Quantifying the embodied carbon cost from demolitions following the Canterbury Earthquakes

R.E. Gonzalez, M.T. Stephens, C.L Toma & K.J. Elwood
The University of Auckland, Auckland.

D. Dowdell
Building Research Association of New Zealand, Porirua.

ABSTRACT

The 2010/2011 Canterbury Earthquake Sequence resulted in severe financial loss, loss of life and disruption in Christchurch due to liquefaction and damage from strong shaking, which led to the widespread displacement of people and business as well as a large number of building demolitions in the central business district. Several studies have since evaluated the prevailing factors which influenced demolition decision making, revealing that environmental impacts were not a direct consideration. To begin to make the case for incorporating environmental factors in designing buildings to resist earthquakes, this research is focused on quantifying the embodied carbon loss from the demolition of buildings following earthquake damage using Christchurch as a case study. A building data set consisting of 142 RC (reinforced concrete) buildings that were demolished following the earthquake was used to quantify the environmental impacts of the decision making. The quantification of embodied carbon was broken into three distinct modules, (1) embodied CO_2 and energy in the building materials, (2) CO_2 emissions of the processes used in construction of the building, and (3) CO_2 emissions of the transport and waste management processes. A material take-off model was used to estimate material quantities across the building set. First, a lifecycle assessment tool was used to calculate the impact in the first and second module. Second, the spatial distribution of the waste generation was defined to determine transportation distance. Finally, the impact of the demolition process, waste disposal and possible benefits of recycling are considered. The results revealed the demolitions had staggering impacts in terms of CO_2 and energy.

1 INTRODUCTION

The building sector has a significant impact on the environment worldwide (Abergel et al. 2018; OECD 2003). In New Zealand, from the greenhouse gas inventory in 2016, the build sector's contribution reached

20 per cent from the consumer-view perspective (Thinkstep 2018). The 2010/2011 Canterbury Sequence caused severe financial loss (20% of New Zealand GDP) and 185 fatalities (Parker and Steenkamp 2012). The event caused significant damage resulting in the demolition of around 1,400 commercial and 7,500 residential properties (Brown and Milke 2016). It is estimated that around 8 million tonnes of debris from demolition and reconstruction works was generated (Milke 2011). The work from Kim et al. (2017) and Marquis et al. (2017) studied factors that influenced the demolition of multi-story buildings in Christchurch. However, environmental considerations were not discussed in the consideration of whether a building was repaired or demolished. The aim of this paper is to present a case study regarding building demolition in a post-earthquake condition for a New Zealand context. Results are presented in term of an estimation of the environmental impact of demolition of part of the building stock after a seismic event to highlight the importance of environmental consideration due to seismic hazards.

This papers first gives an overview of studies about environmental impact of buildings from a New Zealand perspective. Next, a framework to evaluate the environmental impact of buildings in post-earthquake conditions is presented. Finally, the results of the case study covering 223 buildings within Christchurch Central Business District (CBD) are discussed. At this stage only the post-earthquake damage and demolition of buildings is presented, without consideration of repairs due to the complexity of repair strategies.

2 TRADITIONAL LIFE CYCLE ASSESSMENT OF NEW ZEALAND BUILDINGS

New Zealand aims to limit its greenhouses gases to net-zero by 2050 (New Zealand Parliament and New Zealand Government 2019), legislated through the Zero Carbon Amendment Act. The Ministry of Business, Innovation & Employment (MBIE) has released The Building for Climate Change program which proposes to implement a cap of carbon emissions in both the operational and embodied carbon groups (MBIE 2020a, 2020b, 2020c). Regarding environmental analysis, the most accepted methodology to estimate the environmental impact of a building is the Life Cycle Assessment(LCA) method (Bahramian and Yetilmezsoy 2020). The LCA for buildings is addressed in European standards (BSI 2010, 2011, 2012, 2019). The traditional LCA incorporates the following modules: the production stage (A1-A3), the construction stage (A4-A5), use stage (B1-B7), end of life stage (C1-C4), and benefits beyond the system boundary(D) (BSI 2011). The aim is to evaluate the environmental performance of a building in terms of environmental impact categories (e.g. CO_2 emissions, energy, eutrophication).

In New Zealand, several studies have been carried out considering the traditional LCA assessment. Berg, Dowdell, and Curtis (2016b) and Thinkstep (2019) provided reference buildings in New Zealand. Chandrakumar et al. (2020) studied the environmental impact of typical New Zealand housing and limits to meet the global climate target. Ghose et al. (2020) and Ghose, Pizzol, et al. (2017) focus on energy efficiency refurbishments on New Zealand office buildings. Buchanan et al. (2012) compared carbon emission of materials used in hypothetical alternative designs for a building. While some research has been carried out on traditional LCA stages, no previous study has investigated the environmental impact of demolition buildings in post-earthquake conditions in New Zealand.

3 METHODOLOGY

3.1 General framework to consider environmental impact

For assessing the environmental impact of demolishing buildings in a post-earthquake condition, the framework has been divided into three modules: (1) production of materials (A1-A3), (2) transport and construction process (A4-A5), (3) waste management in post-earthquake conditions (Figure 1). Module 1 involves the raw material supply, the transport of materials, and manufacturing process of construction materials. Module 2 includes the transport to the supply place to the construction site and construction and installation process. Module 3 considers demolition of structural components, temporary storage site, and end-of-life condition (Recycling, Landfill or Reclamation). As it has been noted by Brown and Milke (2016), the high quantity of debris produced affected the traditional flow of debris until it reached the final destination. It was necessary to operate a temporary storage site to support the overall recovery process into the disaster area. This module can vary depending on waste composition, disaster severity, waste management policies and debris waste composition.

To estimate environmental impacts, a life cycle inventory data (LCI) is required. A LCI amalgamated emission for a specific process (e.g. production of a kg of reinforcement steel) considers the resources used and energy consumed into environmental impacts (e.g. CO_2,energy) (Simonen 2014). The fidelity and methods underlying these environmental impact inventories, with particular respect to geographical and time representatives, are important because uncertainties can be reduced with a high quality and local inventory. Ghose, McLaren, et al. (2017) noticed a lack of country-specific data for life cycle inventory data in New Zealand. Transport distance can be calculated with the spatial waste distribution (if available).

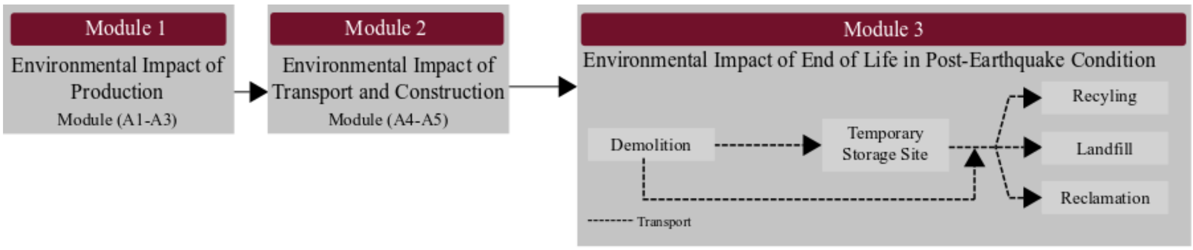


Figure 1: General Framework to calculate environmental impact of demolishing building in post-earthquake conditions.

3.2 Case study

The case study contains 223 reinforced concrete buildings. The buildings were located in CBD Christchurch within four avenues (Deans, Bealey, Fitzgerald, and Moorhouse) (refer to Figure 3). The CBD contains approximately 110 city blocks into an area of 600 hectares. The building data set represents approximately 88% of all the reinforced concrete building with more than three stories in the CBD (Kim et al. 2017).

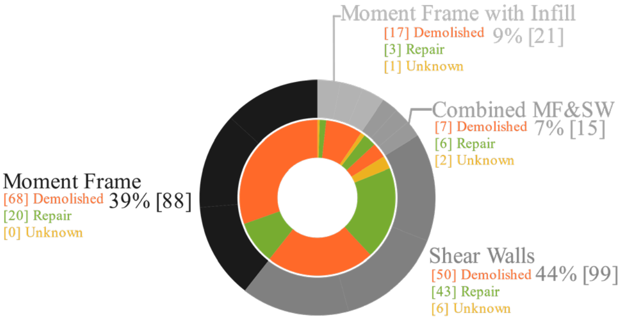


Figure 2: Lateral Load Resisting System Demolition Statistics for Building Data Set

Figure 2 shows the different lateral load resisting systems within the complete data set. Within the data base, 39% correspond to Moment Frame (MF), 44% to Shear Walls (SW), 7% to Combined MF&SW, and 9% Moment Frame with Infill. Up to date, 142 of the total buildings were demolished, 72 were repaired, and 9 are considered no action/unresolved. Within the demolished buildings comprises 68 (48%) MF buildings, 50 (35%) SW buildings, 7 (5%) Combined MF&SW buildings, and 17 (12%) MF with Infill buildings. It is interesting to note that the percentage of demolished MF building is 77% whereas demolished SW buildings correspond to 50% in their categories.

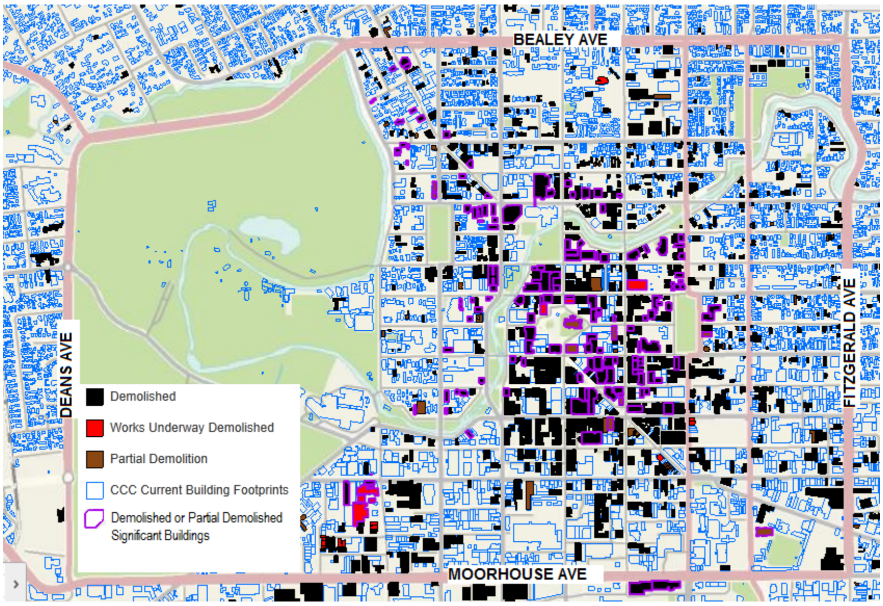


Figure 3: Overview of Demolished Buildings in Christchurch CBD (Reproduced from (Marquis et al. 2017))

To calculate the environmental impact, it is necessary to estimate the quantity of structural and non-structural materials. For structural components, a take-off model was developed. The non-structural components were assumed values from the literature. This is described in the following section. The structural components considered are in-situ concrete foundations, beams, columns and shear walls, precast elements, and reinforced and unreinforced masonry walls. Within the building data set, a subset of 12 buildings with a complete set of structural drawing to develop a material take-off model was selected. The quantity of materials in each building was used to identify the occurrence of the different structural characteristics, namely foundation types, structural walls, pre-cast components (panels, beams, columns), and floor systems. The model considers that different elements (e.g. foundations, beams, columns) contain different volumetric reinforced ratio (ρ_v). The model was fit based on Equation (1).

$$W_{mat} = A \times GFA + B \tag{1}$$

where A, B = coefficients summarised in Table 1; and GFA = Ground Floor Area in m^2.

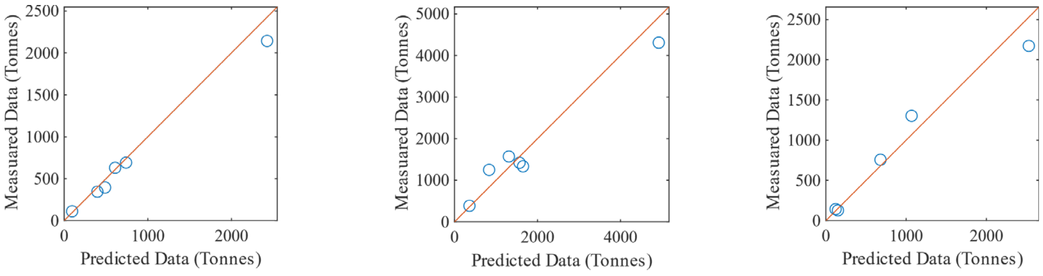
Table 1: Regression Coefficients for Equation 1.

Condition	**A**	**B**
Spread Foundation (in-situ, $\rho_v = 1\%$)	0.205	-29.22
Raft Foundation (in-situ, $\rho_v = 1\%$)	0.118	221.23
Pile Cap (in-situ, $\rho_v = 1\%$)	0.140	17.37
Beams, Columns and Shear Walls in Building with Structural Walls (in-situ, $\rho_v = 1.5\%$)	0.175	-13.09
Beams, Columns and Shear Walls in Building with Structural Walls and Precast elements (in-situ, $\rho_v = 1.5\%$)	0.063	0
Beams and Columns in Buildings without Structural Walls	0.165	2.85

Panels (precast)	0.045	0
Beams or Columns (precast)	0.060	0
Walls (with precast panels)	0.029	100.55
Walls (without precast panels)	0.116	-13.03
Precast Floor Category A* (ρ_v =1%)	0.162	0
In-situ Floor Category A* (ρ_v = 1.5%)	0.191	0
Precast Floor Category B** (ρ_v =1%)	0.218	0
In-situ Floor Category B** (ρ_v = 1.5%)	0.152	0
In-situ Floor Category C*** (ρ_v = 1.5%)	0.325	0
In-situ Floor Category D**** (ρ_v = 1.5%)	0.413	0

*Category A (Rib&Infill and Double T)
**Category B (Unispan and Hollow Core)
***Category C (Steel Deck)
****Category D (Solid Slab)

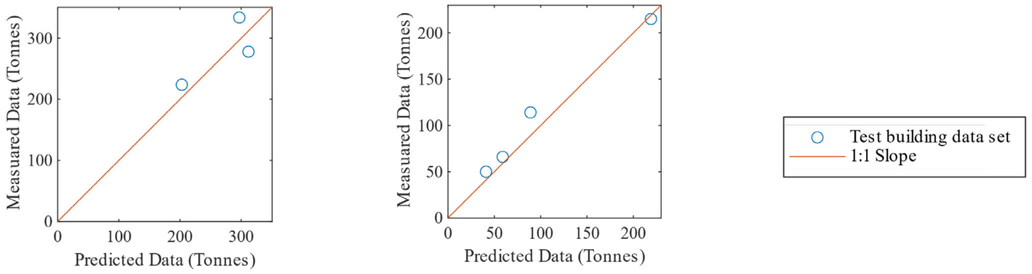
The take-off model was validated with a different subset of six buildings. Six BIM models were developed to obtain the quantity of materials. The error between the take-off model and exact values are between 7-8% for individual components (foundations, beams, columns, etc.). The error for the total weight is 5%. Figure 4 illustrates the accuracy of the take-off model.



a) Foundations

b) Beams, Columns, Shear Wall, and Insitu Slabs

c) Precast Concrete (Slabs&Panels)



d) Precast Concrete (Beams&Columns)

e) Walls

Figure 4: Take-off model compared to BIM models

The take-off model was applied to the entire building data set to obtain the quantity of structural concrete and masonry component materials. The model estimates 592 kilo tonnes of building materials from 142 demolished buildings from the case study. This value corresponds to only values from elements calculated from the take-off model. The breakdown of the building materials is 18% to substructure (in-situ concrete with 1% reinforced ratio) , 82% to superstructure (60% to in-situ concrete with 1.5% reinforced ratio, 17% to precast concrete with 1-1.5% reinforced ratio, and 5% to unreinforced and reinforced masonry walls).

3.2.1 Environmental impacts

It is considered that the environmental impact of module (1) and (2) (refer figure 1) is assuming a like-for-like replacement of materials that were demolished This assumption represents the embodied carbon and energy to build back the lost floor area within the Christchurch CBD. This quantitative assessment of embodied carbon and energy considers that the service life of building materials was cut short by deciding to demolish or repair buildings. These materials were quantified to obtain the potential climate change impact in order to make those materials that was then potentially wasted due to premature demolitions. The typical service life for a New Zealand non-residential building is 60 years based on data from (Dowdell et al. 2016). The environmental data provided for that module (1) and (2) correspond to LCAQuick v3.3. The supporting data obtained from this database can be found in (Dowdell et al. 2020). For module (3), the environmental data correspond to different sources from (BRANZ n.d.; Ecoinvent n.d.; Pacific Steel 2018; Tabata et al. 2017). The non-structural component considered are Glazing & Framing, Mechanical, electrical and plumbing (MEP) and Tenants improvements (TI). The data for Glazing & Framing correspond from (Berg, Dowdell, and Curtis 2016a). It corresponds to the average of embodied impact/m^2 figure from New Zealand reference commercial buildings developed by the authors. The data for MEP (include mechanical, electrical components) and TI (include finishes, furniture and fixtures) is from a study of (The Carbon Leadership Forum 2019). That study estimated a range of values per square meter for these components focussing on commercial office buildings in the United States.

3.3 Results

Figure 5 illustrates the environmental impact of module (1). The beams, columns and slabs are the highest contributors to both carbon and energy categories with 46% and 58%, respectively. The non-structural components encompass 30% of the total embodied carbon and 12% of the total embodied energy (in this percentage is not considered MEP and TI).

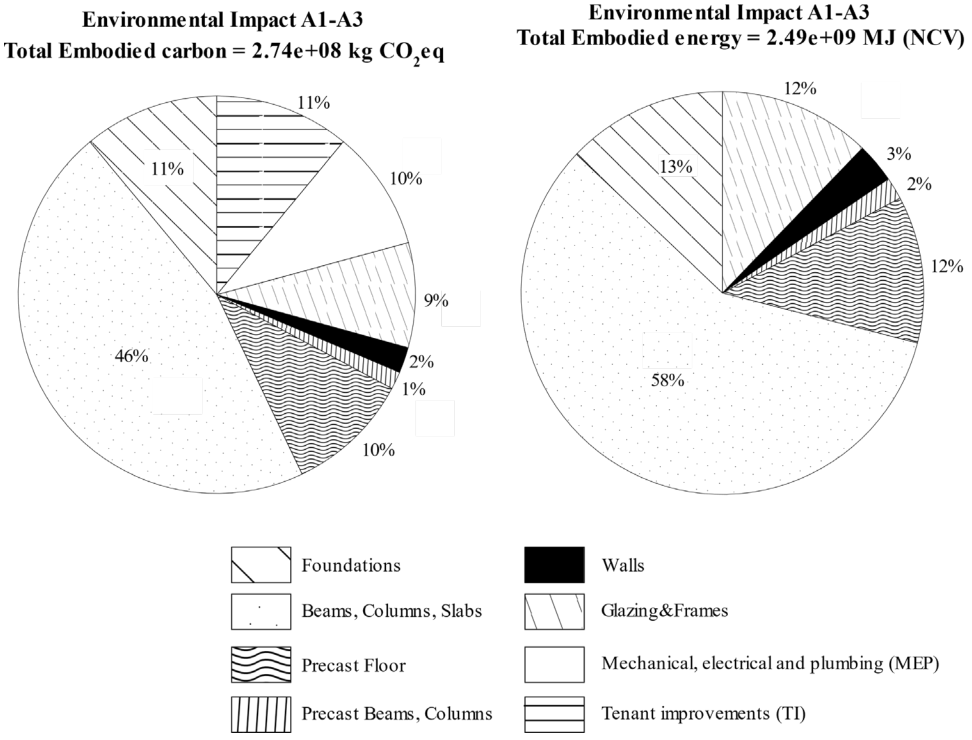


Figure 5: Environmental Impact Module 1 in terms of CO_2 and energy.

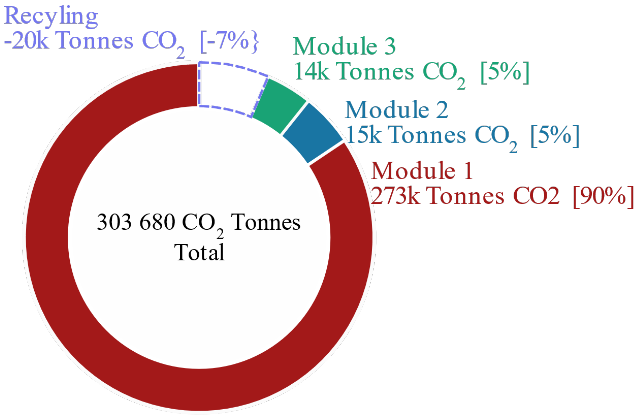


Figure 6: Total Environmental Impact in terms of CO_2 (Module 1,2 and 3)

A total value of 306,608 tonnes embodied carbon was estimated using the model for the 142 buildings, considering the three modules with the split shown in the Figure 6. The product stage (Module 1) contains 90% of the total carbon, followed by Construction and Waste Management stages both with 5%. For recycling from Module 3, the value (7%) corresponds mainly to benefits attributed to recycling of steel scrap.

4 CONCLUSIONS

This paper presents a case study to calculate the environmental impact resulting from demolishing buildings after the Canterbury Earthquake. The embodied carbon and energy were quantified (stages A1-A5), and the carbon emission of the waste management in post-earthquake conditions of 142 concrete buildings in Christchurch CBD. The total of carbon impact of 303,608 T CO_2eq is equivalent to emissions due to the electricity purchased by 400,000 New Zealand houses each year. The result highlights the importance of the environmental impacts of demolishing buildings following earthquakes.

Owing to the large variety of complex conditions after an earthquake, only the environmental impact of demolished buildings was estimated. The large number of other buildings that required a range of repair techniques are not taken into account due to the variety of these repairs. Future work will expand this framework adding seismic repairs over the life span of the New Zealand building stock.

REFERENCES

Abergel, Thibaut, Brian Dean, John Dulac, and Ian Hamilton. 2018. “Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector.” *Global Status Report* 325.

Bahramian, Majid and Kaan Yetilmezsoy. 2020. “Life Cycle Assessment of the Building Industry: An Overview of Two Decades of Research (1995–2018).” *Energy and Buildings* 219:109917.

Berg, Brian, David Dowdell, and Matthew Curtis. 2016a. “New Zealand Whole-Building Whole-of-Life Framework: Development of Reference Office Buildings for Use in Early Design. BRANZ Study Report SR350.”

Berg, Brian, David Dowdell, and Matthew Curtis. 2016b. “New Zealand Whole-Building Whole-of-Life Framework: Development of Reference Office Buildings for Use in Early Design.”

BRANZ. n.d. “LCAQuick V3.3.”

Brown, Charlotte and Mark Milke. 2016. “Recycling Disaster Waste: Feasibility, Method and Effectiveness.” *Resources, Conservation and Recycling* 106:21–32.

BSI. 2010. “EN 15643-1:2010 Sustainability of Construction Works -Sustainability Assessment of Buildings - Part 1 : General Framework.” 1:1–25.

BSI. 2011. “EN 15978:2011 Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method.” *International Standard* (November):1–64.

BSI. 2012. “EN 15643-2:2011 Sustainability of Construction Works - Assessment of Buildings - Part 2 : Framework for the Assessment of Environmental Performance.” 1–36.

BSI. 2019. “EN 15804:2012+A2:2019- Standards Publication Sustainability of Construction Works — Environmental Product Declarations — Core Rules for the Product Category of Construction Products.” 1–76.

Buchanan, Andrew H., John Stephen, and Love Simon. 2012. “LCA and Carbon Footprint of Multi-Storey Timber

Buildings Compared with Steel and Concrete Buildings.” *World Conference on Timber Engineering* (July).

Chandrakumar, Chanjief, Sarah J. McLaren, David Dowdell, and Roman Jaques. 2020. “A Science-Based Approach to Setting Climate Targets for Buildings: The Case of a New Zealand Detached House.” *Building and Environment* 169(August 2019):106560.

Dowdell, David, Brian Berg, Jarred Butler, and Andrew Pollard. 2020. *New Zealand Whole-Building Whole-of-Life Framework: LCAQuick v3.4 - a Tool to Help Designers Understand How to Evaluate Building Environmental Performance*. Porirua, New Zealand.

Dowdell, David, Brian Berg, Nick Marstson, Patricia Shaw, John Burgess, Johannes Roberti, and Brendan White. 2016. “New Zealand Whole-Building Whole-of-Life Framework: Development of Datasheet to Support Building Life Cycle Assessment. Report SR351.”

Ecoinvent. n.d. “Ecoinvent.”

Ghose, Agneta, Sarah J. McLaren, and David Dowdell. 2020. “Upgrading New Zealand’s Existing Office Buildings – An Assessment of Life Cycle Impacts and Its Influence on 2050 Climate Change Mitigation Target.” *Sustainable Cities and Society* 57(October 2019):102134.

Ghose, Agneta, Sarah J. McLaren, David Dowdell, and Robyn Phipps. 2017. “Environmental Assessment of Deep Energy Refurbishment for Energy Efficiency-Case Study of an Office Building in New Zealand.” *Building and Environment* 117:274–87.

Ghose, Agneta, Massimo Pizzol, and Sarah J. McLaren. 2017. “Consequential LCA Modelling of Building Refurbishment in New Zealand- an Evaluation of Resource and Waste Management Scenarios.” *Journal of Cleaner Production* 165(2017):119–33.

Kim, Jenna Jihyun, Kenneth J. Elwood, Frederic Marquis, and Stephanie E. Chang. 2017. “Factors Influencing Post-Earthquake Decisions on Buildings in Christchurch, New Zealand.” *Earthquake Spectra* 33(2):623–40.

Marquis, Frédéric, Jenna Jihyun Kim, Kenneth J. Elwood, and Stephanie E. Chang. 2017. “Understanding Post-Earthquake Decisions on Multi-Storey Concrete Buildings in Christchurch, New Zealand.” *Bulletin of Earthquake Engineering* 15(2):731–58.

MBIE. 2020a. “Building for Climate Change: Transforming the Building and and Improve Climate Resilience.” (July).

MBIE. 2020b. “Transforming Operational Efficiency.” (August).

MBIE. 2020c. “Whole-of-Life Embodied Carbon Emissions Reduction.” (August).

Milke, Mark. 2011. “Disaster Waste Management and the Christchurch Experience.”

New Zealand Parliament and New Zealand Government. 2019. “Climate Change Response (Zero Carbon) Amendment Act 2019.” 32.

OECD. 2003. *Environmentally Sustainable Buildings - Challenges Ad Policies*. Paris.

Pacific Steel. 2018. “Pacific Steel Environmental Product Declaration.”

Parker, Miles and Daan Steenkamp. 2012. “The Economic Impact of the Canterbury Earthquakes.” *Reserve Bank of New Zealand Bulletin* 75(3):13–25.

Simonen, Kathrina. 2014. *Life Cycle Assessment*. (1st ed.). Routledge: Routledge.

Tabata, Tomohiro, Yohei Wakabayashi, Peii Tsai, and Takashi Saeki. 2017. “Environmental and Economic Evaluation of Pre-Disaster Plans for Disaster Waste Management: Case Study of Minami-Ise, Japan.” *Waste Management* 61:386–96.

The Carbon Leadership Forum. 2019. “Estimates of Embodied Carbon for Mechanical , Electrical , Plumbing and Tenant Improvements.” (April 2019).

Thinkstep. 2018. “The Carbon Footprint of New Zealand’s Built Environment.”

Thinkstep. 2019. “Under Construction.”