10.5kg/m2)			87738	kg
Plasterboard 13mm		Total	6572	m2
Gal steel frame		Total	32860	kg

Table 71 Reference - roof system quantity estimate.

Roof System (Slab, Ceiling)				
Item			**Qty**	**Unit**
Suspended slab (roof)				
Concrete - 40 MPa				
Slab (surface)				
Area**	808	m2		
thickness	0.18	m		
		Total	145.44	m3
Form deck (10.5kg/m2)			8484	kg
Steel reinf.				
Reinf. 80 kg/m3	11635.2	kg		
		Total	11635	kg
Ceiling to floor below				
Plasterboard 13mm		Total	808	m2
Gal steel (5kg/m2)		Total	4040	kg
TOTAL - Roof System				
40 MPa concrete		Total	145	m3
Steel reinf.		Total	11635	kg
Form deck (10.5kg/m2)		Total	8484	kg
Plasterboard 13mm		Total	808	m2
Gal steel frame		Total	4040	kg

B.3 Wall material content estimate

Table 72 Reference - wall system material quantity estimate by floor.

Layer	Measure	Assumptions	Unit	LGrd	Grd	1st	2nd	3rd	4th	5th	6th	7th	Total
Internal Walls - concrete panels													
Panel 150/50/SL92 - Internal													
	Wall area	2.9m high	m2	10	93	157	174	157	157	157	157	157	1,217
1	Concrete 50MPa	thick : 150 mm	m3	2	14	23	26	23	23	23	23	23	182
2	Steel (SL92)	desn: 5 kg/m2	kg	51	464	783	870	783	783	783	783	783	6,083
Panel 180/50/SL92 - Internal													
	Wall area	2.9m high	m2	-	81	90	90	49	52	9	6	9	386
1	Concrete 50MPa	thick: 0.18 m	m3	-	15	16	16	9	9	2	1	2	69
2	Steel (SL92)	desn: 5 kg/m2	kg	-	406	450	450	247	261	44	29	44	1,929
Panel 200/60/SL92 - Internal													
	Wall area	2.9m high	m2	-	-	23	-	-	-	-	-	-	23
1	Concrete 60 Mpa	thick: 0.2 m	m3	-	-	5	-	-	-	-	-	-	5
2	Steel (SL92)	desn: 5 kg/m2	kg	-	-	116	-	-	-	-	-	-	116
Internal Walls - linings and partition walls													
Internal partition													
	Wall area	2.9m high	m2	-	186	394	394	339	339	342	342	342	2,680
1	Plasterboard	thick: 13 mm	m2	-	186	394	394	339	339	342	342	342	2,680
2	Gal steel frame	adens: 3.3 kg/m2	kg	-	616	1,308	1,308	1,126	1,126	1,135	1,135	1,135	8,890
3	Plasterboard	thick: 13 mm	m2	-	186	394	394	339	339	342	342	342	2,680
Inter-tenancy lining													
	Wall area	2.9m high	m2	-	139	235	235	186	186	186	186	186	1,537
1	Plasterboard	thick: 13 mm	m2	-	139	235	235	186	186	186	186	186	1,537
2	Gal steel frame	adens: 3.3 kg/m2	kg	-	462	779	779	616	616	616	616	616	5,099
3	Concrete panel	Incl in panels above											
4	Gal steel frame	adens: 3.3 kg/m2	kg	-	462	779	779	616	616	616	616	616	5,099
5	Plasterboard	thick: 13 mm	m2	-	139	235	235	186	186	186	186	186	1,537
Corridors and lobby lining													
	Wall area	2.9m high	m2	-	55	55	55	55	55	55	55	55	441
1	Plasterboard	thick: 13 mm	m2	-	55	55	55	55	55	55	55	55	441
2	Gal steel frame	adens: 3.3 kg/m2	kg	-	183	183	183	183	183	183	183	183	1,462
3	Concrete panel	Incl in panels above											
Corridors and lobbies (non concrete)													
	Wall area	2.9m high	m2	-	119	305	305	276	276	189	189	189	1,844
1	Plasterboard	thick: 16 mm	m2	-	119	305	305	276	276	189	189	189	1,844
2	Gal steel frame	adens: 3.3 kg/m2	kg	-	394	1,010	1,010	914	914	625	625	625	6,119
3	Glasswool	thick: 75 mm	m2	-	119	305	305	276	276	189	189	189	1,844
4	Plasterboard	thick: 16 mm	m2	-	119	305	305	276	276	189	189	189	1,844
Blockwork													
	Wall area	2.9m high	m2	-	174	-	-	-	-	-	-	-	174
1	Blocks (16kg)	12.5p per m2	m2	-	2,175	-	-	-	-	-	-	-	2,175
2	Mortar	25 kg/m2	kg	-	4,350	-	-	-	-	-	-	-	4,350
External Walls - concrete panels													
Panel 150/50/SL92 - External													
	Wall area	2.9m high	m2	270	203	244	244	151	151	152	154	157	1,724
1	Concrete 50MPa	thick : 150 mm	m3	40	30	37	37	23	23	23	23	23	259
2	Steel (SL92)	desn: 5 kg/m2	kg	1,349	1,015	1,218	1,218	754	754	761	769	783	8,620
3	Texture coat	15l/12 m2	l	337.13	253.75	304.50	304.50	188.50	188.50	190.31	192.13	195.75	2,155
Panel 180/50/SL92 - External													
	Wall area	2.9m high	m2	-	64	194	194	202	182	124	124	124	1,208
1	Concrete 50MPa	thick : 150 mm	m3	-	11	35	35	36	33	22	22	22	217
2	Steel (SL92)	desn: 5 kg/m2	kg	-	319	972	972	1,011	910	620	620	620	6,041
3	Texture coat	15l/12 m2	l	-	79.75	242.88	242.88	252.75	227.38	154.88	154.88	154.88	1,510
Panel 200/60/SL92 - External													
	Wall area	2.9m high	m2	-	75								75
1	Concrete 60MPa	thick : 150 mm	m3	-	15	-	-	-	-	-	-	-	15
2	Steel (SL92)	desn: 5 kg/m2	kg	-	377	-	-	-	-	-	-	-	377
3	Texture coat	15l/12 m2	l	-	94.25	-	-	-	-	-	-	-	94
External Walls - linings and partition walls													
External wall (excl panel)													
	Wall area	2.9m high	m2	-	229	421	421	322	322	232	232	232	2,410
1	Plasterboard	thick: 13 mm	m2	-	229	421	421	322	322	232	232	232	2,410
2	Gal steel frame	adens: 3.3 kg/m2	kg	-	760	1,395	1,395	1,068	1,068	770	770	770	-
3	Glasswool	thick: 75 mm	m2	-	229	421	421	322	322	232	232	232	7,995
4	Concrete panel	Incl in panels above		-	-	-	-	-	-	-	-	-	-
5	Texture coat	15l/12 m2	l	-	286.38	525.63	525.63	402.38	402.38	290.00	290.00	290.00	3,012

B.4 Wall type material content

Table 73 Reference - wall quantity estimates per unit area for steel frame walls.

Steel partition wall frame		
Element	**Qty**	**unit**
Height	2.6	m
Length	3	m
Stud spacing	0.6	m
Total studs	6	p
Nogings per void	1	p
Plates	2	m
Channel mass per m	1.1	kg/m
Total length	24.6	m
Total mass	25.9	kg
Total mass per m2	**3.3**	**kg**

B.5 Window system area and circumference estimate

Table 74 Reference - window system area and circumference estimate.

Window Type	**Area per window**	**Circ. per window**	**Qty**	**Area**	**Circ.**
unit	m2	m	p	m2	m
A	11	32	6	66	192
B	2.5	14	35	87.5	490
C	6	20	50	300	1000
D	2.5	11.6	14	35	162.4
E	8.7	24	26	226.2	624
F	1.5	10	32	48	320
G	2.3	12.5	25	57.5	312.5
H	6.5	15.2	8	52	121.6
I	2.5	7	14	35	98
J	1.8	10.8	15	27	162
K	4.5	25.4	28	126	711.2
L	1.5	6	6	9	36
M	5.2	17	3	15.6	51
N	7.5	24	5	37.5	120
O	4.7	19	15	70.5	285
P	2.4	20	3	7.2	60
Q	1.6	14	3	4.8	42
		Total		**907**	**3,321**
		Total per m2 GDA		**0.15**	**0.56**

Appendix C Transport task estimate breakdown.

Table 75 Study Building transport task estimate.

Item	Process Name	Inventory	Mass		Assumptions	Transport Qty	Unit
Concrete	Transport, concrete truck/AU U	AUPLCI	1362.1	t	2.5 km, Boral North Melbourne to Parkville	3405	t.km
Blocks	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	130.5	t	38 km Wollert to Parkville	4960	t.km
Sand bed - 50 mm	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	77.9	t	61 km, Bacchus Marsh to Parkville	4750	t.km
Steel - reinf.	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	45.3	t	1121 km Whyalla to Altona. Then Altona to Parkville.	50774	t.km
Sheet steel (including gal steel frame)	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	65.0	t	1115 km Port Kembla to Western Port VIC then to Parkville.	72479	t.km
Structural steel	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	5.3	t	1101 km Whyalla to Altona. Then Altona to Parkville.	5845	t.km
Framing timber (local)	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	75.0	t	150km Morwell to Parkville	11255	t.km
Framing timber (import)	Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U	AusLCI	40.4	t	22559 km Roterdam to Singapore,Singapore to Melbourne	911445	t.km
Framing timber (import)	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	as above	t	6 km port to Parkville	242	t.km
LVL	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	79.5	t	141 km Mill to Port, NZ	11203	t.km
LVL	Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U	AusLCI	as above		3070 km Aukland to Melbourne	243920	t.km
LVL	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	as above		6 km port to Parkville	477	t.km
Kiln dried hardwood	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	31.0	t	210 km Heywood to Parkville	6500	t.km
Plasterboard	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	205.3	t	38 km Wollert to Parkville	7801	t.km
Systempanel	Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U	AusLCI	159.0	t	10500km Tianjin to Melbourne. Production location known to be China, but exact location not known.	1669730	t.km
Systempanel	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	as above		6 km port to Parkville	954	t.km
Promatect 100	Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U	AusLCI	66.1	t	20500km Rotterdam to Melbourne.	1355526	t.km
Promatect 100	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	as above		6 km port to Parkville	397	t.km
All others	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	66.5	t	50km estimate	3327	t.km

Table 76 Reference Building transport task estimate.

Item	Process Name	Process Source	Mass		Assumptions	Transport Qty	Unit
Concrete - form on site	Transport, concrete truck/AU U	AUPLCI	6561.3	t	2.5 km, Boral North Melbourne to Parkville	16403	t.km
Concrete - precast	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	2202.6	t	2.5 km, Boral North Melbourne to Parkville	5506	t.km
Blocks	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	36.2	t	38 km Wollert to Parkville	1375	t.km
Gravel bed - 0.8 m	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	247.0	t	61 km, Bacchus Marsh to Parkville	15065	t.km
Steel - reinf.	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	220.6	t	1121 km Whyalla to Altona. Then Altona to Parkville.	247243	t.km
Sheet steel (including gal steel frame)	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	167.8	t	1115 km Port Kembla to Western Port VIC then to Parkville.	187081	t.km
Plasterboard	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	278.6	t	38 km Wollert to Parkville	10586	t.km
All others	Transport, articulated truck, >20t, fleet average/AU U	AUPLCI	57.9	t	50km estimate	2894	t.km

Appendix D Characterisation Factors

Climate change			
Compartment	**Flow Description**	**Factor**	**Unit**
Air	1-Propanol, 3,3,3-trifluoro-2,2-bis(trifluoromethyl)-, HFE-7100	297	kg CO2 eq / kg
Air	Butane, 1,1,1,3,3-pentafluoro-, HFC-365mfc	794	kg CO2 eq / kg
Air	Butane, perfluoro-	8860	kg CO2 eq / kg
Air	Butane, perfluorocyclo-, PFC-318	10300	kg CO2 eq / kg
Air	Carbon dioxide	1	kg CO2 eq / kg
Air	Carbon dioxide, fossil	1	kg CO2 eq / kg
Air	Carbon dioxide, land transformation	1	kg CO2 eq / kg
Air	Chloroform	31	kg CO2 eq / kg
Air	Cis-perfluorodecalin	7500	kg CO2 eq / kg
Air	Dimethyl ether	1	kg CO2 eq / kg
Air	Dinitrogen monoxide	298	kg CO2 eq / kg
Air	Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	2310	kg CO2 eq / kg
Air	Ethane, 1-chloro-2,2,2-trifluoro-(difluoromethoxy)-, HCFE-235da2	350	kg CO2 eq / kg
Air	Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	725	kg CO2 eq / kg
Air	Ethane, 1,1-difluoro-, HFC-152a	124	kg CO2 eq / kg
Air	Ethane, 1,1,1-trichloro-, HCFC-140	146	kg CO2 eq / kg
Air	Ethane, 1,1,1-trifluoro-, HFC-143a	4470	kg CO2 eq / kg
Air	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	1430	kg CO2 eq / kg
Air	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	6130	kg CO2 eq / kg
Air	Ethane, 1,1,2-trifluoro-, HFC-143	353	kg CO2 eq / kg
Air	Ethane, 1,1,2,2-tetrafluoro-, HFC-134	1100	kg CO2 eq / kg
Air	Ethane, 1,2-dibromotetrafluoro-, Halon 2402	1640	kg CO2 eq / kg
Air	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	10000	kg CO2 eq / kg
Air	Ethane, 1,2-difluoro-, HFC-152	53	kg CO2 eq / kg
Air	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	609	kg CO2 eq / kg
Air	Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	77	kg CO2 eq / kg
Air	Ethane, chloropentafluoro-, CFC-115	7370	kg CO2 eq / kg
Air	Ethane, fluoro-, HFC-161	12	kg CO2 eq / kg
Air	Ethane, hexafluoro-, HFC-116	12200	kg CO2 eq / kg
Air	Ethane, pentafluoro-, HFC-125	3500	kg CO2 eq / kg
Air	Ether, 1,1,1-trifluoromethyl methyl-, HFE-143a	756	kg CO2 eq / kg
Air	Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl-, HFE-347mcc3	575	kg CO2 eq / kg
Air	Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl-, HFE-347mcf2	374	kg CO2 eq / kg
Air	Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl-, HFE-347pcf2	580	kg CO2 eq / kg
Air	Ether, 1,1,2,2-Tetrafluoroethyl methyl-, HFE-254cb2	359	kg CO2 eq / kg
Air	Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356mec3	101	kg CO2 eq / kg
Air	Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcc3	110	kg CO2 eq / kg
Air	Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcf2	265	kg CO2 eq / kg
Air	Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcf3	502	kg CO2 eq / kg
Air	Ether, 1,2,2-trifluoroethyl trifluoromethyl-, HFE-236ea2	989	kg CO2 eq / kg
Air	Ether, 1,2,2-trifluoroethyl trifluoromethyl-, HFE-236fa	487	kg CO2 eq / kg
Air	Ether, 2,2,3,3,3-Pentafluoropropyl methyl-, HFE-365mcf3	11	kg CO2 eq / kg
Air	Ether, di(difluoromethyl), HFE-134	6320	kg CO2 eq / kg
Air	Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245cb2	708	kg CO2 eq / kg
Air	Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245fa1	286	kg CO2 eq / kg
Air	Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245fa2	659	kg CO2 eq / kg
Air	Ether, ethyl 1,1,2,2-tetrafluoroethyl-, HFE-374pc2	557	kg CO2 eq / kg
Air	Ether, nonafluorobutane ethyl-, HFE569sf2 (HFE-7200)	59	kg CO2 eq / kg
Air	Ether, pentafluoromethyl-, HFE-125	14900	kg CO2 eq / kg
Air	Hexane, perfluoro-	9300	kg CO2 eq / kg
Air	HFE-227EA	1540	kg CO2 eq / kg

Climate change			
Compartment	**Flow Description**	**Factor**	**Unit**
Air	HFE-236ca12 (HG-10)	2800	kg CO2 eq / kg
Air	HFE-263fb2	11	kg CO2 eq / kg
Air	HFE-329mcc2	919	kg CO2 eq / kg
Air	HFE-338mcf2	552	kg CO2 eq / kg
Air	HFE-338pcc13 (HG-01)	1500	kg CO2 eq / kg
Air	HFE-43-10pccc124 (H-Galden1040x)	1870	kg CO2 eq / kg
Air	Methane	25	kg CO2 eq / kg
Air	Methane, biogenic	22.25	kg CO2 eq / kg
Air	Methane, bromo-, Halon 1001	5	kg CO2 eq / kg
Air	Methane, bromochlorodifluoro-, Halon 1211	1890	kg CO2 eq / kg
Air	Methane, bromodifluoro-, Halon 1201	404	kg CO2 eq / kg
Air	Methane, bromotrifluoro-, Halon 1301	7140	kg CO2 eq / kg
Air	Methane, chlorodifluoro-, HCFC-22	1810	kg CO2 eq / kg
Air	Methane, chlorotrifluoro-, CFC-13	14400	kg CO2 eq / kg
Air	Methane, dibromo-	1.54	kg CO2 eq / kg
Air	Methane, dichloro-, HCC-30	8.7	kg CO2 eq / kg
Air	Methane, dichlorodifluoro-, CFC-12	10900	kg CO2 eq / kg
Air	Methane, dichlorofluoro-, HCFC-21	151	kg CO2 eq / kg
Air	Methane, difluoro-, HFC-32	675	kg CO2 eq / kg
Air	Methane, fluoro-, HFC-41	92	kg CO2 eq / kg
Air	Methane, fossil	25	kg CO2 eq / kg
Air	Methane, iodotrifluoro-	0.4	kg CO2 eq / kg
Air	Methane, monochloro-, R-40	13	kg CO2 eq / kg
Air	Methane, tetrachloro-, CFC-10	1400	kg CO2 eq / kg
Air	Methane, tetrafluoro-, CFC-14	7390	kg CO2 eq / kg
Air	Methane, trichlorofluoro-, CFC-11	4750	kg CO2 eq / kg
Air	Methane, trifluoro-, HFC-23	14800	kg CO2 eq / kg
Air	Nitrogen fluoride	17200	kg CO2 eq / kg
Air	Pentane, 2,3-dihydroperfluoro-, HFC-4310mee	1640	kg CO2 eq / kg
Air	Pentane, perfluoro-	9160	kg CO2 eq / kg
Air	PFPMIE	10300	kg CO2 eq / kg
Air	Propane, 1,1,1,2,2,3-hexafluoro-, HFC-236cb	1340	kg CO2 eq / kg
Air	Propane, 1,1,1,2,3,3-hexafluoro-, HFC-236ea	1370	kg CO2 eq / kg
Air	Propane, 1,1,1,2,3,3,3-heptafluoro-, HFC-227ea	3220	kg CO2 eq / kg
Air	Propane, 1,1,1,3,3-pentafluoro-, HFC-245fa	1030	kg CO2 eq / kg
Air	Propane, 1,1,1,3,3,3-hexafluoro-, HCFC-236fa	9810	kg CO2 eq / kg
Air	Propane, 1,1,2,2,3-pentafluoro-, HFC-245ca	693	kg CO2 eq / kg
Air	Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb	595	kg CO2 eq / kg
Air	Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca	122	kg CO2 eq / kg
Air	Propane, perfluoro-	8830	kg CO2 eq / kg
Air	Propane, perfluorocyclo-	17340	kg CO2 eq / kg
Air	Sulfur hexafluoride	22800	kg CO2 eq / kg
Air	Trifluoromethylsulfur pentafluoride	17700	kg CO2 eq / kg

Stratospheric ozone depletion			
Compartment	**Flow Description**	**Factor**	**Unit**
Air	Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	0.07	kg CFC-11 eq / kg
Air	Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	0.12	kg CFC-11 eq / kg
Air	Ethane, 1,1,1-trichloro-, HCFC-140	0.12	kg CFC-11 eq / kg
Air	Ethane, 1,1,1,2-tetrafluoro-2-bromo-, Halon 2401	0.25	kg CFC-11 eq / kg
Air	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	1	kg CFC-11 eq / kg
Air	Ethane, 1,2-dibromotetrafluoro-, Halon 2402	6	kg CFC-11 eq / kg

Stratospheric ozone depletion			
Compartment	**Flow Description**	**Factor**	**Unit**
Air	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	0.94	kg CFC-11 eq / kg
Air	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	0.02	kg CFC-11 eq / kg
Air	Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	0.02	kg CFC-11 eq / kg
Air	Ethane, chloropentafluoro-, CFC-115	0.44	kg CFC-11 eq / kg
Air	Halothane	0.14	kg CFC-11 eq / kg
Air	Methane, bromo-, Halon 1001	0.38	kg CFC-11 eq / kg
Air	Methane, bromochlorodifluoro-, Halon 1211	6	kg CFC-11 eq / kg
Air	Methane, bromodifluoro-, Halon 1201	1.4	kg CFC-11 eq / kg
Air	Methane, bromotrifluoro-, Halon 1301	12	kg CFC-11 eq / kg
Air	Methane, chlorodifluoro-, HCFC-22	0.05	kg CFC-11 eq / kg
Air	Methane, dibromodifluoro-, Halon 1202	1.3	kg CFC-11 eq / kg
Air	Methane, dichlorodifluoro-, CFC-12	1	kg CFC-11 eq / kg
Air	Methane, monochloro-, R-40	0.02	kg CFC-11 eq / kg
Air	Methane, tetrachloro-, CFC-10	0.73	kg CFC-11 eq / kg
Air	Methane, trichlorofluoro-, CFC-11	1	kg CFC-11 eq / kg
Air	Propane, 1,3-dichloro-1,1,2,2,3-pentafluoro-, HCFC-225cb	0.03	kg CFC-11 eq / kg
Air	Propane, 3,3-dichloro-1,1,1,2,2-pentafluoro-, HCFC-225ca	0.02	kg CFC-11 eq / kg

Acidification			
Compartment	**Flow Description**	**Factor**	**Unit**
Air	Ammonia	1.6	kg SO2 eq / kg
Air	Hydrogen chloride	0.88	kg SO2 eq / kg
Water	Hydrogen chloride	0.88	kg SO2 eq / kg
Soil	Hydrogen chloride	0.88	kg SO2 eq / kg
Air	Hydrogen fluoride	1.6	kg SO2 eq / kg
Water	Hydrogen fluoride	1.6	kg SO2 eq / kg
Soil	Hydrogen fluoride	1.6	kg SO2 eq / kg
Air	Hydrogen sulfide	1.88	kg SO2 eq / kg
Water	Hydrogen sulfide	1.88	kg SO2 eq / kg
Soil	Hydrogen sulfide	1.88	kg SO2 eq / kg
Air	Nitric acid	0.51	kg SO2 eq / kg
Water	Nitric acid	0.51	kg SO2 eq / kg
Soil	Nitric acid	0.51	kg SO2 eq / kg
Air	Nitric oxide	0.76	kg SO2 eq / kg
Air	Nitrogen dioxide	0.5	kg SO2 eq / kg
Air	Nitrogen oxides	0.5	kg SO2 eq / kg
Air	Phosphoric acid	0.98	kg SO2 eq / kg
Water	Phosphoric acid	0.98	kg SO2 eq / kg
Soil	Phosphoric acid	0.98	kg SO2 eq / kg
Air	Sulfur dioxide	1.2	kg SO2 eq / kg
Air	Sulfur monoxide	1.2	kg SO2 eq / kg
Air	Sulfur trioxide	0.8	kg SO2 eq / kg
Air	Sulfuric acid	0.65	kg SO2 eq / kg
Water	Sulfuric acid	0.65	kg SO2 eq / kg
Soil	Sulfuric acid	0.65	kg SO2 eq / kg

Eutrophication			
Compartment	**Flow Description**	**Factor**	**Unit**
Air	Ammonia	0.35	kg PO43- eq / kg
Water	Ammonia	0.35	kg PO43- eq / kg
Soil	Ammonia	0.35	kg PO43- eq / kg
Air	Ammonium carbonate	0.12	kg PO43- eq / kg

Eutrophication			
Compartment	**Flow Description**	**Factor**	**Unit**
Air	Ammonium nitrate	0.074	kg PO43- eq / kg
Soil	Ammonium nitrate	0.074	kg PO43- eq / kg
Air	Ammonium, ion	0.33	kg PO43- eq / kg
Water	Ammonium, ion	0.33	kg PO43- eq / kg
Soil	Ammonium, ion	0.33	kg PO43- eq / kg
Water	COD, Chemical Oxygen Demand	0.022	kg PO43- eq / kg
Air	Nitrate	0.1	kg PO43- eq / kg
Water	Nitrate	0.1	kg PO43- eq / kg
Soil	Nitrate	0.1	kg PO43- eq / kg
Air	Nitric acid	0.1	kg PO43- eq / kg
Water	Nitric acid	0.1	kg PO43- eq / kg
Soil	Nitric acid	0.1	kg PO43- eq / kg
Air	Nitric oxide	0.2	kg PO43- eq / kg
Water	Nitrite	0.1	kg PO43- eq / kg
Water	Nitrogen	0.42	kg PO43- eq / kg
Soil	Nitrogen	0.42	kg PO43- eq / kg
Air	Nitrogen dioxide	0.13	kg PO43- eq / kg
Air	Nitrogen oxides	0.13	kg PO43- eq / kg
Water	Nitrogen oxides	0.13	kg PO43- eq / kg
Soil	Nitrogen oxides	0.13	kg PO43- eq / kg
Air	Nitrogen, total	0.42	kg PO43- eq / kg
Water	Nitrogen, total	0.42	kg PO43- eq / kg
Soil	Nitrogen, total	0.42	kg PO43- eq / kg
Air	Phosphate	1	kg PO43- eq / kg
Water	Phosphate	1	kg PO43- eq / kg
Soil	Phosphate	1	kg PO43- eq / kg
Air	Phosphoric acid	0.97	kg PO43- eq / kg
Water	Phosphoric acid	0.97	kg PO43- eq / kg
Soil	Phosphoric acid	0.97	kg PO43- eq / kg
Air	Phosphorus	3.06	kg PO43- eq / kg
Water	Phosphorus	3.06	kg PO43- eq / kg
Soil	Phosphorus	3.06	kg PO43- eq / kg
Air	Phosphorus pentoxide	1.34	kg PO43- eq / kg
Water	Phosphorus pentoxide	1.34	kg PO43- eq / kg
Soil	Phosphorus pentoxide	1.34	kg PO43- eq / kg
Air	Phosphorus, total	3.06	kg PO43- eq / kg
Water	Phosphorus, total	3.06	kg PO43- eq / kg
Soil	Phosphorus, total	3.06	kg PO43- eq / kg

Photochemical oxidation			
Compartment	**Flow Description**	**Factor**	**Unit**
Air	1-Butanol	0.62	kg C2H4 eq / kg
Air	1-Butene	1.08	kg C2H4 eq / kg
Air	1-Butene, 2-methyl-	0.771	kg C2H4 eq / kg
Air	1-Butene, 3-methyl-	0.671	kg C2H4 eq / kg
Air	1-Hexene	0.874	kg C2H4 eq / kg
Air	1-Pentene	0.977	kg C2H4 eq / kg
Air	1-Propanol	0.561	kg C2H4 eq / kg
Air	2-Butanol	0.4	kg C2H4 eq / kg
Air	2-Butanone, 3-methyl-	0.364	kg C2H4 eq / kg
Air	2-Butene (cis)	1.15	kg C2H4 eq / kg
Air	2-Butene (trans)	1.13	kg C2H4 eq / kg
Air	2-Butene, 2-methyl-	0.842	kg C2H4 eq / kg

Photochemical oxidation			
Compartment	**Flow Description**	**Factor**	**Unit**
Air	2-Hexanone	0.572	kg C2H4 eq / kg
Air	2-Hexene (cis)	1.07	kg C2H4 eq / kg
Air	2-Hexene (trans)	1.07	kg C2H4 eq / kg
Air	2-Methyl-1-propanol	0.36	kg C2H4 eq / kg
Air	2-Methyl-2-butanol	0.228	kg C2H4 eq / kg
Air	2-Pentanone	0.548	kg C2H4 eq / kg
Air	2-Pentene (cis)	1.12	kg C2H4 eq / kg
Air	2-Pentene (trans)	1.12	kg C2H4 eq / kg
Air	2-Propanol	0.188	kg C2H4 eq / kg
Air	3-Hexanone	0.599	kg C2H4 eq / kg
Air	3-Methyl-1-butanol	0.433	kg C2H4 eq / kg
Air	3-Pentanol	0.595	kg C2H4 eq / kg
Air	3-Pentanone	0.414	kg C2H4 eq / kg
Air	3,3-Dimethyl-2-butanone	0.323	kg C2H4 eq / kg
Air	4-Hydroxy-4-methyl-2-pentanone	0.307	kg C2H4 eq / kg
Air	4-Methyl-2-pentanone	0.49	kg C2H4 eq / kg
Air	Acetaldehyde	0.641	kg C2H4 eq / kg
Air	Acetic acid	0.097	kg C2H4 eq / kg
Air	Acetone	0.094	kg C2H4 eq / kg
Air	Benzaldehyde	-0.092	kg C2H4 eq / kg
Air	Benzene	0.218	kg C2H4 eq / kg
Air	Benzene, 1,2,3-trimethyl-	1.27	kg C2H4 eq / kg
Air	Benzene, 1,2,4-trimethyl-	1.28	kg C2H4 eq / kg
Air	Benzene, 1,3,5-trimethyl-	1.38	kg C2H4 eq / kg
Air	Benzene, 3,5-dimethylethyl-	1.32	kg C2H4 eq / kg
Air	Benzene, ethyl-	0.73	kg C2H4 eq / kg
Air	Butadiene	0.851	kg C2H4 eq / kg
Air	Butanal	0.795	kg C2H4 eq / kg
Air	Butane	0.352	kg C2H4 eq / kg
Air	Butane, 2,2-dimethyl-	0.241	kg C2H4 eq / kg
Air	Butane, 2,3-dimethyl-	0.541	kg C2H4 eq / kg
Air	Butanol, 2-methyl-1-	0.489	kg C2H4 eq / kg
Air	Butanol, 3-methyl-2-	0.406	kg C2H4 eq / kg
Air	Butyl acetate	0.269	kg C2H4 eq / kg
Air	Carbon monoxide	0.027	kg C2H4 eq / kg
Air	Carbon monoxide, biogenic	0.027	kg C2H4 eq / kg
Air	Carbon monoxide, fossil	0.027	kg C2H4 eq / kg
Air	Chloroform	0.023	kg C2H4 eq / kg
Air	Cumene	0.5	kg C2H4 eq / kg
Air	Cyclohexane	0.29	kg C2H4 eq / kg
Air	Cyclohexanol	0.518	kg C2H4 eq / kg
Air	Cyclohexanone	0.299	kg C2H4 eq / kg
Air	Decane	0.384	kg C2H4 eq / kg
Air	Diethyl ether	0.445	kg C2H4 eq / kg
Air	Diisopropyl ether	0.398	kg C2H4 eq / kg
Air	Dimethyl carbonate	0.025	kg C2H4 eq / kg
Air	Dimethyl ether	0.189	kg C2H4 eq / kg
Air	Dodecane	0.357	kg C2H4 eq / kg
Air	Ethane	0.123	kg C2H4 eq / kg
Air	Ethane, 1,1,1-trichloro-, HCFC-140	0.009	kg C2H4 eq / kg
Air	Ethanol	0.399	kg C2H4 eq / kg
Air	Ethanol, 2-butoxy-	0.483	kg C2H4 eq / kg
Air	Ethanol, 2-ethoxy-	0.386	kg C2H4 eq / kg
Air	Ethanol, 2-methoxy-	0.307	kg C2H4 eq / kg

Photochemical oxidation			
Compartment	**Flow Description**	**Factor**	**Unit**
Air	Ethene	1	kg C2H4 eq / kg
Air	Ethene, dichloro- (cis)	0.447	kg C2H4 eq / kg
Air	Ethene, dichloro- (trans)	0.392	kg C2H4 eq / kg
Air	Ethene, tetrachloro-	0.029	kg C2H4 eq / kg
Air	Ethene, trichloro-	0.325	kg C2H4 eq / kg
Air	Ethyl acetate	0.209	kg C2H4 eq / kg
Air	Ethylene glycol	0.373	kg C2H4 eq / kg
Air	Ethyne	0.085	kg C2H4 eq / kg
Air	Formaldehyde	0.519	kg C2H4 eq / kg
Air	Formic acid	0.032	kg C2H4 eq / kg
Air	Heptane	0.494	kg C2H4 eq / kg
Air	Hexane	0.482	kg C2H4 eq / kg
Air	Hexane, 2-methyl-	0.411	kg C2H4 eq / kg
Air	Hexane, 3-methyl-	0.364	kg C2H4 eq / kg
Air	Isobutane	0.307	kg C2H4 eq / kg
Air	Isobutene	0.627	kg C2H4 eq / kg
Air	Isobutyraldehyde	0.514	kg C2H4 eq / kg
Air	Isopentane	0.405	kg C2H4 eq / kg
Air	Isoprene	1.09	kg C2H4 eq / kg
Air	Isopropyl acetate	0.211	kg C2H4 eq / kg
Air	m-Xylene	1.11	kg C2H4 eq / kg
Air	Methane	0.006	kg C2H4 eq / kg
Air	Methane, biogenic	0.006	kg C2H4 eq / kg
Air	Methane, dichloro-, HCC-30	0.068	kg C2H4 eq / kg
Air	Methane, dimethoxy-	0.164	kg C2H4 eq / kg
Air	Methane, fossil	0.006	kg C2H4 eq / kg
Air	Methane, monochloro-, R-40	0.005	kg C2H4 eq / kg
Air	Methanol	0.14	kg C2H4 eq / kg
Air	Methyl acetate	0.059	kg C2H4 eq / kg
Air	Methyl ethyl ketone	0.373	kg C2H4 eq / kg
Air	Methyl formate	0.027	kg C2H4 eq / kg
Air	N-octane	0.453	kg C2H4 eq / kg
Air	N-propylbenzene	0.636	kg C2H4 eq / kg
Air	Nitric oxide	-0.427	kg C2H4 eq / kg
Air	Nitrogen dioxide	0.028	kg C2H4 eq / kg
Air	Nonane	0.414	kg C2H4 eq / kg
Air	o-Xylene	1.05	kg C2H4 eq / kg
Air	p-Xylene	1.01	kg C2H4 eq / kg
Air	Pentanal	0.765	kg C2H4 eq / kg
Air	Pentane	0.395	kg C2H4 eq / kg
Air	Pentane, 2-methyl-	0.42	kg C2H4 eq / kg
Air	Pentane, 3-methyl-	0.479	kg C2H4 eq / kg
Air	Propanal	0.798	kg C2H4 eq / kg
Air	Propane	0.176	kg C2H4 eq / kg
Air	Propane, 2,2-dimethyl-	0.173	kg C2H4 eq / kg
Air	Propene	1.12	kg C2H4 eq / kg
Air	Propionic acid	0.15	kg C2H4 eq / kg
Air	Propyl acetate	0.282	kg C2H4 eq / kg
Air	Propylene glycol	0.457	kg C2H4 eq / kg
Air	Propylene glycol methyl ether	0.355	kg C2H4 eq / kg
Air	Propylene glycol t-butyl ether	0.463	kg C2H4 eq / kg
Air	s-Butyl acetate	0.275	kg C2H4 eq / kg
Air	Styrene	0.142	kg C2H4 eq / kg
Air	Sulfur dioxide	0.048	kg C2H4 eq / kg

Photochemical oxidation

Compartment	Flow Description	Factor	Unit
Air	Sulfur monoxide	0.048	kg C2H4 eq / kg
Air	t-Butyl acetate	0.053	kg C2H4 eq / kg
Air	t-Butyl alcohol	0.106	kg C2H4 eq / kg
Air	t-Butyl ethyl ether	0.244	kg C2H4 eq / kg
Air	t-Butyl methyl ether	0.175	kg C2H4 eq / kg
Air	Toluene	0.637	kg C2H4 eq / kg
Air	Toluene, 2-ethyl-	0.898	kg C2H4 eq / kg
Air	Toluene, 3-ethyl-	1.02	kg C2H4 eq / kg
Air	Toluene, 3,5-diethyl-	1.29	kg C2H4 eq / kg
Air	Toluene, 4-ethyl-	0.906	kg C2H4 eq / kg
Air	Undecane	0.384	kg C2H4 eq / kg

Abiotic depletion

Compartment	Flow Description	Factor	Unit
Raw	Actinium	6.33E+13	kg Sb eq / kg
Raw	Aluminium	1E-08	kg Sb eq / kg
Raw	Aluminium, 24% in bauxite, 11% in crude ore, in ground	1E-08	kg Sb eq / kg
Raw	Anhydrite	8.42E-05	kg Sb eq / kg
Raw	Anhydrite, in ground	8.42E-05	kg Sb eq / kg
Raw	Antimony	1	kg Sb eq / kg
Raw	Argon	4.71E-07	kg Sb eq / kg
Raw	Arsenic	0.00917	kg Sb eq / kg
Raw	Barite	4.91E-05	kg Sb eq / kg
Raw	Barite, 15% in crude ore, in ground	4.91E-05	kg Sb eq / kg
Raw	Barium	1.06E-10	kg Sb eq / kg
Raw	Baryte, in ground	4.91E-05	kg Sb eq / kg
Raw	Bauxite	2.1E-09	kg Sb eq / kg
Raw	Bauxite, in ground	2.1E-09	kg Sb eq / kg
Raw	Beryllium	3.19E-05	kg Sb eq / kg
Raw	Bismuth	0.0731	kg Sb eq / kg
Raw	Borax	0.001	kg Sb eq / kg
Raw	Borax, in ground	0.001	kg Sb eq / kg
Raw	Boron	0.00467	kg Sb eq / kg
Raw	Bromine	0.00667	kg Sb eq / kg
Raw	Bromine, in ground	0.00667	kg Sb eq / kg
Raw	Cadmium	0.33	kg Sb eq / kg
Raw	Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground	0.33	kg Sb eq / kg
Raw	Calcite	2.83E-10	kg Sb eq / kg
Raw	Calcite, in ground	2.83E-10	kg Sb eq / kg
Raw	Calcium	7.08E-10	kg Sb eq / kg
Raw	Cerium	5.32E-09	kg Sb eq / kg
Raw	Cesium	1.91E-05	kg Sb eq / kg
Raw	Chlorine	4.86E-08	kg Sb eq / kg
Raw	Chromium	0.000858	kg Sb eq / kg
Raw	Chromium ore	0.000258	kg Sb eq / kg
Raw	Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	0.000258	kg Sb eq / kg
Raw	Chrysotile	9.88E-10	kg Sb eq / kg
Raw	Chrysotile, in ground	9.88E-10	kg Sb eq / kg
Raw	Cinnabar	0.427	kg Sb eq / kg
Raw	Coal, 18 MJ per kg	0.0134	kg Sb eq / kg
Raw	Coal, 18 MJ per kg, in ground	0.0134	kg Sb eq / kg
Raw	Coal, 19.5 MJ per kg, in ground	0.0134	kg Sb eq / kg
Raw	Coal, 22.1 MJ per kg, in ground	0.0134	kg Sb eq / kg

Abiotic depletion			
Compartment	**Flow Description**	**Factor**	**Unit**
Raw	Coal, 22.6 MJ per kg, in ground	0.0134	kg Sb eq / kg
Raw	Coal, 26.4 MJ per kg	0.0134	kg Sb eq / kg
Raw	Coal, 26.4 MJ per kg, in ground	0.0134	kg Sb eq / kg
Raw	Coal, 29.3 MJ per kg	0.0134	kg Sb eq / kg
Raw	Coal, 29.3 MJ per kg, in ground	0.0134	kg Sb eq / kg
Raw	Coal, brown	0.00671	kg Sb eq / kg
Raw	Coal, brown, 10 MJ per kg	0.00671	kg Sb eq / kg
Raw	Coal, brown, 10 MJ per kg, in ground	0.00671	kg Sb eq / kg
Raw	Coal, brown, 14.1 MJ per kg, in ground	0.00671	kg Sb eq / kg
Raw	Coal, brown, 8 MJ per kg	0.00671	kg Sb eq / kg
Raw	Coal, brown, 8.2 MJ per kg, in ground	0.00671	kg Sb eq / kg
Raw	Coal, brown, in ground	0.00671	kg Sb eq / kg
Raw	Coal, feedstock, 26.4 MJ per kg	0.0134	kg Sb eq / kg
Raw	Coal, hard	0.0134	kg Sb eq / kg
Raw	Coal, hard, unspecified, in ground	0.0134	kg Sb eq / kg
Raw	Cobalt	2.62E-05	kg Sb eq / kg
Raw	Cobalt, in ground	2.62E-05	kg Sb eq / kg
Raw	Colemanite	0.000117	kg Sb eq / kg
Raw	Colemanite, in ground	0.000117	kg Sb eq / kg
Raw	Copper	0.00194	kg Sb eq / kg
Raw	Copper ore	0.000022	kg Sb eq / kg
Raw	Copper, 0.52% in sulfide, Cu 0.27% and Mo 8.2E-3% in crude ore	0.00194	kg Sb eq / kg
Raw	Copper, 0.59% in sulfide, Cu 0.22% and Mo 8.2E-3% in crude ore	0.00194	kg Sb eq / kg
Raw	Copper, 0.97% in sulfide, Cu 0.36% and Mo 4.1E-2% in crude ore	0.00194	kg Sb eq / kg
Raw	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore	0.00194	kg Sb eq / kg
Raw	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	0.00194	kg Sb eq / kg
Raw	Copper, 1.13% in sulfide, Cu 0.76% and Ni 0.76% in crude ore	0.00194	kg Sb eq / kg
Raw	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore	0.00194	kg Sb eq / kg
Raw	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	0.00194	kg Sb eq / kg
Raw	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore	0.00194	kg Sb eq / kg
Raw	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	0.00194	kg Sb eq / kg
Raw	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore	0.00194	kg Sb eq / kg
Raw	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	0.00194	kg Sb eq / kg
Raw	Copper, Cu 0.38%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Pb 0.014%, in ore	0.00194	kg Sb eq / kg
Raw	Copper, Cu 3.2E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0% in ore	0.00194	kg Sb eq / kg
Raw	Copper, Cu 5.2E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2% in ore	0.00194	kg Sb eq / kg
Raw	Diatomite	1.26E-11	kg Sb eq / kg
Raw	Diatomite, in ground	1.26E-11	kg Sb eq / kg
Raw	Dolomite	1.4E-10	kg Sb eq / kg
Raw	Dolomite, in ground	1.4E-10	kg Sb eq / kg
Raw	Dysprosium	2.13E-06	kg Sb eq / kg
Raw	Energy, from coal	0.000457	kg Sb eq / MJ
Raw	Energy, from coal, brown	0.000671	kg Sb eq / MJ
Raw	Energy, from gas, natural	0.000534	kg Sb eq / MJ
Raw	Energy, from oil	0.00049	kg Sb eq / MJ
Raw	Energy, from sulfur	3.85E-05	kg Sb eq / MJ
Raw	Energy, from uranium	6.36E-09	kg Sb eq / MJ
Raw	Erbium	2.44E-06	kg Sb eq / kg
Raw	Europium	1.33E-05	kg Sb eq / kg
Raw	Fluorine	2.96E-06	kg Sb eq / kg
Raw	Fluorine, 4.5% in apatite, 1% in crude ore, in ground	2.96E-06	kg Sb eq / kg

Abiotic depletion			
Compartment	**Flow Description**	**Factor**	**Unit**
Raw	Fluorine, 4.5% in apatite, 3% in crude ore	2.96E-06	kg Sb eq / kg
Raw	Fluorine, 4.5% in apatite, 3% in crude ore, in ground	2.96E-06	kg Sb eq / kg
Raw	Fluorspar	7.02E-07	kg Sb eq / kg
Raw	Fluorspar, 92%, in ground	7.02E-07	kg Sb eq / kg
Raw	Gadolinium	6.57E-07	kg Sb eq / kg
Raw	Gallium	1.03E-07	kg Sb eq / kg
Raw	Gallium, 0.014% in bauxite, in ground	1.03E-07	kg Sb eq / kg
Raw	Gangue, bauxite, in ground	2.1E-09	kg Sb eq / kg
Raw	Gas, mine, off-gas, process, coal mining/kg	0.0225	kg Sb eq / kg
Raw	Gas, mine, off-gas, process, coal mining/m3	0.0187	kg Sb eq / m3
Raw	Gas, natural, 30.3 MJ per kg	0.0225	kg Sb eq / kg
Raw	Gas, natural, 35 MJ per m3	0.0187	kg Sb eq / m3
Raw	Gas, natural, 36.6 MJ per m3	0.0187	kg Sb eq / m3
Raw	Gas, natural, 36.6 MJ per m3, in ground	0.0187	kg Sb eq / m3
Raw	Gas, natural, 46.8 MJ per kg	0.0225	kg Sb eq / kg
Raw	Gas, natural, 51.3 MJ per kg, in ground	0.0225	kg Sb eq / kg
Raw	Gas, natural, feedstock, 35 MJ per m3	0.0187	kg Sb eq / m3
Raw	Gas, natural, feedstock, 46.8 MJ per kg	0.0225	kg Sb eq / kg
Raw	Gas, natural, in ground	0.0187	kg Sb eq / m3
Raw	Gas, natural/m3	0.0187	kg Sb eq / m3
Raw	Gas, off-gas, oil production	0.0187	kg Sb eq / m3
Raw	Gas, petroleum, 35 MJ per m3	0.0187	kg Sb eq / m3
Raw	Germanium	1.47E-06	kg Sb eq / kg
Raw	Gold	89.5	kg Sb eq / kg
Raw	Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore	89.5	kg Sb eq / kg
Raw	Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground	89.5	kg Sb eq / kg
Raw	Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore	89.5	kg Sb eq / kg
Raw	Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground	89.5	kg Sb eq / kg
Raw	Gold, Au 1.4E-4%, in ore, in ground	89.5	kg Sb eq / kg
Raw	Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore	89.5	kg Sb eq / kg
Raw	Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore, in ground	89.5	kg Sb eq / kg
Raw	Gold, Au 4.3E-4%, in ore	89.5	kg Sb eq / kg
Raw	Gold, Au 4.3E-4%, in ore, in ground	89.5	kg Sb eq / kg
Raw	Gold, Au 4.9E-5%, in ore	89.5	kg Sb eq / kg
Raw	Gold, Au 4.9E-5%, in ore, in ground	89.5	kg Sb eq / kg
Raw	Gold, Au 6.7E-4%, in ore	89.5	kg Sb eq / kg
Raw	Gold, Au 6.7E-4%, in ore, in ground	89.5	kg Sb eq / kg
Raw	Gold, Au 7.1E-4%, in ore	89.5	kg Sb eq / kg
Raw	Gold, Au 7.1E-4%, in ore, in ground	89.5	kg Sb eq / kg
Raw	Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	89.5	kg Sb eq / kg
Raw	Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	89.5	kg Sb eq / kg
Raw	Gypsum	1.55E-05	kg Sb eq / kg
Raw	Gypsum, in ground	1.55E-05	kg Sb eq / kg
Raw	Hafnium	8.67E-07	kg Sb eq / kg
Raw	Helium	148	kg Sb eq / kg
Raw	Holmium	1.33E-05	kg Sb eq / kg
Raw	Indium	0.00903	kg Sb eq / kg
Raw	Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd, in ground	0.00903	kg Sb eq / kg
Raw	Indium, in ground	0.00903	kg Sb eq / kg
Raw	Iodine	0.0427	kg Sb eq / kg
Raw	Iodine, 0.03% in water	0.0427	kg Sb eq / kg
Raw	Iridium	32.3	kg Sb eq / kg
Raw	Iron	8.43E-08	kg Sb eq / kg

Abiotic depletion			
Compartment	**Flow Description**	**Factor**	**Unit**
Raw	Iron ore	4.8E-08	kg Sb eq / kg
Raw	Iron, 46% in ore, 25% in crude ore, in ground	4.8E-08	kg Sb eq / kg
Raw	Kaolinite	2.1E-09	kg Sb eq / kg
Raw	Kaolinite, 24% in crude ore, in ground	2.1E-09	kg Sb eq / kg
Raw	Kieserite	8.31E-05	kg Sb eq / kg
Raw	Kieserite, 25% in crude ore, in ground	8.31E-05	kg Sb eq / kg
Raw	Krypton	20.9	kg Sb eq / kg
Raw	Lanthanum	2.13E-08	kg Sb eq / kg
Raw	Lead	0.0135	kg Sb eq / kg
Raw	Lead ore	0.000677	kg Sb eq / kg
Raw	Lead, Pb 0.014%, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, in ore	0.0135	kg Sb eq / kg
Raw	Lithium	9.23E-06	kg Sb eq / kg
Raw	Lithium, 0.15% in brine, in ground	9.23E-06	kg Sb eq / kg
Raw	Lutetium	7.66E-05	kg Sb eq / kg
Raw	Magnesite	1.07E-09	kg Sb eq / kg
Raw	Magnesite, 60% in crude ore, in ground	1.07E-09	kg Sb eq / kg
Raw	Magnesium	3.73E-09	kg Sb eq / kg
Raw	Manganese	1.38E-05	kg Sb eq / kg
Raw	Manganese ore	6.2E-06	kg Sb eq / kg
Raw	Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	6.2E-06	kg Sb eq / kg
Raw	Mercury	0.495	kg Sb eq / kg
Raw	Molybdenum	0.0317	kg Sb eq / kg
Raw	Molybdenum ore	3.17E-05	kg Sb eq / kg
Raw	Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.016% in sulfide, Mo 8.2E-3% and Cu 0.27% in crude ore, in ground	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.22% in crude ore	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.22% in crude ore, in ground	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	0.0317	kg Sb eq / kg
Raw	Molybdenum, 0.11% in sulfide, Mo 0.41% and Cu 0.36% in crude ore	0.0317	kg Sb eq / kg
Raw	Neodymium	1.94E-17	kg Sb eq / kg
Raw	Neon	0.325	kg Sb eq / kg
Raw	Nickel	0.000108	kg Sb eq / kg
Raw	Nickel ore	1.61E-06	kg Sb eq / kg
Raw	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore	0.000108	kg Sb eq / kg
Raw	Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	0.000108	kg Sb eq / kg
Raw	Nickel, 1.13% in sulfides, 0.76% in crude ore	0.000108	kg Sb eq / kg
Raw	Nickel, 1.98% in silicates, 1.04% in crude ore	0.000108	kg Sb eq / kg
Raw	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	0.000108	kg Sb eq / kg
Raw	Nickel, Ni 2.3E+0%, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Cu 3.2E+0% in ore	0.000108	kg Sb eq / kg
Raw	Nickel, Ni 3.7E-2%, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Cu 5.2E-2% in ore	0.000108	kg Sb eq / kg
Raw	Niobium	2.31E-05	kg Sb eq / kg
Raw	Oil, crude	0.0201	kg Sb eq / kg
Raw	Oil, crude, 38400 MJ per m3	18.4	kg Sb eq / m3

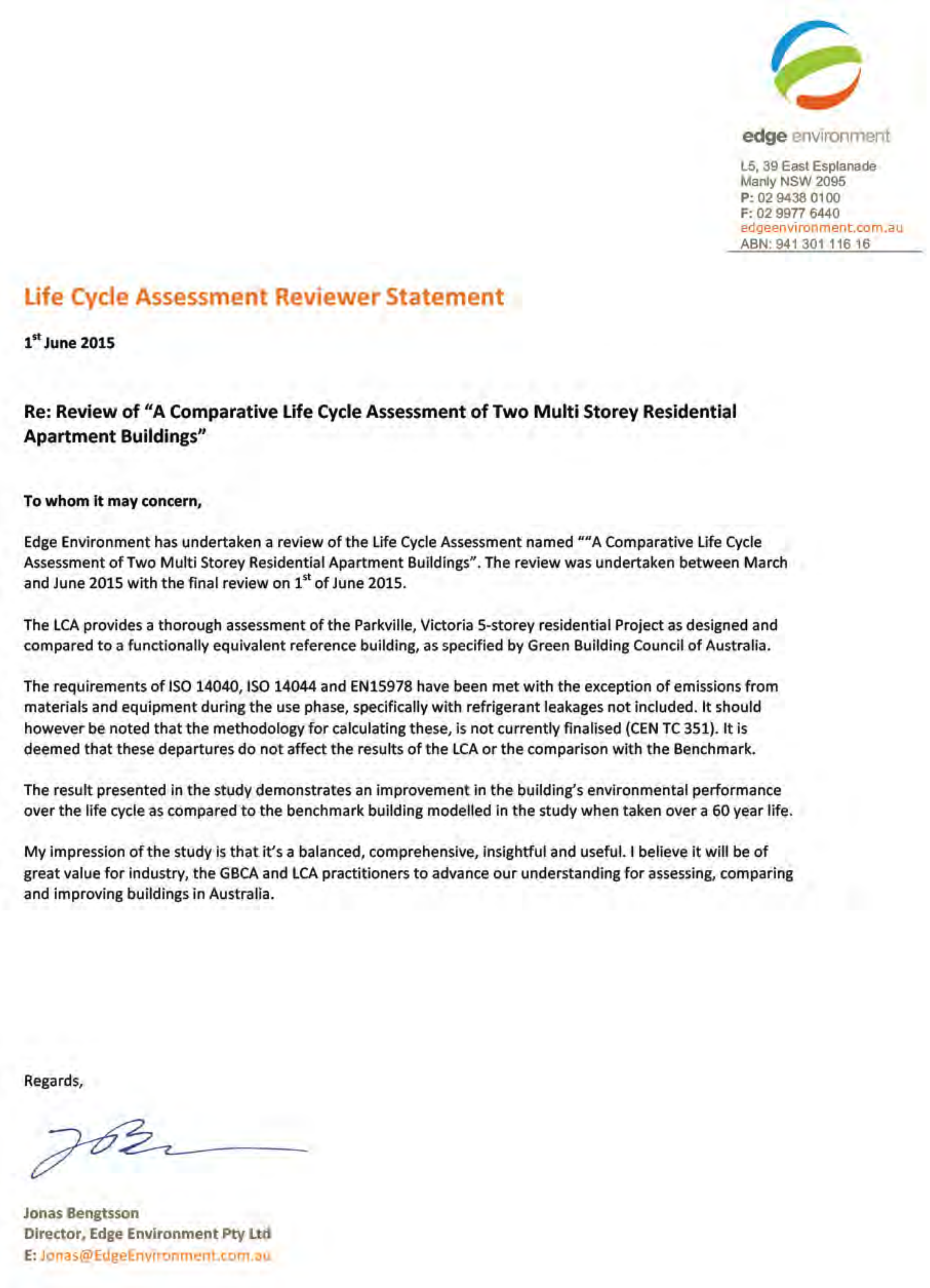
Abiotic depletion			
Compartment	**Flow Description**	**Factor**	**Unit**
Raw	Oil, crude, 41 MJ per kg	0.0201	kg Sb eq / kg
Raw	Oil, crude, 42 MJ per kg	0.0201	kg Sb eq / kg
Raw	Oil, crude, 42 MJ per kg, in ground	0.0201	kg Sb eq / kg
Raw	Oil, crude, 42.6 MJ per kg	0.0201	kg Sb eq / kg
Raw	Oil, crude, 42.7 MJ per kg	0.0201	kg Sb eq / kg
Raw	Oil, crude, 42.7 MJ per kg, in ground	0.0201	kg Sb eq / kg
Raw	Oil, crude, feedstock, 41 MJ per kg	0.0201	kg Sb eq / kg
Raw	Oil, crude, feedstock, 42 MJ per kg	0.0201	kg Sb eq / kg
Raw	Oil, crude, in ground	0.0201	kg Sb eq / kg
Raw	Osmium	14.4	kg Sb eq / kg
Raw	Palladium	0.323	kg Sb eq / kg
Raw	Palladium, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	0.323	kg Sb eq / kg
Raw	Palladium, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	0.323	kg Sb eq / kg
Raw	Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	0.323	kg Sb eq / kg
Raw	Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	0.323	kg Sb eq / kg
Raw	PGM, 4.7E-4% Pt, 3.1E-4% Pd, 0.2E-4% Rh, in crude ore	1.69	kg Sb eq / kg
Raw	Phosphorus	8.44E-05	kg Sb eq / kg
Raw	Phosphorus, 18% in apatite, 4% in crude ore	8.44E-05	kg Sb eq / kg
Raw	Platinum	1.29	kg Sb eq / kg
Raw	Platinum, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore	1.29	kg Sb eq / kg
Raw	Platinum, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore	1.29	kg Sb eq / kg
Raw	Polonium	4.79E+14	kg Sb eq / kg
Raw	Potassium	3.13E-08	kg Sb eq / kg
Raw	Potassium chloride	2.31E-08	kg Sb eq / kg
Raw	Praseodymium	2.85E-07	kg Sb eq / kg
Raw	Protactinium	9770000	kg Sb eq / kg
Raw	Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	1.29	kg Sb eq / kg
Raw	Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	1.29	kg Sb eq / kg
Raw	Pyrite	0.000131	kg Sb eq / kg
Raw	Pyrolusite	8.69E-06	kg Sb eq / kg
Raw	Radium	23600000	kg Sb eq / kg
Raw	Radon	1.2E+20	kg Sb eq / kg
Raw	Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	32.3	kg Sb eq / kg
Raw	Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	32.3	kg Sb eq / kg
Raw	Rhenium	0.766	kg Sb eq / kg
Raw	Rhodium	32.3	kg Sb eq / kg
Raw	Rhodium, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore	32.3	kg Sb eq / kg
Raw	Rhodium, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore	32.3	kg Sb eq / kg
Raw	Rubidium	2.36E-09	kg Sb eq / kg
Raw	Ruthenium	32.3	kg Sb eq / kg
Raw	Rutile	2.64E-08	kg Sb eq / kg
Raw	Rutile, in ground	2.64E-08	kg Sb eq / kg
Raw	Samarium	5.32E-07	kg Sb eq / kg
Raw	Scandium	3.96E-08	kg Sb eq / kg
Raw	Selenium	0.475	kg Sb eq / kg
Raw	Silicon	2.99E-11	kg Sb eq / kg
Raw	Silver	1.84	kg Sb eq / kg
Raw	Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In	1.84	kg Sb eq / kg

Abiotic depletion

Compartment	Flow Description	Factor	Unit
Raw	Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In, in ground	1.84	kg Sb eq / kg
Raw	Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore	1.84	kg Sb eq / kg
Raw	Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore, in ground	1.84	kg Sb eq / kg
Raw	Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore	1.84	kg Sb eq / kg
Raw	Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground	1.84	kg Sb eq / kg
Raw	Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore	1.84	kg Sb eq / kg
Raw	Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground	1.84	kg Sb eq / kg
Raw	Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore	1.84	kg Sb eq / kg
Raw	Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore, in ground	1.84	kg Sb eq / kg
Raw	Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore	1.84	kg Sb eq / kg
Raw	Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	1.84	kg Sb eq / kg
Raw	Sodium	8.24E-11	kg Sb eq / kg
Raw	Sodium chloride	2.95E-08	kg Sb eq / kg
Raw	Sodium chloride, in ground	2.95E-08	kg Sb eq / kg
Raw	Sodium nitrate	2.23E-11	kg Sb eq / kg
Raw	Sodium nitrate, in ground	2.23E-11	kg Sb eq / kg
Raw	Sodium sulfate	0.000081	kg Sb eq / kg
Raw	Sodium sulphate	0.000081	kg Sb eq / kg
Raw	Sodium sulphate, various forms, in ground	0.000081	kg Sb eq / kg
Raw	Spodumene	3.46E-07	kg Sb eq / kg
Raw	Stibnite	0.779	kg Sb eq / kg
Raw	Stibnite, in ground	0.779	kg Sb eq / kg
Raw	Strontium	1.12E-06	kg Sb eq / kg
Raw	Sulfur	0.000358	kg Sb eq / kg
Raw	Sulfur, in ground	0.000358	kg Sb eq / kg
Raw	Talc	7.25E-10	kg Sb eq / kg
Raw	Talc, in ground	7.25E-10	kg Sb eq / kg
Raw	Tantalum	6.77E-05	kg Sb eq / kg
Raw	Tantalum, in ground	6.77E-05	kg Sb eq / kg
Raw	Tellurium	52.8	kg Sb eq / kg
Raw	Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag, in crude ore, in ground	52.8	kg Sb eq / kg
Raw	Terbium	2.36E-05	kg Sb eq / kg
Raw	Thallium	5.05E-05	kg Sb eq / kg
Raw	Thorium	2.08E-07	kg Sb eq / kg
Raw	Thulium	8.31E-05	kg Sb eq / kg
Raw	Tin	0.033	kg Sb eq / kg
Raw	Tin ore	3.3E-06	kg Sb eq / kg
Raw	Tin, 79% in cassiterite, 0.1% in crude ore, in ground	3.3E-06	kg Sb eq / kg
Raw	TiO2, 45-60% in Ilmenite	2.64E-08	kg Sb eq / kg
Raw	TiO2, 54% in ilmenite, 18% in crude ore	2.64E-08	kg Sb eq / kg
Raw	TiO2, 54% in ilmenite, 2.6% in crude ore	2.64E-08	kg Sb eq / kg
Raw	TiO2, 54% in ilmenite, 2.6% in crude ore, in ground	2.64E-08	kg Sb eq / kg
Raw	TiO2, 95% in rutile, 0.40% in crude ore	2.64E-08	kg Sb eq / kg
Raw	TiO2, 95% in rutile, 0.40% in crude ore, in ground	2.64E-08	kg Sb eq / kg
Raw	Titanium	4.4E-08	kg Sb eq / kg
Raw	Tungsten	0.0117	kg Sb eq / kg
Raw	Ulexite	0.000803	kg Sb eq / kg
Raw	Ulexite, in ground	0.000803	kg Sb eq / kg
Raw	Uranium	0.00287	kg Sb eq / kg
Raw	Uranium ore, 1.11 GJ per kg	1.15E-05	kg Sb eq / kg
Raw	Uranium, 2291 GJ per kg	0.00287	kg Sb eq / kg
Raw	Uranium, 451 GJ per kg	0.00287	kg Sb eq / kg

Abiotic depletion			
Compartment	**Flow Description**	**Factor**	**Unit**
Raw	Uranium, 560 GJ per kg	0.00287	kg Sb eq / kg
Raw	Uranium, in ground	0.000803	kg Sb eq / kg
Raw	Vanadium	1.16E-06	kg Sb eq / kg
Raw	Xenon	17500	kg Sb eq / kg
Raw	Ytterbium	2.13E-06	kg Sb eq / kg
Raw	Yttrium	3.34E-07	kg Sb eq / kg
Raw	Zinc	0.000992	kg Sb eq / kg
Raw	Zinc 9%, in sulfide, Zn 5.34% and Pb 2.97% in crude ore, in ground	0.000992	kg Sb eq / kg
Raw	Zinc 9%, Lead 5%, in sulfide	0.000992	kg Sb eq / kg
Raw	Zinc ore	3.95E-05	kg Sb eq / kg
Raw	Zinc, Zn 0.63%, Au 9.7E-4%, Ag 9.7E-4%, Cu 0.38%, Pb 0.014%, in ore	0.000992	kg Sb eq / kg
Raw	Zirconia	1.37E-05	kg Sb eq / kg
Raw	Zirconium	1.86E-05	kg Sb eq / kg
Raw	Zirconium, 50% in zircon, 0.39% in crude ore, in ground	1.86E-05	kg Sb eq / kg

Appendix E Peer reviewer remarks



edge environment
L5, 39 East Esplanade
Manly NSW 2095
P: 02 9438 0100
F: 02 9977 6440
edgeenvironment.com.au
ABN: 941 301 116 16

Life Cycle Assessment Reviewer Statement

1st June 2015

Re: Review of "A Comparative Life Cycle Assessment of Two Multi Storey Residential Apartment Buildings"

To whom it may concern,

Edge Environment has undertaken a review of the Life Cycle Assessment named ""A Comparative Life Cycle Assessment of Two Multi Storey Residential Apartment Buildings". The review was undertaken between March and June 2015 with the final review on 1st of June 2015.

The LCA provides a thorough assessment of the Parkville, Victoria 5-storey residential Project as designed and compared to a functionally equivalent reference building, as specified by Green Building Council of Australia.

The requirements of ISO 14040, ISO 14044 and EN15978 have been met with the exception of emissions from materials and equipment during the use phase, specifically with refrigerant leakages not included. It should however be noted that the methodology for calculating these, is not currently finalised (CEN TC 351). It is deemed that these departures do not affect the results of the LCA or the comparison with the Benchmark.

The result presented in the study demonstrates an improvement in the building's environmental performance over the life cycle as compared to the benchmark building modelled in the study when taken over a 60 year life.

My impression of the study is that it's a balanced, comprehensive, insightful and useful. I believe it will be of great value for industry, the GBCA and LCA practitioners to advance our understanding for assessing, comparing and improving buildings in Australia.

Regards,

Jonas Bengtsson
Director, Edge Environment Pty Ltd
E: Jonas@EdgeEnvironment.com.au

A Comparative Life Cycle Assessment of Two Multi Storey Residential Apartment Buildings– LCA Peer Review Comments and Statements

Introduction

"A Comparative Life Cycle Assessment of Two Multi Storey Residential Apartment Buildings" LCA report, commissioned by Australand Property Group and Forest and Wood Products Australia (FWPA), completed by Andrew Carre and Dr. Enda Crossin of RMIT, was submitted to Jonas Bengtsson of Edge Environment (Edge) for peer review on the 2nd of March 2015. The peer review comments were then sent to RMIT on 20th of March 2015 and a teleconference to discuss the report took place on the 20th of March 2015 with Andrew and Jonas. Required revisions were then made to the LCA model and report as noted in Table 1 below. Final discussions between Jonas and Andrew took place between the 22nd of April and the 29th of May to finalise revisions and the presentation of carbon storage results between the Study Building and the Forte building.

Edge has been commissioned to review the LCA undertaken by RMIT to determine its compliance with ISO 14044 standard (International Organisation for Standardisation 2006) and the requirements set in the Material Life Cycle Impacts section of GBCA's Green Star rating tool. For the credit requirements to be met, an LCA must be completed in compliance with the building scope set out in the EN 15978 standards for the assessment of the environmental performance of buildings (Technical Committee CEN/TC 350 2011).

This review is undertaken primarily against ISO 14044 with some reference to EN 15978, and with a specific focus on the requirements set by the GBCA. The aim is for the review to determine if the LCA undertaken is sufficient to demonstrate the environmental performance benefits claimed within the report given the upstream data used, the methodologies applied and the documentation provided.

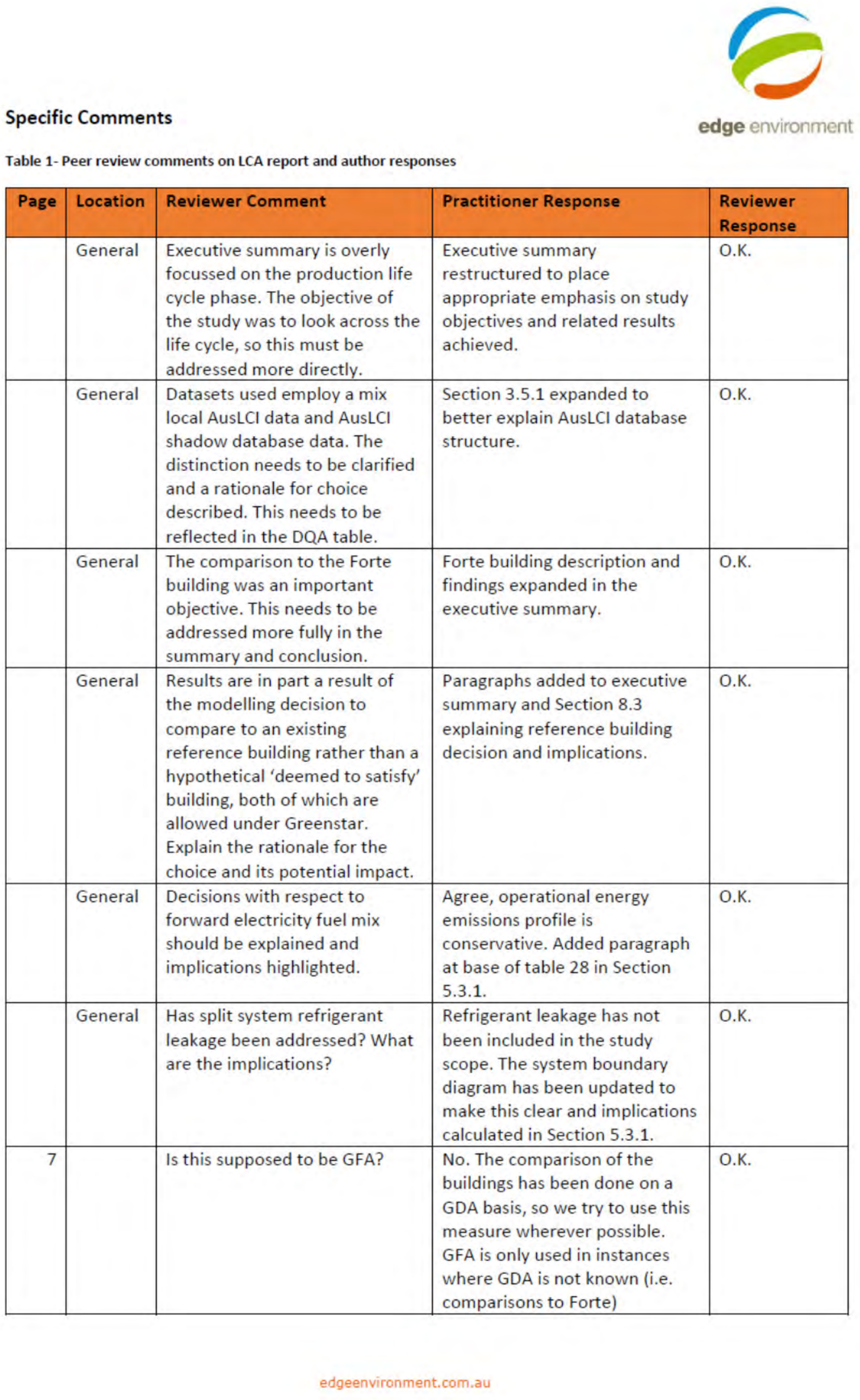
General Comments

The primary aim of the LCA is the demonstration of the benefits of the building as designed when compared to the benchmark and this report achieves this. It is well structured and for the most part had the appropriate level of detail.

The information reported in the report provided by RMIT appears to be robust and to have followed the methodology required by GBCA in the context of Green Star.

The LCA demonstrates improvement from the benchmark building, through improvement at the product and other stages. The materials in construction are quite different however this doesn't translate into many points using the Green Star methodology.

The analysis provides a number of improvement options, which add value to the LCA as do the sensitivity analysis.



Specific Comments

Table 1- Peer review comments on LCA report and author responses

Page	Location	Reviewer Comment	Practitioner Response	Reviewer Response
	General	Executive summary is overly focussed on the production life cycle phase. The objective of the study was to look across the life cycle, so this must be addressed more directly.	Executive summary restructured to place appropriate emphasis on study objectives and related results achieved.	O.K.
	General	Datasets used employ a mix local AusLCI data and AusLCI shadow database data. The distinction needs to be clarified and a rationale for choice described. This needs to be reflected in the DQA table.	Section 3.5.1 expanded to better explain AusLCI database structure.	O.K.
	General	The comparison to the Forte building was an important objective. This needs to be addressed more fully in the summary and conclusion.	Forte building description and findings expanded in the executive summary.	O.K.
	General	Results are in part a result of the modelling decision to compare to an existing reference building rather than a hypothetical 'deemed to satisfy' building, both of which are allowed under Greenstar. Explain the rationale for the choice and its potential impact.	Paragraphs added to executive summary and Section 8.3 explaining reference building decision and implications.	O.K.
	General	Decisions with respect to forward electricity fuel mix should be explained and implications highlighted.	Agree, operational energy emissions profile is conservative. Added paragraph at base of table 28 in Section 5.3.1.	O.K.
	General	Has split system refrigerant leakage been addressed? What are the implications?	Refrigerant leakage has not been included in the study scope. The system boundary diagram has been updated to make this clear and implications calculated in Section 5.3.1.	O.K.
7		Is this supposed to be GFA?	No. The comparison of the buildings has been done on a GDA basis, so we try to use this measure wherever possible. GFA is only used in instances where GDA is not known (i.e. comparisons to Forte)	O.K.

Page	Location	Reviewer Comment	Practitioner Response	Reviewer Response
7		... and parts of EN15978 as per the Green Star innovation credit, especially for building scope definition?	Agree this was unclear. Have added methodology explanation to exec sum and expanded methodology explanation in the body of the report.	O.K.
7		GFA?	No. GDA is primary functional measure throughout report. GBCA method requires this.	O.K.
8		Update table number?	Corrected.	O.K.
8		From a Green Star / GBCA perspective, this is not a consideration. It would be great if the method/framework you used can be brought to the GBCA for consideration.	Agree. We think there is a good opportunity here. To be clear we have added a sentence prior to table 5 making the point that results are included even though they are uncertain.	O.K.
8		Is this only due to the mass of the construction or is it also influenced by using lower impact materials. It's probably a combination.	It is a combined outcome. We have reworded the sentence to make this clear.	O.K.
8		This is potentially misleading to present partial LCA results, when this is read from a Green Star innovation credit perspective. I would recommend making it clear that this graph is not aligned with Green Star.	We have restructured the executive summary to address the study objectives in sequence. The new presentation seeks to delineate the LCA findings from the Green Star calculation.	O.K.
9		Perhaps a quick introduction, location, storeys, floor area, use.	Agree. Have added table 4 to exec sum and description.	O.K.
9		Check number	Figure number corrected.	O.K.
9		It seems from the results in Figure 2, it may be more than just the building mass? Was lower impact materials used? Local procurement? I recall Forte used imported timber products from Austria.	We have reviewed the Forte calculation and corrected an error in the GFA for the building. Comparison shown employs reported impacts per unit GFA. Forte does have a significant transport footprint, but so does the Study Building, so the difference is not so clear in this regard.	O.K.
9		Why was this?	The operational energy estimate for heating and cooling employed Apace Sim for	O.K.

Page	Location	Reviewer Comment	Practitioner Response	Reviewer Response
			podium spaces and NatHERS for apartments. It also employed different HVAC system efficiencies. Hot water was not modelled in the Forte study either. In all it was considered too difficult to fairly compare the two approaches. We have added a footnote to this effect in Exec sum and Section 8.2.	
9		It should be made clear that this comparison, although perhaps what Green Star really want to compare, is not related to the Green Star credit.	Agree. Table title amended and text below.	O.K.
9		It would be good to see in the Summary the contribution from each life cycle stage, e.g. embodied v.s. operational.	Yes. Have included in exec sum and Section 8.1.2	O.K.
9		Did you consider calculating the additional impact categories as well, or what was the reason not to?	The additional impact categories were outside the scope of the original proposal. We wanted to be able to go into some depth when analysing the inventory and didn't feel I could do that across a wide range of indicators.	O.K.
9		Agree, but we interpret this as an error in the table in the Green Star credit. Perhaps worth a call to the GBCA to clarify...	Indeed. We have recalculated the difference based on the stated aim of the credit in the guidance text. The example calculation provided by GBCA must be an error.	O.K.
9		Check number	Figure corrected.	O.K.
10		More so than what you typically have to cope with for a similar LCA?	Agree. The statement adds little value. Deleted.	O.K.
10		Perhaps too strongly worded as the uncertainty was only 80% compared to 90% on the other impacts.	Yes. This wording related to earlier calculations. Updated.	O.K.
10		Perhaps also mention that the development of the fuel matrix for grid electricity and in-building technology efficiencies will significantly influence the	Yes. Some discussion added to Section 5.3.1 and to limitations.	O.K.

Page	Location	Reviewer Comment	Practitioner Response	Reviewer Response
		impact from energy use over the life of the building.		
10		Perhaps make a point that the EN15978 standard provide guidance for how to deal with this in a consistent manner.	Agree. Line added.	O.K.
12		Perhaps a brief description, as requested in the summary.	Added brief intro to Forte. We have tried to separate the forte analysis from the core comparative LCA, as it was undertaken using different methods. For this reason the description in this section is limited.	O.K.
17		What does the astrix following "Construction installation process" refer to?	It should not be there. Removed.	O.K.
17		It's probably fair to say it's also arguably immaterial for a building assessed over 60 years.	Agree.	O.K.
17		Nice	Ha. Thanks ☺	O.K.
17		remove	Removed.	O.K.
18		Agree		O.K.
19		No need to use ecoinvent or the AusLCI shadow database?	The section below figure 11 has been re-written. Shadow data based on Eco invent has been used extensively.	O.K.
19		I'm surprised Australand wasn't able to provide a BoQ in Excel format. Perhaps it was too early in the project stage? Please elaborate on why the BoQ was derived from the drawings. As you mention, this increases uncertainty.	Tabulated elemental BOQ data was not available for the Study Building, nor the Reference Building. Both buildings were in construction at the time of writing.	O.K.
21		I wonder if the EN15978 and EN15804 approach is strictly ISO14044 compliant in that sense?	Although usually debatable, I think the EN standards are still compliant. The ISO hierarchy for allocation allows for a range of responses and all EN seems to be doing is trying to classify where reporting takes place.	O.K.
22		Good we're aligned...	Long term (1000 year plus) storage of carbon in landfill seems theoretically possible, but practically unlikely. It is unlikely to ever be widely	O.K.

Page	Location	Reviewer Comment	Practitioner Response	Reviewer Response
			accepted as a form of sequestration in my view.	
25		end bracket	Corrected.	O.K.
25		Some of this, obviously not all, could be explained by the reference building having 3 more storeys.	As the stories are added the area of the building will increase so the weight to floor ration should remain reasonably stable. The height does drive up structural requirements and foundation size, however I'd argue the rate at which that increase is happening is due to the massive nature of the building material system. A light-weight building's mass efficiency would not be as sensitive to building height.	O.K.
26		This is a very interesting and insightful section. However, it should probably be acknowledged and clarified upfront that most of the AusLCI data references relate to the shadow database, which of course is ecoinvent v2.2 data crudely adapted for use in Australia. When compared with true native sources it's not necessarily an apple and apples comparison.	Agree. We have attempted to make this clear at the start of the Section 5.1.3.	O.K.
27		Also, the BPIC/CMAA data includes less emissions than what is reported by the cement and concrete industry through the NPI, so it's less complete.	Indeed.	O.K.
28		I would have thought this was the very lowest density of softwood and hardwood. Perhaps the density assumption plays in, higher density would lead to lower GWP if the inventory is per m3...	Agree. Timber inventories reported per kg are difficult to compare to cubic inventories. Species and moisture could well have been different across the studies surveyed by Hammond and Jones.	O.K.
29				
33		Did the drawing provide measurements n 3D? The thickness and depth of aluminium frames would	Capral 400 series or similar was specified. We used a cross section through this to estimate	O.K.

Page	Location	Reviewer Comment	Practitioner Response	Reviewer Response
		obviously make a big difference on the total volume/amount required.	aluminium mass per metre perimeter.	
35		Minor point, but I would argue that the construction energy should be filled with some reasonable estimates or literature. This since otherwise the Green Star % comparison would falter a bit.	Agree with the sentiment, and I have done this in the past. Reasonable studies for site construction energy exist for North America, but they tend to be for commercial buildings and contain climate related energy such as heating for curing concrete. We formed the view that US estimates were likely to overstate construction energy significantly. More work need to be done in this area.	O.K.
35		75km average?	Added para under table 24 explaining average distances.	O.K.
35		50km average?	Added para under table 24 explaining average distances.	O.K.
36		Table 6 says no metal is wasted during construction.	Metals removed from table.	O.K.
38		compared to production of virgin products and materials	Amended sentence in Section 5.5.	O.K.
39		Per m2 GDA	Added text second para of Section 5.6	O.K.
41		Although the data quality may be good overall, it needs to be considered throughout that when the AusLCI shadow database is used, it's European data fundamentally. We cannot know, as far as I'm aware, how well this relates to Australian conditions.\rI would suggest this be reflected in the Pedigree Matrix under Geographical Correlation.	We have classified each data set's geography in the DQA table and updated the descriptive paragraph. Data pedigree has been reviewed and is believed to be appropriate to the geography noted in the DQA table. As mentioned earlier in the report, the uncertainty analysis does not assess uncertainty associated with modelling decisions employing international data in place of local data, so underestimates the total uncertainty. The DQA table attempts to compensate for this, at least in part.	O.K.
41		Are there any comments to be offered regarding substances not assessed in the study. It's	Added section on non-assessed substance checks completed at base of Section 5.8.	O.K.

Page	Location	Reviewer Comment	Practitioner Response	Reviewer Response
		obviously tough, but do the authors have any observations on what might have been missed with the used LCIA methods?		
43		It would be helpful to see this graph with each life cycle stage broken out.	Agree. Added graphs in Section 8.1.2	O.K.
43		What's driving ozone depl.? Is it a significant impact, say using normalisation?		O.K.
43		It would be useful to see this graph with main contributing materials. Perhaps supplementary pie charts?	Graphs are presented in Section 8.1.2	O.K.
46		Better than using actual BoQ?	Restated paragraph. Detailed BOQ data was not available for the buildings so estimates had to be developed from drawings	O.K.
46		Or use project BoQ?	As above.	O.K.
47		Ah, that's what the earlier comment related to.	Rephrased. Approach taken is the best of those available.	O.K.
52		Although largely excluded from the study	Not largely. Inbound transport and excavation are a big chunk of construction. Added parenthetical to section 7.6 to remind reader on-site excluded.	O.K.
55		What methodology please.	Footnoted.	O.K.
57		Yes, but according to the credit you can scale back energy to BCA compliance. Granted this is then more an energy credit than material, and thus missing the point.	Agree. Have added commentary highlighting this	O.K.