Integrating Building Information Modelling (BIM) and Whole Building Life Cycle Assessment (WBLCA) for Green Building Rating Systems

Fatma Abdelaal

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Abstract

Buildings are one of the largest contributors to global warming and climate change in recent decades. Therefore, promoting sustainability in the built environment has been an increasing concern for both academics and stakeholders in the building industry. Despite the global efforts to develop and adopt various environmental assessment tools, methods and technologies that reduce building environmental impacts, building carbon emissions throughout the whole lifecycle continue to raise, reaching their highest global share in 2019. Therefore, the ultimate goal of this thesis is to optimize building environmental assessment and enhance the validity and reliability of the green building rating systems, therefore, accelerating decarbonization in the built environment. Hence, this thesis proposes a framework that integrates scientific environmental assessment methods such as Life Cycle Assessment (LCA) and building technologies such as Building Information Modelling (BIM) in order to (1) enhance the reliability, validity and structure of the existing green building rating assessment systems, (2) develop science-based carbon emissions benchmarks for buildings (3) identify the current emissions gaps to achieve the international reduction targets, (4) automate the building environmental assessment process. In addition, the research recognizes and explores the influence of the social factor, represented in the industry stakeholders, on adopting green building tools and technologies.

The research, foremost, compares various international Green Building Rating Systems (GBRSs) from Life Cycle Assessment (LCA) perspective to investigate their reliability as building environmental assessment tools. In the following step, this thesis develops science-based carbon emissions benchmarks for residential buildings in New Zealand using an integrated approach of Whole Building LCA (WBLCA) and the Distance to Target (DTT) methods. The developed carbon emissions benchmarks can achieve the Paris Agreement and the International Panel on Climate Change (IPCC) reduction targets for 2030 and 2050 to limit global warming to 1.5 °C. Furthermore, the research identifies the current carbon emissions gaps throughout building lifecycle stages from cradle to grave. Following, the research explores the feasibility to integrate building technologies such as Building Information Modelling (BIM) tools into the building environmental assessment process. First, the research develops a comprehensive BIM-based Green Building rating System framework that can achieve the requirements of each assessment criteria within the green building rating systems. In the later step, the thesis develops an integrated BIM-based LCA framework for the green building rating systems that, as well, incorporates the developed science-based carbon emissions benchmarks in order to optimize and automate the environmental assessment process of the existing green building rating systems.

Due to the significance of the stakeholders' role in the building industry, this thesis conducts stakeholders' analysis research as a non-technical factor that can influence the implementation of green buildings and the environmental assessment tools. This thesis investigates multiple stakeholders' perspectives and attitudes towards green buildings, Green Building Rating Systems, BIM and LCA applications. The outcome of the stakeholders' research provides a comprehensive picture of green building practices in New Zealand and proposes a number of practical recommendations that aim to enhance the collaboration and decision-making process in the building industry.

The thesis contributes to the body of scientific knowledge of green buildings and carbon budget research. It connects the dots and integrates the science, technology and social factors to provide a holistic and scientific approach that enhances the building assessment process and mitigates building environmental impacts on the planet.

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'He who is not grateful to people is not grateful to God (Allah)'
Prophet Muhammad (ﷺ)

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I dedicate this thesis to my little brother, soon to be Mechanical Engineer, Serag

List of Publications

Published Journal Articles

1- F. Abdelaal, B.H.W. Guo, "Knowledge, attitude and practice of green building design and assessment: New Zealand case", Building and Environment, 201 (2021) 107960. (Chapter 6)

2- F. Abdelaal, B.H.W. Guo, "Stakeholders' Perspectives on BIM and LCA for green buildings", Journal of Building Engineering, (2021) 103931. (Chapter 7)

Conference Proceedings

1- F. Abdelaal, B.H.W. Guo, Y. Zou, M.S. Ahmed, "Integrating BIM into green residential building assessment" Proceedings of the 4th International Conference on Civil and Building Engineering Informatics, Japan, November 2019. (Parts of Chapter 5)

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In Preparation

F. Abdelaal, B.H.W. Guo, "BIM-based LCA framework for optimizing environmental assessment of buildings". (Parts of Chapter 5)

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Chapter 1. Introduction

1.1 Background

Buildings worldwide account for around 40% of global carbon emissions (UNEP, 2020). Thus, the value of sustainable development has been increased and it becomes necessary for the building industry to adopt sustainability in its practices to reduce building potential environmental impacts (Berardi, 2012; Ramesh et al., 2010). Sustainable development is commonly defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", this definition was introduced by the World Commission on Environment and Development (WCED 1987) in a report called "Our common future", also known as the Brundtland Report (Papajohn et al., 2016). As a result, the concept of "green buildings" was introduced and gained momentum in recent decades to achieve sustainable development in the built environment. "Green buildings" is a term encompassing techniques, methods, tools and products that can create an environmentally friendly building in terms of resource consumption and environmental impacts (Ding, 2008; Hoffman & Henn, 2008). Subsequently, several building assessment tools such as Green Building Rating Systems (GBRSs) were put into practice around the world to evaluate the environmental performance of buildings (Azhar et al., 2011; Illankoon et al., 2017). The global GBRSs, such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM), consist of common assessment criteria and are similar in terms of their evaluation methods for energy consumption, indoor environmental quality, water efficiency, waste management and material use of a building (Doan et al., 2017; Shan & Hwang, 2018). The international GBRSs have been subject to comparison in the green building literature to identify their similarity, difference, strength and weakness in terms of sustainability aspects (Awadh, 2017; Doan et al., 2017; Mattoni et al., 2018).

Life Cycle Assessment (LCA) is another environmental assessment method for buildings, it is a scientific and reliable method that can evaluate building potential environmental impacts throughout their lifecycle stages (Anand & Amor, 2017; Papajohn et al., 2016). During the last 20 years, there has been a growing interest in the LCA of buildings (Weißenberger et al., 2014). Accordingly, the United States Green Building Council (USGBC) introduced LCA as an optional assessment criterion in LEED version 2009 (Alshamrani et al., 2014; Collinge et al., 2015; Trusty & Horst, 2007). Several studies have been conducted to investigate LCA integration in the international GBRSs (Lee et al., 2017; Ramani & García De Soto, 2021; Sartori et al., 2021).

Building Information Modelling (BIM) is a building technology tool that can provide an effective platform for attaining compliance with GBRSs as it affords great potential for optimizing the building environmental assessment process (Jalaei & Jrade, 2015; Lu et al., 2017; Yahya et al., 2016). BIM provides an integrated data-rich model that allows complex analysis such as environmental performance analysis (Azhar et al., 2009). According to Krygiel and Nies (2008), BIM can aid in different aspects of sustainable buildings design and assessment, for instance, building orientation, building massing, daylight analysis, water harvesting, energy modelling and materials selection, therefore, facilitating the green building assessment process. Several studies have been conducted in order to demonstrate BIM's capability to support achieving the assessment criteria of the existing GBRSs (Abdelaal et al., 2019; Azhar et al., 2011; Barnes & Castro-lacouture, 2009; Gandhi & Jupp, 2014; J. K. W. Wong & Kuan, 2014).

Recently, the potential integration of BIM and LCA has been receiving increasing interest in academic research, as well as, the building industry since BIM, as a data repository, can simplify LCA calculations (Antón & Díaz, 2014; Carvalho et al., 2020; Kreiner et al., 2015; Marrero et al., 2020; Naneva et al., 2020; Palumbo et al., 2020; Santos et al., 2020; Soust-Verdaguer et al., 2017; Veselka et al., 2020).

Apart from the technical aspects of green buildings, the stakeholders play a significant role in shifting the built environment towards sustainability. According to the World Green Building Council, decarbonizing the whole lifecycle of buildings before 2050 is possible if stakeholders across the building value chain work collaboratively together (WGBC, 2019). Stakeholders' analysis research highlights the influence, interest and engagement of various stakeholders in the decision-making process (García-Rosell et al., 2011; H. X. Li et al., 2018). The importance of the stakeholders' analysis research has been recently recognized in academic research as an influential research area that helps understand the dynamic relationships and interactions between multiple stakeholders in the building industry (Abdelaal & Guo, 2021; Berawi et al., 2019; Herazo & Lizarralde, 2016; Karatas & El-Rayes, 2015; Nduka, 2015; Pan & Pan, 2020; Yang & Zou, 2014). Furthermore, previous studies highlighted that a decision of whether an industry will adopt a particular technology, method or tool is mainly based on its stakeholders' attitudes and perspectives (Linderoth, 2010; Sträub, 2009).

In the context of New Zealand, New Zealand is a small country with small population size, around 5 million. However, its gross emissions per person are the 5th highest among the developed countries (known as Annex 1) with 17.2 tonnes (in carbon dioxide equivalent) per person (Leining & Kerr, 2016). According to the Climate Action Tracker (CAT), New Zealand's domestic emissions reduction targets in 2030 is not consistent with the Paris Agreement 1.5°C temperature limit. New Zealand is relying on the mitigation potential of the land use and forestry sector to meet its reduction target rather than focusing efforts on reducing emissions from high emitting sectors such as the building sector. The building sector in New Zealand contributes up to 20% of the country's total emissions (Thinkstep, 2019). The CAT, therefore, rates New Zealand's current climate targets, policies and actions as "highly insufficient" (Climate Action Tracker, 2021).

In order to contribute to the global effort under the Paris Agreement, the New Zealand government established the Climate Change Commission in 2019 to advise the government on climate change action within the framework of the Climate Change Response (Zero-Carbon) Amendment Act 2019 to reduce net emissions of greenhouse gases (except methane from plants and animals) to zero by 2050 (New Zealand Government, 2019). Since the New Zealand building sector contributes 20% of the country's GHG emissions (Vickers et al., 2018), the government announced a new programme, Building for Climate Change, to promote sustainability in the built environment (MBIE, 2020). Despite these efforts, green building uptake in New Zealand is still low. According to the New Zealand Green Building Council, there are only around 200 commercial buildings and 3200 residential buildings certified as "Green Buildings" in New Zealand since the launch of the New Zealand Green Building rating Systems in 2007 (NZGBC, 2021). Furthermore, the results of previous green buildings research are not necessarily applicable to the New Zealand context, this is because New Zealand, as a small trade-reliant country, has a unique regulatory system and emissions profile compared to other countries (Weeks, 2017).

1.2 Statement of problem

Despite the academic and professional efforts in recent years to address and mitigate building environmental impacts, global carbon emissions associated with the building industry have reached their highest share in 2019 according to the United Nation Environment Programme (UNEP) report (UNEP, 2020). Therefore, a holistic science-based approach that integrates methods and tools is a pressing need in order to optimize green building design and assessment and minimize carbon emissions throughout buildings the whole lifecycle. Furthermore, it is vital to understand the stakeholders' knowledge of green buildings and their attitude towards the environmental assessment tools and methods in order to provide a practical solution that enhances the stakeholders' collaboration and decision-making process in the building industry.

As highlighted in the introductory section, there are several building environmental assessment systems and tools around the world. According to Doan et al. (2017), there are around 600 GBRSs globally. However, these GBRSs lack a holistic assessment approach for a building whole lifecycle (Awadh, 2017; Cordero et al., 2019; Lessard et al., 2018). Attempts have been made to improve the assessment process of a few of the GBRSs by incorporating LCA as an assessment criteria since LCA is a scientific method that evaluates building environmental impacts throughout its life stages (Anand & Amor, 2017; Papajohn et al., 2016). As a result, LCA has been recently incorporated into a few GBRSs such as LEED, BREEAM, CABSEE, BEAM Plus and Green Star (Lee et al., 2017; Ramani & García De Soto, 2021; Sartori et al., 2021). Despite these advancements, LCA applications for green building assessment are not yet widespread due to the complexity of the LCA process (Nwodo & Anumba, 2019; Soust-Verdaguer et al., 2016; Suzer, 2015). The absence of building environmental benchmarking is another critical issue with the existing building environmental assessment methods, neither LCA nor GBRSs denotes building environmental impacts on the remaining carbon budget (Carmody et al., 2007; Chandrakumar et al., 2020). In terms of utilizing advanced building technologies such as BIM to simplify and enhance green building practices, the integration between BIM and Green Building Rating Systems as a research area has remained isolated and under-researched (Darko et al., 2019). Previous studies demonstrated that BIM affords great potential for optimizing the green building assessment process (Abdelaal et al., 2019; Azhar et al., 2011; Barnes & Castro-lacouture, 2009; Gandhi & Jupp, 2014; J. K. W. Wong & Kuan, 2014; Yahya et al., 2016). Nevertheless, BIM adoption in green building assessment is still immature and unsystematic and its full potential is yet to be explored, which invites further investigations (Ansah et al., 2019; Bueno et al., 2018; Solla et al., 2016; Wu & Issa, 2013). Furthermore, few studies have been conducted recently to investigate the relation between the LCA, BIM and GBRSs (Carvalho et al., 2020; Veselka et al., 2020).

Previous research has demonstrated the significance of the multiple stakeholders' perspectives, as a social and non-technical research area (Linderoth, 2010; Sträub, 2009; Y. Wang et al., 2020; S. C. Wong & Abe, 2014), yet it revealed that stakeholders' analysis is still underestimated and overlooked in green buildings literature (Abdelaal & Guo, 2021; Herazo & Lizarralde, 2016; Karatas & El-Rayes, 2015; Pan & Pan, 2020).

1.3 Research Objectives

The ultimate goal of this research is to optimize building environmental assessment during the design stage and enhance the validity and reliability of the green building rating systems. Therefore, reduce building environmental impacts during the whole lifecycle stages, from cradle to grave, and accelerate decarbonization in the built environment.

To reach that ultimate goal, the research aims to achieve three main objectives, each main objective consists of two sub-objectives:

Objective 1

To develop science-based carbon emissions benchmarks for buildings using an integrated Whole Building LCA (WBLCA) and Distance to Target (DTT) approach, the developed carbon emissions benchmarks can be incorporated into the GBRSs to enhance their validity and reliability as building environmental assessment tools.

To achieve this main objective, the research, first, compares several international GBRSs from the LCA perspective to explore the level of LCA integration, the recognition and weightings of the building embodied and operational carbon emissions and carbon auditing requirements.

In the second step, the research integrates the WBLCA method and DTT weighting approach in order to develop science-based short-term and long-term benchmarks for buildings carbon emissions. The benchmarks cover each LCA stage of the building's service life (i.e., materials production, construction, operations, maintenance and end-of-life). Furthermore, the research identifies the current carbon emissions gaps for the New Zealand buildings in relation to the global carbon budgets. The developed benchmarks align with the carbon reduction global targets such as the Paris Agreement targets for 2030 and 2050 and limit global warming to 1.5 °C.

Objective 2

To develop an integrated BIM-based LCA framework for GBRSs that incorporates the science-based carbon emissions benchmarks. The framework can optimize and facilitate the building environmental assessment process in order to increase the uptake of green building certifications.

The research, first, analyses BIM capabilities and functions as an environmental analysis platform to achieve the requirements of the GBRSs. In addition, the research identifies the additional data, environmental analysis software and data exchange schemes that can be integrated into a BIM to automate the green building assessment and certification process. Based on the outcomes of the first task, the research develops a comprehensive BIM-based LCA framework for each assessment criterion within the existing GBRSs. Furthermore, the framework integrates the carbon emissions benchmarks, in order to optimize the building environmental assessment process and report reliable results.

Objective 3

To conduct the stakeholders' analysis that investigates the influence of the stakeholders' perspectives on green building practices and BIM and LCA applications for building environmental assessment. First, the thesis investigates the Knowledge, Attitude, and Practice (KAP) levels of various stakeholders towards green building design and assessment to understand the correlation between KAP levels among the multiple stakeholders. Additionally, the research identifies the motivations and barriers to green buildings and building environmental tools. The research explores current BIM and LCA applications for green buildings in New Zealand and the stakeholders' levels of agreement on the integration of BIM and LCA for building environmental assessment.

1.4 Scope and limitations

Sustainability in the built environment is a broad research area, this research focuses on the environmental impacts of buildings. Therefore, the other pillars of sustainability; social and economic, are not included in the research scope.

LCA has several environmental impact categories such as the Ozone Depletion Potential (ODP) and Acidification Potential (AP), etc. However, these impact categories are not subject to study in the research. The focus of this research is on the Global Warming Potentials (GWP) as an environmental impact of buildings LCA.

The research conducts a national survey to examine the knowledge, attitude and practice of multiple stakeholders towards green buildings in New Zealand, as a small country. Although a small number of developers and contractors in the country usually participate in green building projects, both stakeholder groups might be underrepresented in this research.

New Zealand reports its carbon emissions (in CO_2) for the following sectors: land use, land-use change and forestry, agriculture, energy, industrial processes and product use, waste and Tokelau. Notice that the carbon emissions associated with the building sector are not yet officially measured and reported. Because of the absence of any official data on the carbon emissions of the building sector in New Zealand, the research relies on the carbon emissions reported in the Building Research Association of New Zealand (BRANZ) studies to develop the carbon emissions benchmarks for residential buildings. However, the integrated Whole Building LCA and DTT approach presented in this thesis can be applied to any set of data for different building types, in any country. It is a generic methodology for developing carbon emissions benchmarks, as well as benchmarks for the other LCA environmental impact categories.

Finally, the research proposes a conceptual framework for BIM and LCA integration that can facilitate achieving green building certifications. No technical attempt has been made to develop a tool that implements the BIM-based LCA framework for building environmental assessment.

1.5 Research Methods

In order to achieve the research objectives, the research adopts various methods, each method is expected to accomplish a research objective as follows:

Objective 1:

Develop science-based carbon emissions benchmarks for buildings using an integrated Whole Building LCA (WBLCA) and Distance to Target (DTT) approach, the developed carbon emissions benchmarks can be incorporated into the GBRSs to enhance their validity and reliability as building environmental assessment tools.

In order to achieve this objective, the research first, analysis and compares several international GBRSs from the LCA perspective. The comparison study aims to explore the level and scope of LCA integration into the GBRSs. Additionally, it aims to investigate the reliability of these GBRSs in addressing and reporting the building embodied and operational carbon emissions by presenting the credits weightings and carbon auditing requirements (Chapter 3).

Based on the results of the comparison study in Chapter 3, Chapter 4 integrates the Whole Building LCA (WBLCA) and the Distance to Target (DTT) methods to develop science-based carbon emissions benchmarks for the residential buildings in New Zealand.

In the first step, the research calculates the Weighting Factors (WFs) for the carbon emissions targets in 2030 and 2050 according to the Intergovernmental Panel on Climate Change (IPCC) 1.5 °C global warming scenario. Consequently, the research applies the WFs to the New Zealand building carbon emissions to develop short-term and long-term carbon emissions benchmarks for each lifecycle stage of a building service life. These science-based carbon emissions benchmarks can be incorporated into the New Zealand green building rating systems in order to improve the building environmental assessment process.

Finally, the research performs LCA for a case study of a New Zealand stand-alone house. to compare the results of the case study’s carbon emissions with the carbon emissions benchmarks in order to validate the proposed benchmarks and to indicate the current carbon emissions gaps.

Objective 2:

Develop an integrated BIM-based LCA framework for GBRSs that incorporates the science-based carbon emissions benchmarks to facilitate and enhance the building environmental assessment process.

In Chapter 5, after conducting an extensive review of the assessment requirements of the technical manual of the Homestar v4 rating system, as a case study of GBRSs, the research identifies the potential of BIM tools that achieve the assessment requirements. Autodesk Revit is the BIM platform that was considered for this research. The research identifies the additional information required for the assessment and the supporting environmental analysis software such as Integrated Environmental Solution (IES), Geographic Information System (GIS), LCA tools, etc. Furthermore, the research identifies the BIM data exchange schemes such as Foundation Classes (IFC) and Green Building XML (gbXML) that can facilitate the interoperability and data transmission between the BIM model and the environmental analysis software.

In the third and last step, the research develops a BIM-based LCA framework that integrates the proposed carbon emissions benchmarks (in Chapter 4) into the Homestar assessment system. The framework aims to enhance and automate the environmental assessment of residential buildings in New Zealand throughout their lifecycle.

Objective 3:

Conduct stakeholders' analysis that investigates the influence of the stakeholders' perspectives on green building practices and BIM and LCA applications for building environmental assessment.

In Chapter 6, the research designs a Knowledge, Attitude, and Practice (KAP) questionnaire based on an extensive literature review (Chapter 2) and the World Health Organization

(WHO) guide on developing KAP surveys (World Health Organization, 2008), and discussions with several stakeholders in the New Zealand building industry. The questionnaire investigates the stakeholders' KAP towards the green building design and assessment in New Zealand and identifies the stakeholders' motivations and barriers to the wide implementation of building environmental assessment tools.

The research, moreover, conducts another national questionnaire (Chapter 7) to explore the BIM and LCA applications for green buildings in New Zealand. Moreover, it investigates the stakeholders' level of agreement on the significance of BIM and LCA as building environmental assessment tools, and the stakeholders' agreement on the potential integration of BIM and LCA.

1.6 Significance of the research

This thesis contributes to the body of knowledge, as well as the global efforts towards mitigating climate change and reducing the environmental impacts associated with the built environment. The research provides a novel approach that integrates scientific methods and building technologies to improve the building environmental assessment process. Moreover, the research emphasizes the significance of the social factor in influencing green building practices.

First, the research demonstrates that the existing Green Building Rating Systems (GBRSs) are insufficient in terms of evaluating the building performance and reporting accurate environmental impacts throughout the building lifecycle. The international GBRSs lack building environmental benchmarks that can guide the stakeholders in the building sector to meet the global carbon reduction targets. To overcome this international challenge, the research represents a novel approach to developing carbon emissions benchmarks for each lifecycle stage of buildings using reliable and scientific methods, namely the Whole Building LCA and Distance to Targets (DTT). To our knowledge, the research is the first research that integrates WBLCA and DTT and proposes science-based carbon emissions benchmarks for the whole building LCA. Moreover, it's the first to propose carbon emissions benchmarks that limit global warming to 1.5 °C rather than 2 °C as recommended recently in the IPCC report (IPCC, 2021). The research, as well, identifies the carbon emission gaps for New Zealand buildings in relation to the global climate targets in 2030 and 2050. Incorporating the developed science-based carbon emissions benchmarks into the GBRSs can improve the radiality and validity of these systems as environmental assessment tools.

Second, the thesis contributes to the existing literature on BIM and LCA integration for building rating systems. Previous research made attempts to integrate either BIM or LCA for a number of the assessment credits in the building rating system such as energy and materials. However, this thesis investigates BIM and LCA integration into each assessment criterion in the rating systems. Besides, it incorporates the carbon benchmarks into the BIM-based LCA framework to improve the accuracy of building environmental assessment. This thesis represents an effort to develop a comprehensive BIM and LCA framework to optimize the environmental assessment of the building and promote digitalization in the building sector. Furthermore, the research findings contribute to improving the structure of the existing GBRSs. The research proposes recommendations for replacing and reviewing the requirements of the assessment criteria according to the LCA approach.

The research is the first research that proposes an integrated BIM and LCA framework for the New Zealand residential buildings since the research uses the Homestar rating system to validate the research approach, therefore, the framework can assist the stakeholders with the residential building environmental assessment process and increase the uptake of Homestar certifications.

Lastly, the thesis contributes to bridging the research-industry gap as it highlights the importance of the stakeholders’ analysis research area that has been overlooked in the green building academic literature. The research is the first to investigate the knowledge, attitude, practice and perspective of the multiple stakeholders in the New Zealand building sector towards green buildings. The research provides a holistic picture of current green building design and assessment in New Zealand from multiple stakeholders’ perspectives. Additionally, it identifies knowledge gaps and behavioural patterns of various stakeholders that can enhance their collaboration and engagement and improve the decision-making process. The research, as well, explores the current BIM and LCA applications for green buildings in New Zealand from the stakeholders’ perspectives and it investigates the stakeholders’ perspectives on the integration of BIM and LCA for the building environmental design and assessment process. To our knowledge, no research has been conducted on the BIM and LCA integration from the stakeholders’ point of view.

In terms of practical implementation, New Zealand currently faces enormous challenges to mitigate its carbon emissions and achieve the Paris Agreement goals. Currently, there are no clear national policies that report and tackle carbon emissions in the building sector. According to the New Zealand government, the first “Emissions Reduction Plan” will be released in May 2022 (Beehive, 2021). The plan is expected to set the direction for reducing carbon emissions across various areas including construction. Therefore, the research aims to guide the emissions reduction plan and bridge the current gap between academia and policymaking.

1.7 Thesis outline

This research consists of 8 chapters as the following (Figure 1.1):

- **Chapter 1** introduces the research framework by providing background information on green buildings and the environmental assessment tools. It gives a brief review of the previous studies and identifies the research gaps, the research scope and its limitations. It then presents the research objectives and the methods. In a conclusion, it presents the significance and outline of the research.

- **Chapter 2** reviews the literature related to the building environmental assessment and benchmarking, BIM, LCA and stakeholders' research. This detailed literature review aims to define the research gaps and to determine the research objectives and methods.

- **Chapter 3** compares several GBRSs such as LEED, BREEAM, BEAM Plus and the New Zealand rating systems (i.e. Green Star and Homestar) from LCA perspective.
- **Chapter 4** develops science-based carbon emissions benchmarks for buildings using an integrated LCA-DTT approach. Besides, it identifies the carbon emissions gaps in New Zealand buildings using a residential building as a case study.
- **Chapter 5** Develops a comprehensive framework that integrates BIM, LCA and the carbon emissions benchmarks for the existing Green Building Rating Systems in order to improve their validity and reliability.
- **Chapter 6** presents the Knowledge, Attitude and Practice (KAP) of the multiple stakeholders in the New Zealand building industry. In addition, it investigates the stakeholders' motivations and barriers to green buildings.
- **Chapter 7** investigates the stakeholders' perspective on BIM and LCA applications in green buildings and it explores the stakeholders' agreement on a potential BIM and

LCA integration for building environmental design and assessment.

- **Chapter 8** provides meaningful conclusions, and practical recommendations and discusses future research directions.

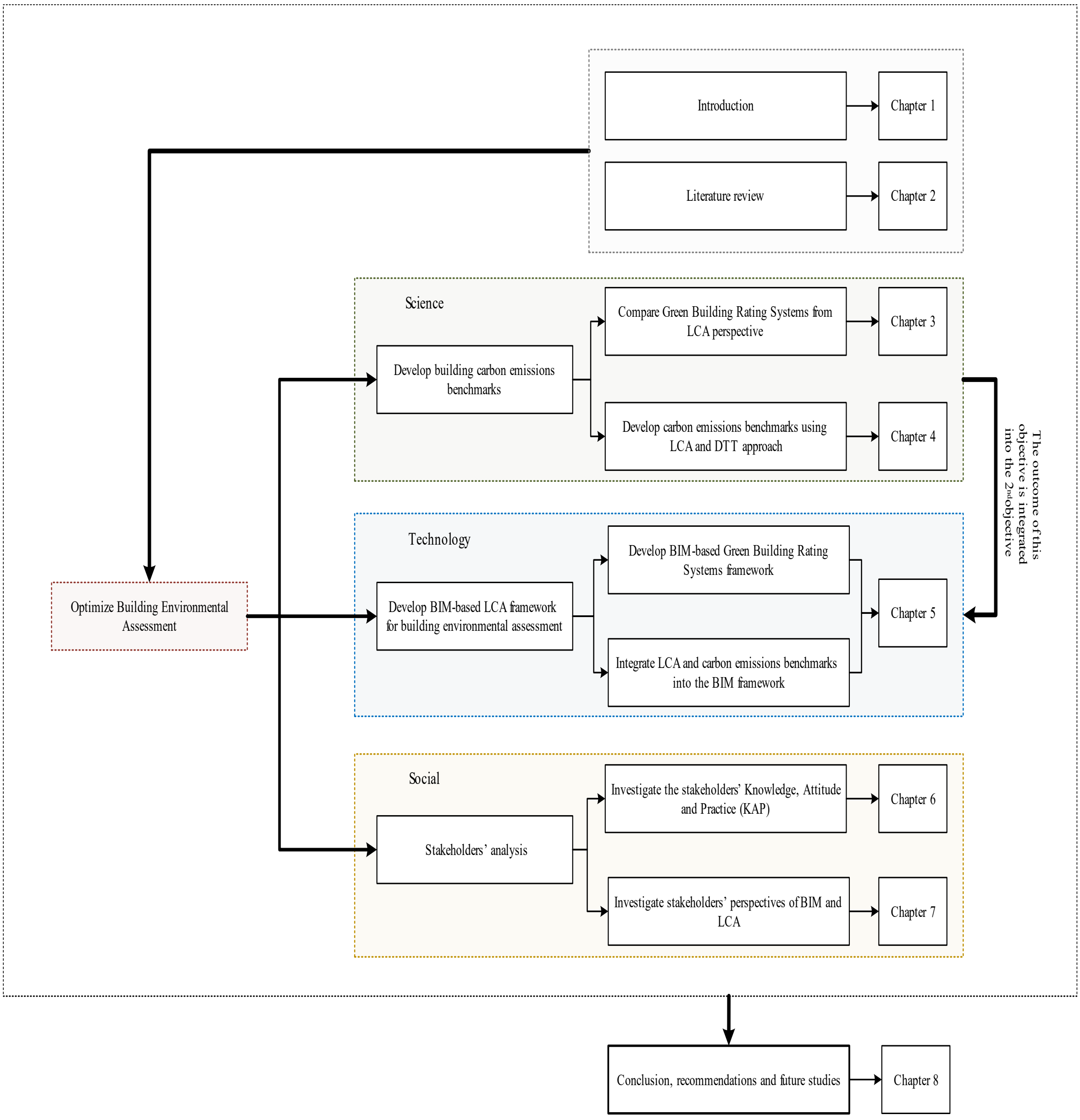


Figure 1.1 Thesis structure

Chapter 2. Literature review

2.1 Life Cycle Assessment (LCA) for building environmental assessment

Life Cycle Assessment (LCA) is often called cradle to grave assessment since it assesses the environmental performance and potential impacts of a product, process or building over its whole life service (Anand & Amor, 2017; Papajohn et al., 2016). In terms of buildings, LCA considers the environmental impacts of a particular building component or system or the whole building, starting from the material extraction and construction phase to end-of-life (Kayaçetin & Tanyer, 2018). LCA for building environmental assessment has been an extensively studied research area over the past decade because of the increasing environmental impacts of the built environment (Al-Ghamdi & Bilec, 2015; Anand & Amor, 2017; Lessard et al., 2018). Previous LCA research has highlighted the importance of LCA for building environmental analysis since it considers several environmental impact categories, including carbon emissions and energy demand (Heinonen et al., 2011). Scheuer et al. (2003) used the LCA method to identify and evaluate key design parameters that influence a building's environmental performance. Evangelista et al. (2018) and Cuéllar-Franca and Azapagic (2012) conducted complete LCA from ‘‘cradle to grave” to quantify the environmental performance of residential buildings in Brazil and the UK, respectively. Roberts et al. (2020) conducted a systematic review of academic literature to explore the incorporation of LCA at various stages of the building design process.

As a result, LCA has been incorporated as an assessment criterion into a few GBRSs around the world such as BREEAM, LEED, CABSEE, BEAM Plus, Green Star, etc. In 2004, the United States Green Building Council (USGBC) established the USGBC Life Cycle Assessment working group (Howard & Dietsche, 2005; Trusty, 2006) to investigate the feasibility of incorporating LCA into the LEED rating system to enhance the sustainability assessment of buildings. Based on their recommendations, LEED v2009 was released as the first GRBS that integrates LCA as an evaluation criterion (Alshamrani et al., 2014; Collinge et al., 2015). One major driver for the integration of LCA into GBRSs is the need to assess building environmental impacts such as the carbon emissions of a building during its lifespan (Darko et al., 2019; Tytti Bruce-Hyrkäs, Panu Pasanen, 2018). Previous studies have been conducted to investigate LCA integration in the international GBRSs. Lee et al. (2017) investigated integrating LCA into the Green Standard for Energy and Environmental Design (G-SEED), South Korea's GBRS and the study proposed a conceptual framework to integrate LCA of seven major building materials into G-SEED. Ramani & García De Soto (2021) evaluated the assessment method of the Pearl Rating System (PRS) in Abu Dhabi based on LCA, the study has found that LCA is superficially included in the PRS rating system. LCA has been recently incorporated into the "Materials" category of Green Star, the Australian GBRS (Zuo et al., 2017). Zabalza Bribián et al. (2009) developed a simplified LCA framework as a complement for energy certifications to improve buildings' energy efficiency in the European countries. Alshamrani et al. (2014) presented an integrated LCA-LEED model for the structure and envelope systems of Canadian school buildings to achieve a high level of sustainability assessment. Zhang et al. (2006) developed a building environmental performance analysis system (BEPAS) for three aspects of a building; facilities, materials and location, based on the LCA framework.

However, the implementation of LCA in building environmental assessment has remained a challenge (Jusselme et al., 2018). LCA is still considered a complicated method (Hollberg et al., 2021), due to a number of identified barriers such as its complexity, poor knowledge of environmental impacts, excessively complicated calculations applications, the absence of benchmarks or references and its cost (Carmody et al., 2007; Roberts et al., 2020; Zabalza Bribián et al., 2009).

2.1.1 Environmental benchmarks for buildings

Defining building environmental targets or benchmarks that consider the lifecycle stages of buildings is a critical step to support the transition of the built environment toward decarbonization (Roberts et al., 2020). An environmental benchmark is defined as a reference standard or point that enables comparison (Trigaux et al., 2021). Developing benchmarks is usually influenced by either political targets or policies, values in codes and standards or statistical evaluation of a set of data (Gervasio et al., 2018). Existing building environmental benchmarks were developed based on one of the following approaches; top-down, bottom-up, technical feasibility and economic feasibility (Frischknecht et al., 2019). Zimmermann et al (2005) determined thresholds for the maximum acceptable environmental load per building unit (m^2 floor area and year), using the top-down approach, in line with Switzerland's sustainability targets. König and De Cristofaro (2012) calculated benchmarks for Life Cycle Cost (LCC) and LCA for multifamily dwellings based on specified criteria of the German green building certification system (DGNB) using reference buildings. Ji et al. (2016) established benchmarks for elementary school buildings in South Korea using the statistical analysis of a set of 23 reference buildings. Gervasio et al. (2018) developed environmental performance benchmarks of the structural system of residential buildings based on statistical evaluation of a sample of buildings, in line with the assessment of safety criteria of the Eurocodes. Following the same method, Rasmussen et al. (2019) set LCA-based benchmarks for residential buildings in Denmark and Northern Italy. Chandrakumar et al. (2020) calculated climate target for the New Zealand new-built detached houses using the top-down approach, the calculated climate targets achieve the 2° C Paris climate goals.

2.1.2 Distance to Target (DTT) weighting approach

Several LCA weighting approaches have been developed during the 1990s (Bengtsson & Steen, 2000). The commonly used weighting approaches can be distinguished as social and expert scoring, monetization and distance-to-target (Lin et al., 2005). DTT as a weighting method is widely used in LCA methods such as Swiss Ecoscarcity and the Dutch Environmental Performance Indicators (EPls) (Muhl et al., 2021; Powell et al., 1997). It combines an impact assessment with environmental policies (X. Li et al., 2015). Weighting Factors (WFs) in the DTT approach are based on calculations that are performed on normalization factors (Castellani et al., 2016). A weighting factor identifies an impact category's magnitude within the reference scale of this category. The greater the DTT value is, the greater the environmental mitigation required (Soares et al., 2006). According to the framework of the Dutch and Swedish Environmental Theme (ET) method (Seppala & Hamalainen, 2001), the WF of an impact category is defined as

$$WF_{i\,(\mathrm{t}y)} = \frac{EP_{i\,(\mathrm{r}y)}}{EP_{i\,(\mathrm{t}y)}}$$

Where *WFi* is a weighting factor of an impact category *i* in the year (*ty*), which represents the target year. *EPi (ry)* is the environmental impact potential of impact category *i* in the year (*ry*) which represents the reference year, while *EPi (ty)* is the environmental impact potential of the same impact category in the year *ty* (the target year).

According to Su et al. (2019), the DTT approach demonstrated quantifiability, feasibility and predictability compared to the monetization and expert scoring methods for LCA weightings. Lin et al. (2005) used the DTT approach to drive the weights of the LCA environmental impact categories based on the Chinese environmental policies for the Development of the

National Economy and Society. Castellani et al. (2016) calculated WFs for the LCA impact categories, except for the water depletion impact category, and so developed DTT weighting factors for the European Union (EU) domestic impacts that are derived from the European policy for 2020 (TRs2020). Weiss et al. (2007) applied the DTT method to evaluate LCA results for the non-renewable energy consumption, global warming potential, eutrophication potential and acidification potential for bio-based and fossil-based products in Germany. Su et al. (2019) developed a dynamic weighting system for the ecology and resource impact categories in China using the DTT method. While Li et al. (2015) used the DTT weightings to develop an evaluation index system for the pre-use stage of buildings in China.

2.2 Building Information Modelling (BIM) for green building assessment

Building Information Modelling (BIM) has been proposed as an innovative technology that can lead to a technological and procedural shift in the building industry (Panuwatwanich & Peansupap, 2013) as it is a methodology to manage the essential building design and project data in a digital format throughout its lifecycle (Succar, 2009). BIM provides an integrated and data-rich model that has the ability to carry out complex environmental analyses (Azhar et al., 2011). According to Krygiel & Nies (2008), BIM can aid in different aspects of sustainable building design, for instance, building orientation, building massing, daylight analysis, water harvesting, energy modelling and materials. Previous studies have made attempts to integrate BIM into the rating systems as presented in Table 2.1. Barnes and Castro-lacouture (2009) demonstrated that 13 credits of total LEED credits can be directly evaluated through BIM. Azhar et al. (2011) confirmed that BIM tools such as Autodesk Revit and Integrated Environmental Solutions (IES) software have the ability to assist in achieving more than 35% of the LEED total points. Ilhan & Yaman (2016) claimed that automatic sustainability assessment can be achieved when BIM is integrated with the BREEAM rating system. Wong and Kuan (2014) demonstrated that twenty-six (26) credits of the Hong Kong 'BEAM Plus' sustainable building rating system can be achieved using BIM technology. Gandhi & Jupp (2014) stated that nearly 90% of Green Star Australia credits can be assisted through BIM. Abdelaal et al. (2019) demonstrated that 76 points of a total of 120 points of the New Zealand Homestar rating tool can be achieved using BIM software.

Table 2.1 Summary of developed BIM-based GBRSs frameworks

Authors	GBRS	Assessment category	BIM tool	Data exchange scheme
Barnes & Castro-lacouture (2009)	LEED	Heat Island Effect Materials	Revit	NA
Azhar et al. (2011)	LEED	Energy and Atmosphere Water Efficiency Indoor Environmental Quality	Revit	Green Building XML (gbXML)
Jalaei & Jrade (2015)	LEED	Energy and Atmosphere	Revit	Application Programming Interface (API)
Ilhan & Yaman (2016)	BREEAM	Materials	ArchiCAD	Industry Foundation Classes (IFC)
Wong & Kuan (2014)	BEAM Plus	Materials Water Use	Revit	NA
Akcay & Arditi (2017)	LEED	Optimize Energy Performance	Revit	Microsoft Excel

However, Wu & Issa (2013) criticized the development of green BIM as 'immature and unsystematic' as it still has a limited impact on the green building certification process (Jrade & Jalaei, 2013). Although BIM as advanced technology can provide an effective platform for attaining compliance with Green Building Rating Systems (GBRSs) and optimizing the green building certification process (Yahya et al., 2016), it still has limited impact on the green building assessment practices (Jrade & Jalaei, 2013). According to Ansah et al. (2019), previous research on BIM and GBRSs integration failed to propose a replicable approach that investigates the BIM integration for each assessment criterion within the rating systems.

2.3 BIM and LCA integration for building environmental assessment

Recently, the integration of BIM and LCA for the building environmental assessment process has received major interest in academic research (Naneva et al., 2020). Alvarez and Díaz (2014) highlighted the importance of integrating LCA in the BIM environment in the early design stages. Kreiner et al. (2015) developed a methodology for building environmental assessment based on LCA, the study acknowledged the integration of LCA into BIM as a way of improving the sustainability performance of buildings. Soust-Verdaguer et al. (2017) carried out a methodological analysis of BIM and LCA integration in order to demonstrate that the integration of BIM and LCA could help stakeholders to obtain quick and reliable results on the environmental performance of buildings. Carvalho et al. (2020) addressed the relation between LCA and building environmental assessment within BIM for the Portuguese context. Santos et al. (2019) discussed the potential of BIM as a data repository and its capacity for supporting an automatic or semi-automatic LCA and Life Cycle Cost (LCC) analysis. While Marrero et al. (2020) proposed a BIM-LCA model to evaluate the environmental impact of an urbanization process. Few studies have investigated the potential integration of BIM and LCA for the Green Building Rating Systems (GBRSs). Veselka et al. (2020) explored the applicability of integrating BIM and LCA for achieving the “Materials” credits in the SBTool rating system in the Czech Republic using the One Click LCA software. Carvalho et al. (2020) addressed the relationship between BIM and LCA for building sustainability assessment within the Portuguese context. However, the study concluded that the integration of BIM and LCA in building environmental assessment systems has not been adequately explored yet.

2.4 Stakeholders' knowledge, attitude and practice (KAP) of green buildings

The importance of multiple stakeholders' analysis has been recently realized in sustainable building development research as it highlights the influence, interest and engagement of various stakeholders in order to improve the decision-making process (H. X. Li et al., 2018). Multiple stakeholder analysis research is an influential research area that helps understand the dynamic relationships and interactions between multiple stakeholders (García-Rosell et al., 2011). In terms of green buildings, multiple stakeholders research, as a non-technical research area, has been conservatively applied. For example, Herazo & Lizarralde (2016) have investigated stakeholders' knowledge of sustainability in the built environment, the study has focused on the clients, users and community perspectives. Yang & Zou (2014) have investigated risks in complex green building projects from multiple stakeholders' perspectives. Berawi et al. (2019) presented stakeholders' perspectives on green building rating tools in Indonesia, a large percentage of the participants represented research institutions rather than industry professionals. Analysing multiple stakeholders' perspectives approach has been adopted to improve the management of green retrofits in China (Liang et al., 2015). Another research has been conducted to assess different stakeholders' roles in implementing sustainable retrofits (Menassa & Baer, 2014). Herazo & Lizarralde (2016) demonstrated that different definitions and perceptions of sustainability between stakeholders lead to different sustainability approaches in building projects at the early design stage. Nduka (2015) classified stakeholder groups according to types of business and then compared their perception of various factors that determine the adaptability of green building principles in the Nigerian construction industry. On the scale of urban neighbourhoods, Karatas & El-Rayes (2015) evaluated the performance of sustainable development based on multiple stakeholders' feedback.

Few KAP research explored multiple stakeholders' perspectives in the green building industry. A KAP study on zero carbon buildings has been conducted in Hong Kong as a high-density city to examine multiple stakeholders' perspectives (Pan & Pan, 2020), in this study; architects, engineers, contractors, manufacturers and suppliers were classified as one stakeholder group which underestimates the vast and critical differences between these stakeholders. Azami et al. (2018) used the KAP method to determine the barriers to green construction from the contractors' perspective in Malaysia. While in Zambia, Sichali & Banda (2017) investigated the level of awareness, attitudes and perceptions of green building practices amongst stakeholders participating in a residential project. The existing literature has concluded the significance of the KAP framework, yet it revealed that green building KAP of multiple stakeholders' research is still underestimated and limited.

2.4.1 Stakeholders' motivations and barriers to green buildings

Although multiple stakeholders involved in the building industry show interest in green buildings, motivations and barriers to adopting green building standards and certifications differ for different stakeholder groups (Darko et al., 2017). These motivations and challenges have a significant influence on the collaboration among multiple stakeholders and the decision-making process in the green building industry (Olubunmi et al., 2016). According to Allouhi et al. (2015), building regulations and codes that are developed in collaboration between public and private organizations in the green building sector have progressively shifted the built environment in Europe and the Scandinavian countries towards sustainability. Qi et al. (2010) found that managerial concern and government regulatory pressure are the main motivations for adopting green building practices from the contractors' viewpoint. According to Darko et al. (2017), reducing whole lifecycle costs, especially the operational energy cost, comes as the second main drive for green buildings from the stakeholders' perspective, after government regulations. Financial incentives are considered another major driver to promote green buildings (Pitt et al., 2009). The promotion of environmental initiatives is the most important motivation for green buildings followed by lowering building life cycle cost or energy costs (S. C. Wong & Abe, 2014). Hoffman & Henn (2008) argued that promoting green building practices requires more than advancement in green technologies and overcoming economic challenges, social and psychological barriers must be addressed and overcome for structural changes. Affordability and lack of clients' demand are considered key barriers to sustainable built development (Pitt et al., 2009). Wong & Abe (2014) identified the major barriers to achieving Comprehensive Assessment System for Built Environment Efficiency (CASBEE) certifications in Japan as the following; the complexity of the assessment tool, time, and resources required for the assessment process. Tokbolat et al. (2020) found the great barrier to green buildings in Kazakhstan is related to economic aspects, in addition to the lack of government support and social awareness. In Nigeria, lack of awareness from clients and lack of experience among professionals in the construction sector are the key barriers to adopting sustainability standards and practices (Nduka, 2015). Lack of experience from building owners and developers is a major challenge in the Indonesian building industry (Berawi et al., 2019). In view of that, there are differences regarding motivations and barriers, and their ranking, in the previous studies. Motivations and barriers differ between countries based on several variations such as geographical location, market limitations, policy support, as well, between stakeholders according to their knowledge, attitude and practice levels towards green buildings.

2.4.2 Stakeholders' perspective on BIM for green buildings

Another critical benefit of BIM technology is that it facilitates effective collaboration among stakeholders due to a shared vision of the project (Y. Wang et al., 2020) unlike its predecessor, Computer-Aided Design (CAD). BIM can address problems inherent in the construction process which is related to stakeholders' collaboration (Mihindu & Arayici, 2008). To exploit this capability, researchers have sought to better understand stakeholders' collaboration process. Wong et al. (2013) compared the roles of major stakeholders in public and private sectors in the Scandinavian countries for BIM implementations in the building industry, and the study proved that strong public sector support would be still required for the nationwide implementation of BIM. Wang et al. (2020) analysed the relationship among various stakeholders and its dynamic changes throughout a BIM project delivery stages. Becerik-Gerber & Rice (2010) presented the perceived value of BIM in the U.S. building industry, as seen by various stakeholders. Lewis et al. (2019) investigated the perceptions of the stakeholders with regard to the value of BIM-based energy simulation. Murphy (2014) has identified gaps in current BIM literature with respect to stakeholder competency. Linderoth (2010) uncovered mechanisms facilitating and constraining the creation of actor networks in which BIM is adopted and used in the Sweden context.

2.4.3 Stakeholders' perspective on LCA for green buildings

Although the increased number of buildings LCA research, most of these studies considered the technical aspects of LCA for building environmental assessment. Limited research investigated the stakeholders' perspective on LCA value and applications for green buildings. Schlanbusch et al. (2016) conducted 57 semi-structured interviews with different stakeholders in the Nordic building industry with varying knowledge levels of LCA, the results emphasized the need for a better understanding of the LCA process. Sibiude et al. (2014) conducted a survey with the stakeholders in Spain to understand their needs regarding performing LCA and expressing the outcomes. Balouktsi et al. (2020) investigated the designers' level of awareness and acceptance of environmental performance assessment and LCA of buildings.

Chapter 3. Comparison of Green Building Rating Systems from LCA perspective

3.1 Introduction

Buildings account for a considerable proportion of global carbon emissions throughout their lifecycle. As shown in Figure 3.1, emissions in buildings are usually classified as embodied carbon emissions and operational carbon emissions (Cole & Kernan, 1996; Ramesh et al., 2010). Embodied carbon emissions are incurred in the product and construction stages of the building's lifecycle, although embodied emissions may be extended to include the end-of-life carbon emissions, while the operational carbon emissions incurred during the operation stage of the building's lifecycle (Akbarnezhad & Xiao, 2017). The carbon footprint of a building during its lifecycle stages consists of 40% of energy use, 25% of water use, 30% of raw materials use and 25% of solid waste (UNEP, 2020). In this context, there is a growing level of awareness of building environmental impacts on climate change and global warming.

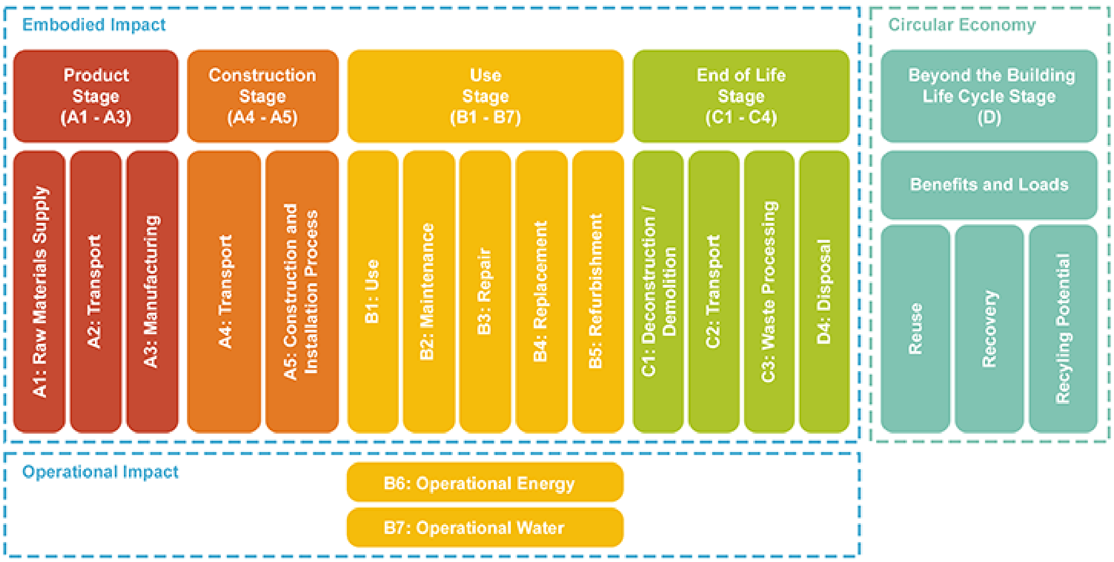


Figure 3.1 Building carbon emissions LCA stages as defined in EN 15978 (WGBC, 2019)

Since the 1990s, Green Building Rating Systems (GBRSs) were developed to evaluate the environmental sustainability of buildings by using similar assessment methodological approaches that cover building energy consumption, indoor environmental quality, water efficiency, waste management and material selection (Solla et al., 2019). Research on rating systems has been carried out since the first GBRS; the British Building Research Establishment Environmental Assessment Method (BREEAM) (Cordero et al., 2019; Mattoni et al., 2018). Chen et al. (2015) examined five GBRSs; BREEAM, LEED, CASBEE, BEAM Plus and GBL-ASGB in terms of the recognition of the passive house approaches and building energy use. Illankoon et al. (2019) compared green building rating tools in Australia and other countries or regions around the world. Bernardi et al. (2017) identified differences in six rating schemes (BREEAM, LEED, CASBEE, DGNB, HQE™ and SBTool) to understand their main features and identify their possible implications. Cordero et al. (2019) demonstrated the heterogeneity of current GRBSs in the European Union (EU) scenario and the difference between sustainability assessments.

Life Cycle Assessment (LCA) is a comprehensive method that was developed in the mid-1980s to evaluate the potential environmental impacts of a product or a process from a life cycle perspective (Finnveden et al., 2009). During the last 20 years, there has been a growing interest in the LCA of buildings (Weißenberger et al., 2014). However, LCA application in buildings is not yet widespread (Soust-Verdaguer et al., 2016) due to its complexity, lack of knowledge and the absence of references (Cavalliere et al., 2018; Roberts et al., 2020; Saade et al., 2020). Recently, LCA has been incorporated into a few GBRSs such as BREEAM, LEED, CABSEE, BEAM Plus, Green Star, etc., at different levels in order to enhance the building environmental assessment process. For instance, the United States Green Building Council (USGBC) established the USGBC Life Cycle Assessment working group in 2004 (Howard & Dietsche, 2005; Trusty, 2006) to investigate the feasibility of incorporating LCA into the LEED rating system to improve the sustainability assessment of buildings. Based on their recommendations, LEED v2009 was released as the first GRBS that integrates LCA and building carbon emissions as an assessment creation (Collinge et al., 2015).

Previous research has been conducted to investigate LCA integration into the international GBRSs (Lee et al., 2017; Ramani & García De Soto, 2021; Sartori et al., 2021; Zuo et al., 2017). Most studies related to LCA integration into GBRSs focused on energy use and carbon emissions produced during the operational stage (Y. Chen & Thomas Ng, 2016). However, some studies have recently argued that the embodied carbon emissions of buildings share a considerable proportion of a building total emissions throughout its lifecycle (Basbagill et al., 2013; Dixit, 2017; Ibn-Mohammed et al., 2013; Iddon & Firth, 2013). Röck et al. (2020) applied a systematic approach to identifying and analysing carbon emissions in the building lifecycle. The results revealed the importance of the upfront carbon emissions, carbon emissions associated with the product and construction stages, as the ration between the embodied emissions and operational emissions increases up to and beyond a ratio of 1:1. Therefore, this chapter aims to compare several GBRSs that incorporates LCA in terms of the (1) LCA integration, (2) recognition and weightings of the building embodied and operational carbon emissions and (3) carbon auditing requirements.

3.2 Methodology

For this comparison study, the latest versions of five existing GBRSs, namely BREEAM, LEED, BEAM Plus, Green Star NZ and Homestar, were reviewed in detail to determine their recognition and weightings of the LCA, moreover, the carbon emissions auditing requirements. The following criteria were considered while choosing the GBRSs for this comparison study; (i) the incorporation of LCA as an assessment criterion, (ii) following a credit-based assessment system, (iii) similar weightings and scoring system, (iv) rating systems for new construction and (v) the availability of English language versions. Table 3.1 shows the selected GBRSs for this study.

To achieve the purpose of this comparison study, the assessment categories of the technical manuals of BREEAM, LEED, BEAM Plus, Green Star NZ and Homestar were examined to determine whether the Whole Building LCA (WBLCA) is integrated as an independent assessment criterion. Following, the study analysed the level of LCA integration, the number of available points and weighting, and the requirements of carbon assessment and auditing. For the embodied carbon emissions, the study explored the assessment categories that evaluate the following building LCA stages: (1) material extraction, (2) manufacturing, (3) construction and assembly, (4) use, replacement and maintenance and (5) end-of-life. Since the operational carbon emissions encompass activities related to the use of a building throughout its life span, this study will explore the assessment categories that cover space and water heating and cooling, lighting and operating appliances (Ibn-Mohammed et al., 2013).

Table 3.1 GBRSs subject to comparison in this study

GBRS	Country	Version	Year
BREEAM	UK and Worldwide	International New Construction v2.0	2016
LEED	USA, Canada and Worldwide	Building Design and Construction v4.0	2019
BEAM Plus	Hong Kong	New Buildings v2.0	2019
Green Star	Australia, New Zealand and South Africa	Design and As-Built v1.0	2019
Homestar	New Zealand	Homestar v4.1	2020

3.3 Findings

3.3.1 Building Research Establishment Environmental Assessment Method (BREEAM)

In the UK, the Building Research Establishment (BRE) released BREEAM in 1990 as the first green building rating system in the world. Subsequently, the international versions of BREEAM were adopted in over 70 countries for evaluating green buildings (BRE, 2016).

The latest international version of BREEAM which was issued in 2016, includes 9 assessment categories for new construction buildings: Management, Health and Wellbeing, Energy, Transport, Water, Land Use and Ecology, Materials, Waste, and Pollution. BREEAM International assesses a wide range of building types such as residential, commercial and education buildings.

In terms of the recognition of Whole Building LCA, there are up to 5 points available for performing LCA of the main building elements using an appropriate LCA tool. However, green building projects can obtain a BREEAM certificate without performing WBLCA as it is an optional assessment criterion. In terms of the recognition of building Embodied Emissions (EE), they are recognised in the "Materials" and "Waste" categories in the BREEAM rating system with 6 points and 4 points, respectively, as shown in Table 3.2.

Table 3.2 LCA and building carbon emissions in BREEAM

	Categories	Credits	Carbon Auditing	Points
LCA	Materials	MAT 01 Life Cycle Impacts	Yes	5*
EE	Materials	MAT 01 Life Cycle Impacts (EPDs) MAT 03 Responsible Sourcing of Construction Products MAT 06 Material Efficiency	Partially	6
	Waste	WST 01 Construction Waste Management WST 02 Recycled Aggregates	No	4
OE	Energy	ENE 01 Energy Use & Carbon Emissions ENE 04 Low Carbon Design ENE 05 Energy-Efficient Refrigeration Systems ENE 08 Energy Efficient Equipment	Yes	23
	Water	WAT 01 Water Consumption WAT 04 Water Efficient Equipment	No	6

* Optional

Reporting and auditing building embodied carbon emissions is partially required in the form of submitting the Environmental Product Declarations (EPDs) for at least five construction materials. On the other hand, the Operational Emissions (OE) are assessed within the "Energy" and "Water" categories with 29 available points of the total points. Reporting the total operational CO_2 emissions is required to achieve credit "ENE 01 Energy use and carbon emissions", but no minimum standards or benchmarks have been set to achieve this credit.

3.3.2 Leadership in Energy and Environmental Design (LEED)

The first version of LEED was released in 1998 by the US Green Building Council (USGBC) (Awadh, 2017). LEED is the most popular rating system in the world based on the number of countries, over 160 countries issued LEED certifications in 2017 (Doan et al., 2017). The latest version of LEED v4 consists of 6 assessment categories; Integrative Process, Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources and Indoor Environmental Quality (USGBC, 2019).

Table 3.3 LCA and building carbon emissions in LEED

	Categories	Credits	Carbon Auditing	Points
LCA	Material and Resources	MR Building Life Cycle Impact Reduction	Yes**	3*
EE	Material and Resources	MR Building Life Cycle Impact Reduction MR Environmental Product Declarations MR Sourcing of Raw Materials MR Construction and Demolition Waste	Partially	11
OE	Energy and Atmosphere	EA Optimize Energy Performance EA Renewable Energy Production EA Enhanced Refrigerant Management EA Green Power and Carbon Offsets	Yes	24
	Water Efficiency	WE Outdoor Water Use Reduction WE Indoor Water Use Reduction	No	8

* Optional (Option 4)
** Report at least three of the following LCA impact categories for reduction:
Global warming potential (greenhouse gases), in kg CO2e;
Depletion of the stratospheric ozone layer, in kg CFC-11;
Acidification of land and water sources, in moles H+ or kg SO2;
Eutrophication, in kg nitrogen or kg phosphate;
Formation of tropospheric ozone, in kg NOx, kg O3 eq, or kg ethene; and
Depletion of non-renewable energy resources, in MJ.

Similar to BREEAM, LEED awards points on the basis of conducting the Whole Building LCA for a building's structure and enclosure. Up to 3 points are available under the fourth option of the "Building Life-Cycle Impact Reduction" assessment criterion that requires demonstrating a minimum of 10% reduction in at least 3 of the LCA impact categories, one of them must be Global Warming Potential (GWP) which represents greenhouse gas emissions (CO_2eq).

However, performing WBLCA is not a mandatory requirement in order to achieve a LEED certification. EE are represented in LEED within the “Materials and Resources” category, which includes EPDs and a sustainable management of construction and demolition waste, with a total of 11 points out of 100 points. On contrary, 32 points are available when assessing building operational impacts through meeting LEED requirements for energy and water use, as shown in Table 3.3.

3.3.3 Building Environmental Assessment Method (BEAM) Plus

BEAM Plus is a voluntary green building rating system in Hong Kong, its first version was issued in 1996 based on the BREEAM rating system (J. K. W. Wong & Kuan, 2014). BEAM Plus consists of 6 assessment categories that cover: Integrated Design and Construction Management, Materials and Waste, Energy Use, Water Use, Health and Wellbeing, and Sustainable Site.

Table 3.4 LCA and building carbon emissions in BEAM Plus

	Categories	Credits	Carbon Auditing	Points
LCA	Materials and Waste	MW10 Life Cycle Assessment	Yes**	1*
EE	Materials and Waste	MW1 Building Re-use MW3 Prefabrication MW5 Sustainable Forest Products MW6 Recycled Materials MW7 Ozone Depleting Substances MW8 Regional Materials MW9 Use of Certified Green Products	Partially	10
OE	Energy Use	EU1 Low Carbon Passive Design EU2 Reduction of CO2 Emissions EU3 Peak Electricity Demand Reduction EU5 Renewable and Alternative Energy Systems EU8 Energy Efficient Appliances	Yes	27
	Water Use	WU1 Annual Water Use WU2 Water Efficient Irrigation WU3 Water Efficient Appliances	No	6

* Optional
** Report at least three of the following LCA impact categories for reduction:
Global warming potential (greenhouse gases), in kg CO2e;
Depletion of the stratospheric ozone layer, in kg CFC-11;
Acidification of land and water sources, in moles H+ or kg SO2;
Eutrophication, in kg nitrogen or kg phosphate;
Formation of tropospheric ozone, in kg NOx, kg O3 eq, or kg ethene; and
Depletion of non-renewable energy resources, in MJ.

In its latest version, BEAM Plus recognises WBLCA. Only 1 point can be awarded for submitting a building LCA report that reports at least three LCA impact categories that do not necessarily include GWP. BEAM Plus requires that the LCA report should cover elements and materials used in the building foundations, walls, façade, and primary and secondary structure (HKGBC, 2019).

Table 3.4 shows that 10 points are available for the "Materials and Waste" assessment category. Similar to BREEAM and LEED, BEAM Plus awards points for materials EPDs, yet it is not mandatory to audit and report the building embodied emissions. Assessment categories that evaluate the building operational phase, Energy and Water, weigh a total of 34 points.

3.3.4 Green Star Design and As-Built

Green Star was first launched by the Green Building Council of Australia (GBCA) in 2003 (Gandhi & Jupp, 2014), and then it was adopted in New Zealand in 2007 (NZGBC, 2021). Green Star is the most used rating system in Australia and New Zealand (Abdelaal & Guo, 2021; Gandhi & Jupp, 2014) and it has 8 assessment categories; Management, Indoor Environmental Quality, Energy, Transport, Water, Materials, Land Use and Ecology, and Emissions, with 100 available points.

In Green Star Design and As-Built, 6 points are available under the "Materials" category for conducting a Whole Building LCA as shown in Table 3.5. Points are awarded based on a cumulative percentage impact reduction (from 30% to 130% reduction) of the LCA impact categories compared to a reference building (NZGBC, 2019). Similar to the other international GBRSs, LCA is an optional assessment criterion in Green Star. Building embodied emissions are recognised within the "Materials" assessment credits with 8 available points, yet auditing embodied emissions is not a requirement to achieve these credits. Building operational emissions are evaluated and reported within the "Energy" and "Water" categories. In order to achieve a Green Star certificate, a building must achieve at least a 10% reduction of GHG emissions during the operational phase compared to a reference building (NZGBC, 2019).

Table 3.5 LCA and building carbon emissions in Green Star Design and As-Built

	Categories	Credits	Carbon Auditing	Points
LCA	Materials	19A.1 LCA	Yes	6*
EE	Materials	20 Responsible Building Materials 21 Sustainable Products 22 Construction and Demolition Waste	Partially	8
OE	Energy	15 Greenhouse Gas Emissions 16 Peak Electricity Demand Reduction	Yes	22
	Water	18 Potable Water	No	12

*Optional

3.3.5 Homestar

Homestar is the New Zealand rating system for residential buildings, which was released in 2010. As shown in Table 3.6, LCA is not recognised in the current version of Homestar v4.1 and the auditing of building carbon emissions; embodied and operational emissions, is not required to obtain the certificate. However, the rating system requires providing recognized environmental certifications for at least 50% of the used construction materials to achieve the "Sustainable Materials" credit.

Table 3.6 LCA and building carbon emissions in Homestar

	Categories	Credits	Carbon Auditing	Points
LCA	-	-	-	-
EE	Materials Waste	MAT-1 Sustainable Materials WST-1 Construction Waste Minimization	No	15
OE	EHC*	EHC-1 Thermal Comfort EHC-2 Efficient Space Heating EHC-5 Hot Water Heating EHC-8 Renewable Energy	Optional	39
	Water	WAT-1 Water Use WAT-2 Sustainable Water Supply	No	14

*Energy, Health and Comfort

In terms of the assessment of the operational phase, Homestar recognises reducing the operational carbon emissions using local renewable electricity generation systems to achieve the “Renewable Energy” assessment credit (NZGBC, 2020). Recently, the New Zealand Green Building Council (NZGBC) issued a pilot version of Homestar v5 that recognises the building embodied impacts and allocated 6 points out of 120 points for the reduction in the building upfront embodied carbon during the product and construction stages.

3.3.6 Comparison of BREEAM, LEED, BEAM Plus, Green Star and Homestar

Table 3.7 shows that the whole building LCA criteria weighting is less than 6% in the studied international rating systems. Green Star Design and As-Built allocates the largest weighting for WBLCA among the analysed rating systems with 5.5% of its total available points. Auditing building carbon emissions is not a requirement of the rating systems except for LEED which mandates reporting the GWP impact category only if a project aimed to achieve the WBLCA credit. Moreover, measuring and reporting building embodied carbon emissions throughout its lifecycle stages is missing in the studied GBRSs. Submitting the Environmental Product Declarations (EPDs) for the construction materials is voluntary and the projects can achieve green building certificates without assessing the embodied impacts. In terms of building operational impacts, the five rating systems recognise and require auditing the operational carbon emissions within the requirements of the “Energy” credits.

Table 3.7 LCA and buildings emissions assessment in five GBRSs

	WB-LCA		Embodied Emissions		Operational Emissions	
	Weighting	CO_2 auditing	Weighting	CO_2 auditing	Weighting	CO_2 auditing
BREEAM	3.3%	Optional	6.6%	Optional (EPDs)	19.3%	Partially
LEED	2.7%	Yes (GWP)	10%	Optional (EPDs)	29.1%	Partially
BEAM Plus	0.5%	Optional	4.8%	Optional	15.9%	Partially
Green Star	5.5%	Optional	7.3%	Optional (EPDs)	30.1%	Partially
Homestar	0%	No	11.5%	Optional (EPDs)	40.7%	Partially

Figure 3.2 illustrates the difference in the average weighting of the embodied and operational assessment in the five rating systems, the average weighting of the embodied emissions assessment in the GBRSs equals almost one-third of the operational emissions assessment. Homestar has the largest portion of the available points for the embodied impacts and the operational impacts with almost 11.5% and 41%, respectively. On the other hand, BEAM Plus has the least weighting for evaluating building total carbon emissions with a total of 21% of the available credits.

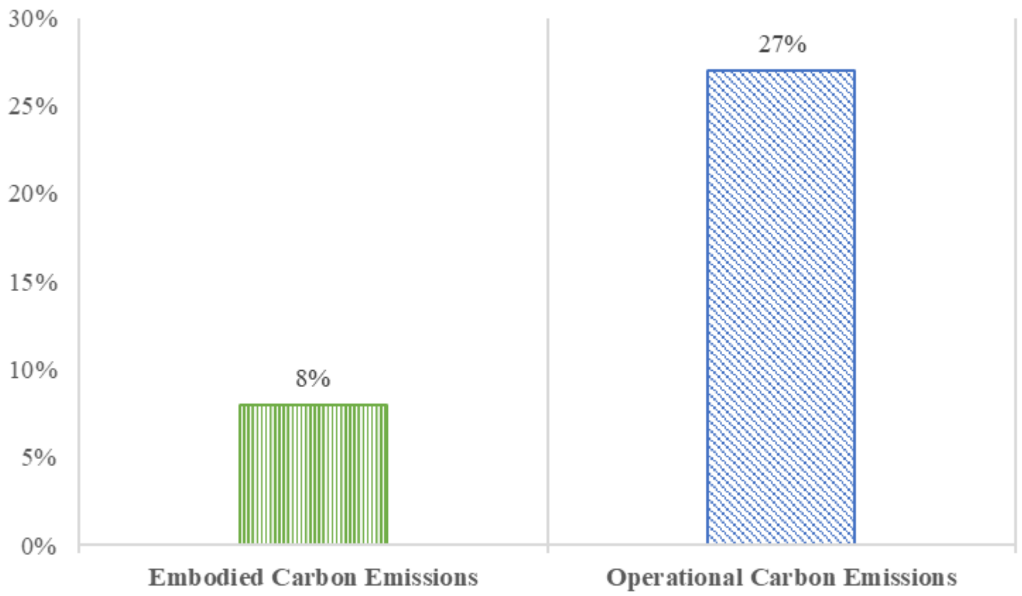


Figure 3.2 Difference in the average weighting of the embodied and operational emissions

3.4 Discussion

Based on the results, LEED, BREEAM, BEAM Plus, Green Star and Homestar share similarities in their recognition and weightings of LCA and building carbon emissions, the embodied and operational emissions. It has been observed that there is almost no difference between an old and widely used rating tool such as BREEAM and young and local rating tools such as Green Star in terms of the recognition and weighting of Whole Building LCA. Conducting WBLCA is an optional assessment criterion in the five rating tools and the available points represent less than 6% of the total points in the rating systems. Previous studies on LCA demonstrated that the complexity and cost associated with the LCA process are the major barriers to LCA (Carmody et al., 2007; Roberts et al., 2020; Zabalza Bribián et al., 2009). Therefore, increasing the weighting of WBLCA in the international rating systems can motivate stakeholders to conduct LCA and report building carbon emissions.

Embodied carbon emissions are usually recognised within materials and waste categories in the GBRSs. However, these systems lack a systematic assessment and auditing of embodied carbon emissions. Although the green building rating systems encourage the selection of sustainable construction materials, building materials are assessed based on qualitative methods as the quantitative analysis, such as LCA and EPDs, is difficult to interpret and requires a robust database (Waldman et al., 2020).

The assessment of building operational stage makes up the major portion of the studied GBRSs, the operational carbon emissions are assessed within the “Energy” and “Water” categories. However, the rating systems require auditing and reporting carbon emissions associated with the energy use stage (B6) as a part of the energy modelling requirement. In contrast, the operational carbon emissions associated with the water use stage (B7) are neglected.

Although the United Nations Environment Global Status reported in 2017 (UN Env. and IEA, 2017) that the embodied carbon emissions will be responsible for almost half of total new construction emissions between now and 2050 (Pomponi et al., 2017), the existing GBRSs are still operational energy-oriented rating systems (as illustrated in Figure 3.3). Therefore, it is doubtful that green building certifications could accurately reflect building environmental impacts during its lifecycle.

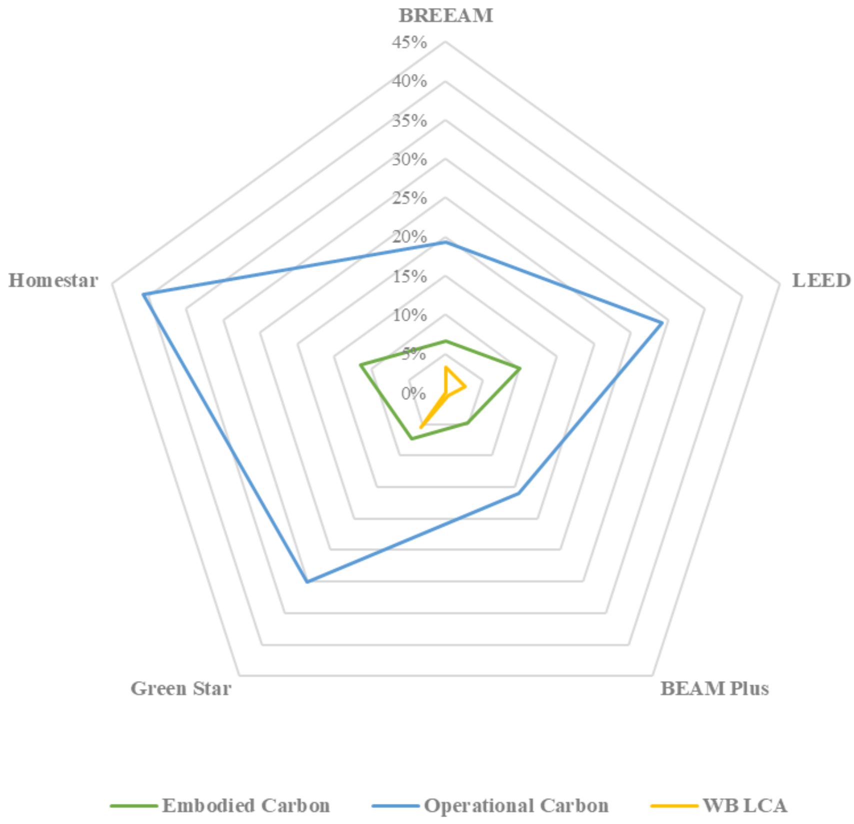


Figure 3.3 Comparison of GRBSs regarding LCA weighting

Furthermore, the absence of environmental benchmarks is another critical issue with the international rating systems, the rating systems lack science-based benchmarks for the building embodied and operational carbon emissions. Although LEED requires a 10% reduction in the Global Warming Potential (CO_2) impact category, this reduction is based on a comparison to a reference building which does not necessarily represent the best practice in terms of the carbon budget and reduction targets.

3.5 Summary

Buildings account for a considerable proportion of global greenhouse gas (GHG) emissions throughout their lifecycle. Green Building Rating Systems (GBRSs) have been developed globally to evaluate building environmental performance and mitigate their impacts on climate change. Recently, Life Cycle Assessment (LCA) as a science-based environmental analysis method has been recognised in the GBRSs to enhance building environmental assessment. Regardless of the wide implementation of GBRSs, building CO_2 emissions have continued to rise by nearly 1% per year since 2010. Furthermore, no academic research has been conducted to compare GBRSs assessment criteria from the LCA perspective in respect of the recognition and weighting of (1) Whole Building LCA, (2) embodied carbon emissions and (3) operational carbon emissions. To this end, this chapter evaluated the efficiency, validity and reliability of five international and widespread GBRSs (i.e., LEED, BREEAM, BEAM Plus, Green Star and Homestar) in terms of assessing and auditing the building total carbon emissions; embodied and operational emissions. Results showed that the existing GBRSs are operational carbon-oriented systems since the assessment requirements for the operational carbon emissions make up the major portion of the total weighting. However, the rating systems ignore the operational emissions during the water use stage of the lifecycle of buildings. By contrast, the assessment and auditing of embodied carbon emissions are limited since the construction materials are assessed qualitatively. Moreover, Whole Building LCA is an optional assessment criterion with negligible weighting. Therefore, shifting focus from operational carbon towards a full life cycle perspective is urgently needed to achieve the emissions reduction targets and so decarbonise the built environment. In a conclusion, this chapter demonstrated that the existing GBRSs are not sufficient and do not provide a holistic assessment method for building environmental impacts and carbon emissions. Based on these results, the following chapter presents a novel approach that integrates WBLCA and the

Distance to Target (DTT) methods to develop science-based carbon emissions benchmarks that can be incorporated into the building rating systems to enhance their validity and reliability.

Chapter 4. Developing carbon emissions benchmarks for buildings using an integrated WBLCA and DTT approach

4.1 Introduction

Processes and practices involved throughout buildings' lifecycle stages (i.e. materials production, construction, operations, maintenance and end-of-life) are intrinsically carbon-intensive. According to the United Nations Environment Programme (UNEP), buildings remain a major area that lacks specific carbon reduction policies despite their importance to global carbon emissions as the share of residential building carbon emissions is 17% in 2019, and 11% for non-residential buildings (UNEP, 2020). Therefore, it is increasingly unlikely for the building industry to achieve the 1.5 °C Paris Agreement climate goals (UNEP, 2020; WGBC, 2021). Several tools and systems were developed for assessing the environmental impacts of buildings such as Green Building Rating Systems (GBRSs). However, the structure and weighting of these tools and systems do not provide a holistic environmental assessment for buildings (Cordero et al., 2019) nor lead to significant reductions in building carbon emissions as demonstrated in the previous chapter of this thesis. Moreover, the existing GBRSs were developed based on technical or economic feasibility rather than the scientifically defined carbon reduction targets (UN and IPCC reports (Frischknecht et al., 2019). The Intergovernmental Panel on Climate Change (IPCC) is an international body devoted to providing a scientific basis for the governmental development of climate-related policies. Hence the existing building environmental assessment systems are considered insufficient.

Life Cycle Assessment (LCA) is another approach for assessing the environmental impacts of buildings, and it is considered a reliable methodology for the environmental decision-making process in the building sector (Anand & Amor, 2017). Although LCA provides scientifically accepted results for building environmental impacts throughout its lifespan, these results do not denote the building environmental impacts on the remaining global carbon budget (Anand & Amor, 2017; Chandrakumar et al., 2020). Therefore, a science-based approach that compares building climate impacts to the global climate reduction targets is necessary to support the built environment transition towards decarbonization.

In recent years, various LCA-based environmental benchmarks were developed as part of academic literature, regulations and building rating systems (Chandrakumar et al., 2020; König & De Cristofaro, 2012; Rasmussen et al., 2019; Roberts et al., 2020; Schlegl et al., 2019; Trigaux et al., 2021; Zimmermann et al., 2005). Regardless of the previous attempts to develop environmental benchmarks for buildings, short-term and long-term carbon emissions benchmarks that achieve the 1.5 °C Paris climate targets are still absent.

The Distance to Target (DTT) is a common weighting approach in LCA that is based on the principle that environmental impacts are weighted according to their distance from the current environmental situation to a defined environmental target (Muhl et al., 2021; Powell et al., 1997). ISO standards define the weighting in LCA as the process of converting indicator results of an impact category into a single value using numerical factors (Muhl et al., 2021), enabling the comparison of LCA results of an environmental impact category. Therefore, the DTT approach can be utilized to develop weighting factors for the building LCA carbon emissions that support carbon mitigation movement. Previous studies investigated the feasibility of DTT in LCA for environmental government policies in China (Lin et al., 2005) and Europe (Castellani et al., 2016), energy and fuels (Weiss et al., 2007) and buildings (X. Li et al., 2015; Su et al., 2019). However, the existing DTT studies have not yet explored the potential of the DTT approach to support establishing carbon emissions benchmarks for buildings throughout LCA stages that align with the global carbon reduction targets.

In that context, this research aims to develop science-based carbon emission benchmarks for buildings based on an integrated LCA-DTT approach. The developed short-term and long-term carbon emission benchmarks are consistent with the Paris Agreement 2030 and 2050 reduction targets and the IPCC 1.5 °C global warming scenario rather than 2 °C. The research also breaks down the carbon emission benchmarks into embodied carbon emissions and operational carbon emissions for the building sector. Moreover, it proposes carbon emissions benchmarks for each LCA stage of buildings. The integrated LCA-DTT approach will be used to develop carbon emissions benchmarks for the residential buildings in New Zealand, where this research is conducted since the New Zealand government is about to release the country's first carbon emissions reduction plan in mid-2022. In the later step, a stand-alone house, which represents a common residential building in New Zealand, is used as a case study to validate the developed benchmarks. LCA will be performed for the case study and the results will be compared with the developed carbon emissions benchmarks in order to identify the current carbon emissions gaps.

4.2 Methodology

4.2.1 The Weighting Factors (WFs) in the DTT method

According to the framework of the Dutch and Swedish Environmental Theme (ET) method (Seppala & Hamalainen, 2001), the WF formula of an impact category is defined as

$$WF_{i\,(\mathrm{t}y)} = \frac{EP_{i\,(\mathrm{r}y)}}{EP_{i\,(\mathrm{t}y)}} \tag{1}$$

Where *WFi* is a weighting factor of an impact category *i* in the year (*ty*), which represents the target year. *EPi (ry)* is the environmental impact potential of impact category *i* in the year (*ry*) which represents the reference year, while *EPi (ty)* is the environmental impact potential of the same impact category in the year *ty* (the target year). Therefore, the reference year and target year are the main indicators in the DTT calculation formula. In order to calculate the WFs of Global Warming Potential (GWP) in CO_2eq, the years 2030 and 2050 were selected as reduction target years according to the Paris Agreement and IPCC report. The year 2018 is the reference year and it was chosen as a reference year in this study due to the availability of the climate impacts data for the New Zealand residential buildings.

4.2.2 The carbon emissions reduction targets

Since the Global Warming Potential (GWP) as an ecological damage category has potential impacts on global climate change (UNEP, 2013), the WFs for the carbon emissions (CO_2eq) will be calculated based on the global emissions reduction targets rather than national policies. Therefore, current global carbon emissions and climate targets in this research are mainly extracted from international statistics and reports, namely, the UNEP Emissions Gap reports (United Nations Environment Programme, 2018, 2020) and the IPCC latest synthesis report (IPCC, 2021). Another factor that has been considered while using the global climate impacts and reduction targets is that the values are derived from the unconditional National Determined Contributions (NDC) scenarios rather than the conditional NDC scenarios. Since the “unconditional NDC” is what countries could implement based on their own resources and capabilities, without any conditions, to achieve the carbon emissions reduction targets (Taibi & Konrad, 2018).

4.2.3 Developing carbon emissions benchmarks for buildings

The calculated WFs will be applied to the climate impact of New Zealand's detached housing sector in order to develop carbon emissions benchmarks for residential buildings for the whole building LCA stages. Detached houses represent up to 80% of New Zealand residential buildings (Chandrakumar et al., 2020; Johnstone, 2001). Due to the absence of official data and statistics on carbon emissions for the New Zealand building sector, the climate impact values in this research are derived from the Building Research Association of New Zealand (BRANZ) research (Chandrakumar et al., 2020). BRANZ calculated the average climate impacts of the housing sector in 2018 using the LCA methodology, following the EN 15978:2011 standard. The scope of the LCA analysis is cradle to grave, for the following life cycle stages: product stage (A1-A3), construction process stage (A4-A5), maintenance (B2) and replacement (B4), operational energy use (B6), operational water use (B7) and end-of-life stage (C1-C4). It was assumed that a New Zealand detached house is properly maintained over its lifetime; therefore, the life cycle stage repair (B3) was not considered. Table 4.1 shows the average carbon emissions of the New Zealand residential building sector in 2018 throughout the building lifecycle. The total climate impact for the new detached housing sector in New Zealand in 2018 was 5950 ktCO_2eq with a total area of 4159782 square metres (Chandrakumar et al., 2020).

Table 4.1 Carbon emissions of New Zealand detached housing sector in 2018 (KgCO_2eq)

LCA stages	A1 - A3	A4 - A5	B2 & B4	B6	B7	C1 - C4
Carbon emissions in 2018	7.23E+08	1.58E+08	7.62E+08	3.59E+09	5.15E+08	2.11E+08

4.3 Results

4.3.1 Weighting Factors (WFs) for the Global Warming Potential (GWP)

Table 4.2 shows the global climate reduction targets for the carbon emissions in carbon dioxide equivalent (CO_2eq) that can keep the level of global warming at 1.5 °C by 2100 based on the recent UNEP and IPCC reports (IPCC, 2021; UNEP, 2020). After applying the DTT equation (1) (Section 4.2.1), the WFs of the carbon emissions are 2.2 and 2.4 for the years 2030 and 2050 respectively (see Table 4.3). By 2050, the carbon emissions need to be 76% lower than in 2018 to limit global warming to 1.5 °C, and the reduction in carbon emissions in 2030 should be 55% lower than emissions in 2018.

Table 4.2 Global targets for carbon emissions reduction (in GtCO_2eq)

Category	Substance	Impact scale	Emissions in 2018*	Target in 2030**	Target in 2050**
GWP	CO_2eq	Globe	5.5E+10	2.5E+10	1.3E+10

*(United Nations Environment Programme, 2020)

**(IPCC, 2021; United Nations Environment Programme, 2020)

Table 4.3 WFs of GWP impact category

Environmental impact	WF (2030)	WF (2050)
GWP (CO_2 eq)	2.2	4.2

4.3.2 Development of carbon emissions benchmarks for the building sector

Table 4.4 presents the carbon emissions of New Zealand's detached housing sector in 2018 and the carbon emissions targets in 2030 and 2050 based on the calculated WFs in the methodology section. When breaking the climate targets down into embodied carbon emissions and operational carbon emissions, 8.43E+08 kgCO_2eq and 4.41E+08 kgCO_2eq are the embodied emissions targets in 2030 and 2050, respectively. While 1.86E+09 kgCO_2eq is the operational carbon emissions target in 2030 and 9.76E+08 $kgCO_2eq$ is the target in 2050 (see Figure 4.1).

Table 4.4 Carbon emissions and climate targets for New Zealand detached housing sector (in $kgCO_2eq$)

	Emissions in 2018	Targets in 2030	Targets in 2050
Carbon emissions	5.95E+09	2.71E+09	1.42E+09

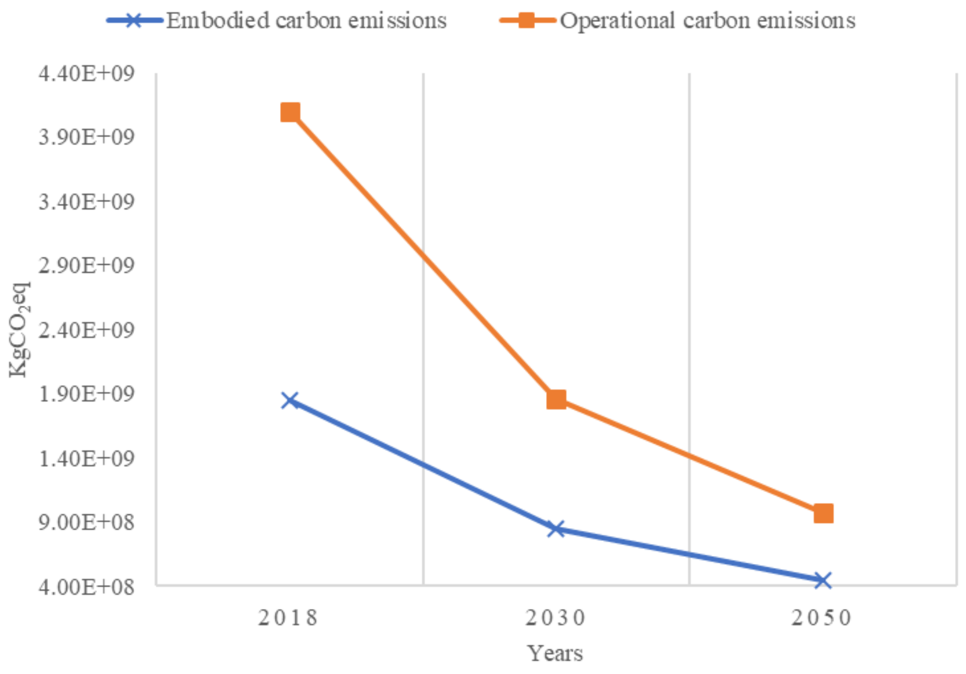


Figure 4.1 Carbon reduction goals for the embodied and operational emissions

4.3.3 Carbon emissions benchmarks for building LCA stages

According to Table 4.5, the average carbon emissions threshold per m^2 of floor area for a new detached house in New Zealand throughout its lifecycle in 2030 for the production stage (A1-A3) is 79 $kgCO_2eq$, 17.3 $kgCO_2eq$ for the construction stage (A4-A5), 83.3 $kgCO_2eq$ for the maintenance and replacement stages (B2 and B4), 23 $kgCO_2eq$ for the end-of-life stage (C1-C4) and 448 $kgCO_2eq$ during the operational stage for energy and water use (B6 and B7).

Carbon emissions benchmarks for 2050 for a New Zealand detached house are around 50% lower than the 2030 benchmarks to allow achieving the 1.5 °C climate target as the following, 234.7 kgCO_2eq for the energy and water use stage and 106 kgCO_2eq for the embodied carbon stages during 90 years which is the life span period of New Zealand houses. Around 41 kgCO_2eq for the product phase, 9 kgCO_2eq during the construction process, 43.6 kgCO_2eq in the maintenance and replacement stages and 12 kgCO_2eq at the building end of life phase.

Table 4.5 Carbon emissions benchmarks for a residential building per square metre (in kgCO_2eq)

LCA stages	Emissions in 2018 per m^2	Targets in 2030 per m^2	Targets in 2050 per m^2
A1 – A3	1.74E+02	7.90E+01	4.14E+01
A4 – A5	3.81E+01	1.73E+01	9.06E+00
B2 & B4	1.83E+02	8.33E+01	4.36E+01
B6	8.62E+02	3.92E+02	2.05E+02
B7	1.24E+02	5.63E+01	2.95E+01
C1 – C4	5.06E+01	2.30E+01	1.21E+01

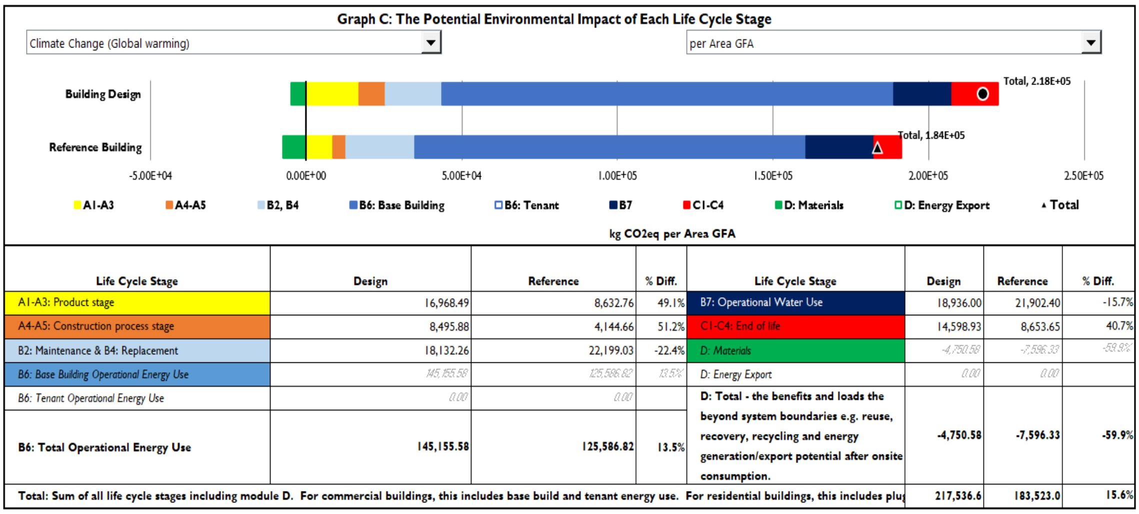
4.3.4 Carbon emissions gaps: a case study

A residential building is used as a case study to validate the developed carbon emissions benchmarks and identify the current carbon emissions gaps by comparing the carbon emissions of the case study and the proposed 2030 and 2050 carbon emissions benchmarks. The case study is a timber-framed stand-alone house in Auckland city, New Zealand. The house was built in 2018 with a typical HVAC system and its total Ground Floor Area (GFA) is 130 m^2. The BIM model of the house was used to extract the building design specifications and bill of quantities for the construction materials to perform the LCA analysis. LCAQuick V3.4 tool was used for that purpose (Figure 4.2); the tool was developed by BRANZ and it is tailored for the New Zealand building sector. The total carbon emissions of the case study are 22.23 ktCO_2eq over its lifecycle. The embodied and operational carbon emissions are 5.8

ktCO$_2$eq and 16.4 ktCO$_2$eq, respectively. Table 4.6 shows the carbon emissions for each lifecycle stage of the case study in kgCO$_2$eq.

Table 4.6 Carbon emissions of the case study over its life span (in kgCO2eq)

LCA stages	A1 - A3	A4 - A5	B2 & B4	B6	B7	C1 - C4
Total carbon emissions	1.70E+06	8.50E+05	1.81E+06	1.45E+07	1.89E+06	1.46E+06
Carbon emissions/m^2	1.31E+04	6.54E+03	1.39E+04	1.12E+05	1.46E+04	1.12E+04



Life Cycle Stage	Design	Reference	% Diff.	Life Cycle Stage	Design	Reference	% Diff.
A1-A3: Product stage	16,968.49	8,632.76	49.1%	B7: Operational Water Use	18,936.00	21,902.40	-15.7%
A4-A5: Construction process stage	8,495.88	4,144.66	51.2%	C1-C4: End of life	14,598.93	8,653.65	40.7%
B2: Maintenance & B4: Replacement	18,132.26	22,199.03	-22.4%	D: Materials	-4,750.58	-7,596.33	-59.9%
B6: Base Building Operational Energy Use	145,155.58	125,586.82	13.5%	D: Energy Export	0.00	0.00	
B6: Tenant Operational Energy Use	0.00	0.00		D: Total - the benefits and loads the beyond system boundaries e.g. reuse, recovery, recycling and energy generation/export potential after onsite consumption.	-4,750.58	-7,596.33	-59.9%
B6: Total Operational Energy Use	145,155.58	125,586.82	13.5%				
Total: Sum of all life cycle stages including module D. For commercial buildings, this includes base build and tenant energy use. For residential buildings, this includes plu					217,536.6	183,523.0	15.6%

Figure 4.2 LCAQuick tool

Figure 4.3 illustrates the emissions gaps between the carbon emissions of the case study and the developed carbon emissions benchmarks for 2030 and 2050. Among all LCA stages, the end-of-life stage (C1 – C4) has the largest carbon emissions gap, followed by the construction stage (A4 – A5). The operational carbon emissions (B6 and B7) of the case study came as third place in terms of the carbon emissions gap compared to the developed benchmarks, then the maintenance and replacement stages (B2 and B4). Finally, the product stage (A1 – A3) has the smallest carbon emissions gap between the carbon emissions in 2018 and carbon reduction targets for the years 2030 and 2050.

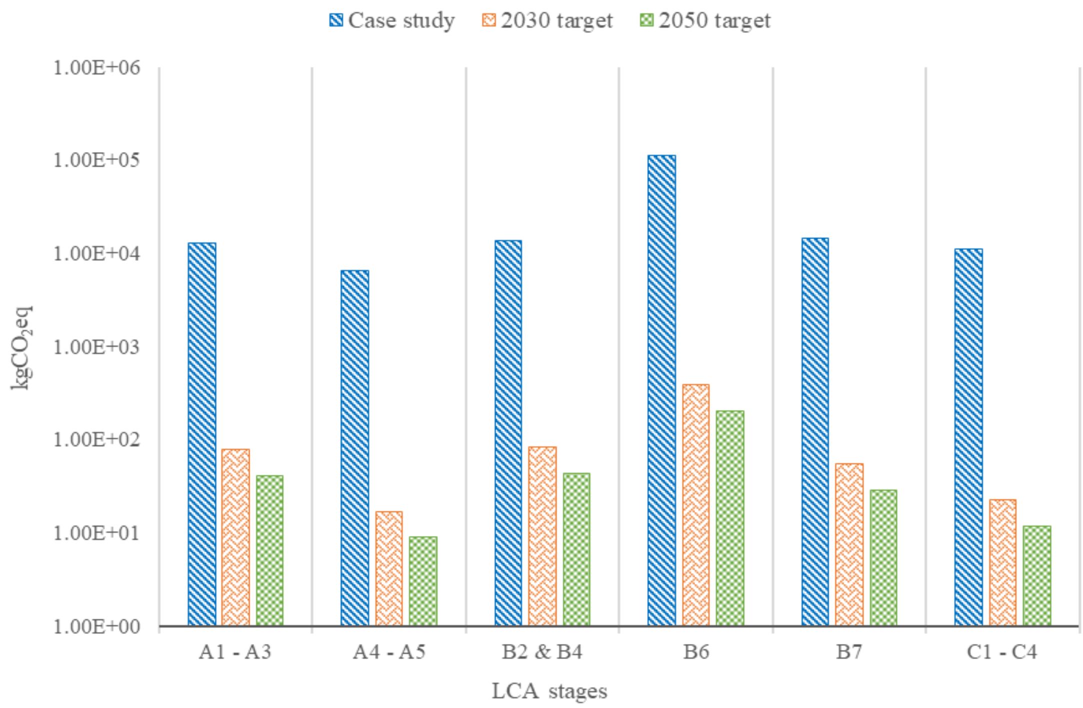


Figure 4.3 Carbon emissions of the case study compared to the carbon benchmarks (in the logarithmic scale)

4.4 Discussion

The absence of scientific-based environmental benchmarks for buildings delays carbon mitigation in the building sector, which is one of the largest contributors to climate change. For this reason, the research developed short-term and long-term carbon emissions benchmarks for the buildings using an integrated LCA-DTT approach, which is a science-based approach. The developed benchmarks are in line with achieving the 1.5 °C global warming that has been scientifically recommended by the IPCC recently.

After applying the calculated WFs values to the building carbon emissions in 2018 in New Zealand, the results reveal that a significant reduction in building carbon emissions is urgent for New Zealand in order to commit to its international obligations. More than a 50% reduction in the total carbon emissions of the New Zealand building sector is required to reach 2710 ktCO_2eq before 2030 for the 1.5°C goals.

The global efforts have been focused on operational carbon emissions in the recent decades which resulted in several energy rating systems such as the Passive House standards. Furthermore, the existing GBRSs lack benchmarks for buildings carbon emissions, theses GBRSs as demonstrated in the previous chapter are operational carbon emissions-oriented and allocate a large portion of the awarded points for the energy use stage (B6). Moreover, the previous chapter demonstrated that the assessment of building embodied carbon is largely based on the quantities of the construction materials regardless of each material's carbon profile. Moreover, LCA exists in the available GBRSs as a merit credit and it represents less than 6% of the total available points. As a result, it has been challenging to track, yet mitigate the embodied carbon emissions of buildings. This chapter shows that to achieve the Paris Agreement goals, a reduction of 1.01E+09 kgCO_2eq and 1.41E+09 kgCO_2eq in the building embodied carbon emissions is needed in 2030 and 2050, respectively. For the operational carbon emissions, the emissions should be reduced to 2.24E+09 kgCO_2eq in 2030, and 3.12E+09 kgCO_2eq in 2050. Therefore, incorporating the developed embodied carbon emissions benchmarks into the existing GBRSs can enhance the reliability and validity of the GBRSs as environmental assessment tools.

A case study of a residential building was used to validate the developed carbon emissions benchmarks and identify the current carbon emissions gaps in New Zealand. Although the operational carbon emissions during the B6 and B7 stages are the largest contributor to building total carbon emissions, the largest emissions gaps were found in the embodied carbon emissions stages, namely the end-of-life (C1 – C4) and construction stages (A4 – A5). Considering the technological developments that reduce operational carbon emissions in buildings, the emissions gap in embodied carbon emissions is expected to continue increasing over time.

The results highlighted that climate mitigation efforts in New Zealand must be allocated towards tracking and mitigating building carbon emissions associated with the embodied carbon stages rather than operational carbon emissions or at least place equal efforts for both carbon emissions. Reducing embodied can emissions can be achieved in several ways such as renovating and reusing buildings, limiting carbon-intensive materials like aluminium and foam insulation, using low-carbon, local and recycled materials, implementing sustainable construction methods that minimize construction and demolition waste, etc. which will have a significant impact on reducing buildings embodied carbon emissions and improving buildings environmental performance. Strict policies and regulations such as carbon tax for exceeding those benchmarks can assist with the carbon reduction process as well.

The carbon emissions gap is increasing rapidly and so achieving long-term targets for 2050 depends strongly on implementing mitigation near-term action by 2030. Thus, this research contributes to the global efforts by developing science-based carbon emissions benchmarks for buildings that can guide the decision-making process and environmental policies in order to overcome the existing carbon emissions gaps in the building sector.

Because of the absence of any official data on the carbon emissions of the building sector in New Zealand, the developed benchmarks relied on BRANZ studies. However, the methodology presented in this chapter, the DTT-LCA integrated approach, can be applied to any set of data for different building types, in any country. It is a generic methodology for developing carbon emissions benchmarks, as well as, for developing benchmarks for the other LCA environmental impact categories such as the Ozone Depletion Potential (ODP) and Acidification Potential (AP), etc.

4.5 Summary

Green Building Rating Systems (GBRSs) have been widely adopted worldwide to evaluate building environmental impacts. However, these GBRSs lack environmental benchmarks for building carbon emissions that evaluate building environmental impacts throughout the whole LCA stages as proved in the previous chapter (Chapter 3). Therefore, developing science-based benchmarks for building carbon emissions that align with the global carbon reduction targets is a crucial step toward reducing building environmental impacts and accelerating decarbonization. To achieve that, this chapter, first, calculated the Weighting Factors (WFs) for the carbon emissions targets in 2030 and 2050 using the Distance to Target (DTT) weighting method. Subsequently, this chapter developed short-term and long-term benchmarks for the embodied carbon emissions and operational carbon emissions for buildings that are aligned with limiting global warming to 1.5 °C. This chapter, furthermore, proposed benchmarks for building carbon emissions for each lifecycle stage from cradle to grave. A residential building was used as a case study to validate the proposed benchmarks and to identify the current emissions gaps by comparing the case study's carbon emissions against the proposed benchmarks for 2030 and 2050. The results revealed significant emissions gaps between the current carbon emissions of the case study and the developed carbon benchmarks for 2030 and 2050. Regardless that the operational phase is the largest contributor to building carbon emissions, the largest carbon emissions gaps have been found in the embodied carbon emissions, in particular, the end-of-life stage (C1-C4) and the construction stage (A4-A5). The proposed WFs and carbon emission benchmarks can effectively guide government carbon reduction policies for the building sector to achieve the 1.5 °C Paris climate targets. Besides, the benchmarks can be incorporated into the GBRSs to enhance their validity and reliability as environmental assessment tools. The following chapter of this thesis will investigate the feasibility of integrating BIM, LCA and the proposed carbon emissions benchmarks to enhance the automation of the assessment process of the green building rating systems.

Chapter 5. BIM-based LCA Framework for Green Building Rating Systems

5.1 Introduction

The Building sector is a substantial contributor to global carbon emissions (UNEP, 2020). As a result, the value of sustainable development has been increased, and it becomes a necessity for the industry to adopt sustainability in order to reduce building environmental impacts (Ramesh et al., 2010). Whilst the world is moving towards its 2050 challenge of achieving zero carbon buildings, it is vital to highlight tools and methods that assist in achieving that goal. Green Building Rating Systems (GBRSs) are assessment tools for evaluating the environmental performance of buildings in the face of the increased demand for sustainability. Over the past two decades, several GBRSs have been issued and applied internationally, such as LEED and BREEAM. New Zealand, as well, has a number of GBRSs to measure and rate the environmental performance of new and existing buildings according to the local specific conditions.

In 2011, the New Zealand Green Building Council (NZGBC) introduced the Homestar rating system as a comprehensive, independent national rating tool that measures the health, warmth, and efficiency of New Zealand residential buildings based on seven (7) categories; Energy, Health, and Comfort (EHC), Density and Resource Efficiency (DRE), Water, Waste, Management, Materials and Site (NZGBC, 2017). However, similar to the majority of GBRSs procedures, the Homestar assessment process requires the end-users (e.g. architect, engineer, quantity surveyor, etc.) to be involved in each step of the assessment process. As shown in Figure 5.1, in order to achieve Homestar certification, the end-user needs to manually collect and enter the required data for the assessment in various calculators (i.e. materials, energy, lighting and water) in the Homestar scorecard to obtain the points. For example, for the assessment of materials category, the end-user has to manually enter relevant data such as material name, manufacturer, material quantity and whether the material has an environmental certificate, eco-label or EPD. Hence, the assessment process is considered inefficient, time-consuming and error-prone.

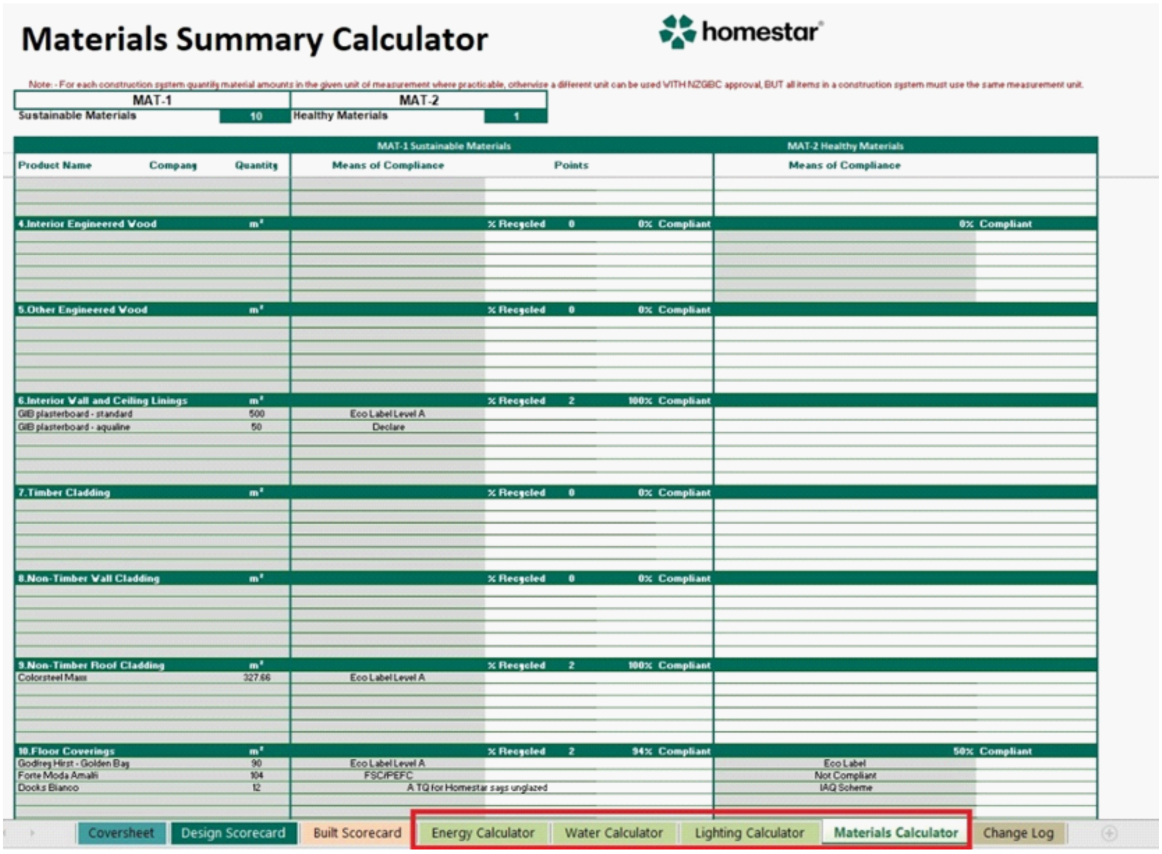


Figure 5.1 Homestar scorecard

Building Information Modelling (BIM) technology provides numerous benefits for building environmental design and assessment (Azhar et al., 2009). It can aid in different aspects of sustainable design, for instance, building orientation, building massing, daylight analysis, water harvesting, energy modelling, and materials selection (Krygiel & Nies, 2008). Previous studies demonstrated that BIM affords great potential for optimizing the green building assessment process (Azhar et al., 2011; Barnes & Castro-lacouture, 2009; Gandhi & Jupp, 2014; J. K. W. Wong & Kuan, 2014; Yahya et al., 2016). However, the adoption rate of BIM in green buildings is still very low and its full potential is yet to be explored (Bueno et al., 2018). Besides, previous research on integrating BIM and GBRSs has not investigated the BIM integration for each assessment criterion within the green building rating systems (Ansah et al., 2019).

Life Cycle Assessment (LCA) is a method that assesses the potential environmental impacts associated with a building's lifecycle stages from cradle to grave (Nwodo & Anumba, 2019; Sibiude et al., 2014). Existing studies on LCA demonstrated its significant impact when incorporated into the building environmental assessment process (Alshamrani et al., 2014; Dekkiche & Taileb, 2016; Humbert et al., 2007). Although LCA has been recently incorporated into several GBRSs at different levels in order to enhance the building environmental assessment process (as discussed in Chapter 3), this incorporation is partial and voluntary (Lee et al., 2017; Ramani & García De Soto, 2021; Sartori et al., 2021; Zuo et al., 2017). Moreover, LCA applications in buildings are not yet widespread (Soust-Verdaguer et al., 2016) due to the complexity of the LCA calculations and available tools (Cavalliere et al., 2018; Saade et al., 2020).

The integration of BIM and LCA has drawn considerable attention in academic research. Recent studies have shown that the integration of LCA and BIM can significantly reduce the time and effort needed for building environmental assessment (Nizam et al., 2018; Nwodo & Anumba, 2019). Efforts have been made to develop and present integrated frameworks and workflows for BIM-LCA in green building literature (Horn et al., 2020; Marrero et al., 2020; Naneva et al., 2020; Santos et al., 2019). Recently, limited studies investigated the relationship between the three approaches; BIM, LCA and GBRSs (Carvalho et al., 2020; Veselka et al., 2020). Veselka et al. (2020) explored the applicability of integrating BIM and LCA for achieving the "Materials" credits in the SBTool rating system in the Czech Republic using the One Click LCA tool. Carvalho et al. (2020) addressed the relationship between BIM and LCA for building sustainability assessment within the Portuguese context. However, the study concluded that the integration of BIM and LCA in building environmental assessment systems has not been adequately explored yet. Thus, the LCA application in the current practices of GBRSs is still infrequent and unusual (Llatas et al., 2020).

In order to fill the research gaps, this chapter aims to (1) develop a comprehensive BIM-based Homestar framework and identified additional data, analysis software and data exchange schemes that support the framework, (2) incorporate LCA and the science-based carbon emissions benchmarks into the tool and (3) develop an integrated BIM-LCA framework for Homestar to optimise the environmental assessment process and enhance the reliability and validity of green building certifications.

5.2 Methodology

As abovementioned, this research aims to present a novel framework that integrates BIM, LCA and GBRSs. This chapter develops an integrated BIM-based LCA framework that incorporates the carbon emissions benchmarks in order to facilitate and optimise the building environmental assessment process. To achieve the aim of this research, a two-step method was adopted (as summarised in Figure 5.2). The first step aimed to develop a comprehensive BIM-based Homestar framework that analyses Homestar requirements compared to the available BIM functions. For that purpose, Autodesk Revit is the BIM platform used for this study as it is the most used BIM tool in the New Zealand building industry (Abdelaal & Guo, 2022). The second step is to integrate LCA and the developed carbon emissions benchmarks into the BIM-based Homestar framework to upgrade the framework to an integrated BIM-LCA framework for Homestar.

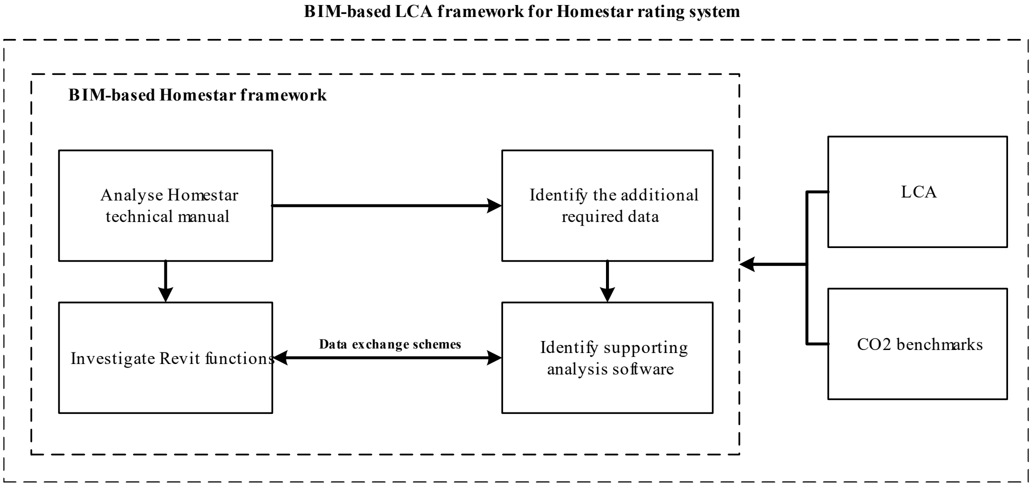


Figure 5.2 Research procedure

5.2.1 Developing a comprehensive BIM-based Homestar framework

In order to develop a BIM-based framework for Homestar, this chapter analyses Homestar v4 Technical Manual to investigate the assessment requirements for each credit within the manual. Thus, the research identifies the potentials and functions of Revit software that simplify and automate each assessment credit of the Homestar v4.1 rating system. A brief introduction of Homestar assessment categories and available points is presented in Table 5.1.

Table 5.1 Homestar assessment categories and points allocation

Category	Number of credits	Points available	Weighting
Density and Resources Efficiency (DRE)	1	8	6%
Energy, Health and Comfort (EHC)	11	60	50%
Water (WAT)	2	14	12%
Waste (WST)	2	6	5%
Management (MAN)	3	6	5%
Materials (MAT)	2	14	12%
Site (STE)	4	12	10%
Total	25	120	100%

In the following step, the research identifies Homestar credits that can be assessed fully or partially using Revit, as well, it identifies credits that can be achieved directly or indirectly using Revit platform. Based on the results of the analysis, BIM capabilities and limitations for the Homestar environmental assessment process were identified and assessed.

For the Homestar credits that can only be assessed partially or indirectly using Revit, this research explores and presents the additional data that need to be collected, the supportive analysis software that can be used for the assessment and the BIM data exchange that enable exporting data from the Revit model and importing it into the supportive environmental analysis software such as Integrated Environmental Solutions (IES), Geographic Information System (GIS), LCA tools, etc. BIM data exchange schemes such as Industry Foundation Classes (IFC) and Green Building XML (gbXML) facilitate the interoperability and data transmission between Autodesk Revit and the analysis software. Moreover, the data exchange formats prevent loss of information, avoid data re-entry, eliminate time-consuming and enhance accuracy (Su et al., 2020).

5.2.2 Developing BIM-based LCA framework for Homestar

This step aims to integrate LCA and the developed carbon emissions benchmarks into the BIM-based Homestar framework in order to develop an integrated BIM and LCA framework for Homestar assessment. To achieve this aim, the research identifies the LCA input data such as energy and water consumption, building service life and materials quantities), and integrates LCA into the Materials, Energy and Water categories of Homestar. LCAQuick tool is used for this integration, Following, the research integrates the carbon emissions benchmarks into the BIM-based LCA framework for Homestar assessment, therefore, the framework can compare the building operation and embodied carbon emissions to the carbon emissions benchmarks. As a result, a BIM-based LCA framework for the Homestar rating system was proposed, the framework incorporates science-based carbon emissions benchmarks for residential buildings in New Zealand for 2030 and 2050. Thus, the framework contributes to optimizing the environmental assessment of the residential buildings in New Zealand during the design stage.

5.3 Results and discussion

5.3.1 BIM-based Homestar framework

5.3.1.1 ***Analysing Homestar assessment credits requirements and Revit functions***

The findings of the research are presented according to the eight categories of the Homestar rating system.

Density and Resource Efficiency (DRE) category

The DRE category awards points for reducing the areas of a residential building and therefore reducing construction materials and resource consumption during the operational stage of the building lifecycle. Information regarding the building areas (such as conditional floor area, gross floor area and building footprint) is required to calculate points underlying this category. According to the Homestar technical manual, the conditional space is the area within the thermal envelope of the building, while the Building Footprint (BF) is “the total floor area of the ground floor, including the thickness of exterior walls. Areas that normally count towards the building footprint include conservatories, garages, permanent outhouses, fully enclosed permanent waste storage areas, communal garages or storage rooms, and any other permanent buildings used by the occupants” (NZGBC, 2020, p. 30). Therefore, data required to achieve the DRE category in Homestar can be fully obtained from the Revit model, and no additional analysis software or external information is needed.

Energy, Health, and Comfort (HEC) category

The second category of the Homestar rating system is Energy, Health and Comfort (HEC). It is considered one of the key categories as it weighs 50% of the total Homestar score. The category focuses on building environmental performance during the energy and water use stages of the building lifecycle such as the heating, ventilation and air conditioning (HVAC) systems, lighting and acoustics. Table 5.2 shows the evaluation of the EHC category using Revit. Data such as building geometry and areas, materials schedule, opening areas (windows and doors), and elements of the surrounding environment causing overshadowing (e.g., buildings, trees) can be directly extracted from the Revit model. However, classes and families can be created in the Revit software for various types of missing building information. For instance, R-values for insulations, Water Efficiency Labelling Scheme (WELS) rating for plumbing fixtures and acoustic ceiling tiles. Afterwards, these data can be extracted from the Revit model using quantify schedule function. On the other hand, the supportive analysis software for energy, thermal and daylight modelling requires external data. For example, in order to comply with the requirements of credits EHC-1 and EHC-2, the suppliers' glazing data sheets are required. In addition, the local weather files for the building site that can be downloaded from the National Institute of Water and Atmospheric Research (NIWA) New Zealand website. The user can avoid this step by relying on the Revit "location" function since Revit collects the required data for the energy simulation (i.e., weather data and sun path) from the nearest local weather station.

Thermal comfort, Efficient space heating and natural lighting credits can be achieved using supportive environmental analysis software such as Integrated Environmental Solution (IES), Autodesk Green Building Studio (GBS) and Revit Insight. GBS and Revit Insight are Autodesk tools, similar to Revit. Therefore, it is a straightforward process to exchange data between Autodesk different tools using data green building XML (gbXML) format for conducting the thermal and daylight analysis.

Table 5.2 Evaluation of the Energy, Health and Comfort (EHC) category

Assessment credit	Revit model	Analysis software	Additional data
EHC-1 Thermal comfort	Partially	IES, GBS, InSight	Local weather files and glazing datasheets.
EHC-2 Efficient space heating			
EHC-3 Ventilation	Partially		Ventilation systems specifications.
EHC-4 Surface and interstitial moisture	Partially		R-values* and the results of air leakage testing.
EHC-5 Hot water heating	None		Type, capacity and pressure of the water system, efficiency ratings of the plumbing fixtures.
EHC-6 Lighting	Partially		Lighting efficacy (lumens per watt) and lighting control systems.
EHC-7 Natural Lighting	Partially	IES, Daysim, Radiance, Dialux	Local weather files and glazing data.
EHC-8 Renewable energy	Partially	BRANZ photovoltaic calculator	Electric Vehicle (EV) charging system specifications.
EHC-9 Sound insulation	Partially		Sound Transmission Class (STC) of the windows.
EHC-10 Inclusive design	Fully		
EHC-11 Energy efficient drying	Fully		

*R-value (also known as thermal resistance) measures the insulation resistance to heat flow

Water category

Water is the third category of the Homestar rating system with 14 points in total. It consists of two (2) sub-categories; water use and sustainable water supply. The water category aims to reduce potable water consumption through using water-efficient fixtures, collecting and using rainwater and encouraging installing separate metering for water consumption. The Revit model usually includes the plumbing data such as the quantities of the plumbing fixtures in the building and the rainwater tank size. However, to complete the assessment process of this category, additional data should be added to the Revit model. For instance, the fixtures specification, and the collection and harvesting systems used for the rainwater (as shown in

Table 5.3). By adding this information to the Revit model, it can allow full assessment of the water category.

Table 5.3 Evaluation of the Water category

Assessment credit	Revit model	Analysis software	Additional data
WAT-1 Water use	Partially	GBS	Water Efficiency Labelling Scheme (WELS) of the plumbing fixtures.
WAT-2 Sustainable water supply	Partially	GBS	Fixtures fitted to the rainwater harvesting system, runoff coefficient of the roof,

Waste category

The Waste category encourages effective waste management practices onsite during the construction stage by implementing a Site Waste Minimisation Plan (SWMP). In addition, it recognizes providing spaces for separating and sorting recyclables and organic waste and therefore reducing the household waste going to the landfill. To achieve WST-1 credit, the Site Waste Minimisation Plan (SWMP) for the entire duration of construction work should be provided. Thus, this credit cannot be assessed using Revit. On the contrary, Table 5.4 shows that by adding the capacity or volume of the internal and external recycle bins to the Revit model, the model can be used for the Household Waste Minimisation assessment credit.

Table 5.4 Evaluation of the Waste category

Assessment credit	Revit model	Analysis software	Additional data
WST-1 Construction waste minimization	-	-	-
WST-2 Household waste minimization	Partially		Volume of internal and external recycled bins

Management category

The main purpose of the Management category is to encourage designing a safe, secure and adaptable house and neighbourhood. Revit can only support the assessment of one credit out of three credits under this management category. The architectural Revit model has the required information for the MAN-1 credit assessment. However, compliance with MAN-2 and MAN-3 credits requires submitting several non-technical documents that cover the features of the building such as Operation and Maintenance manuals, Building User Guide, the contractor’s accreditations, etc. Thus, these two credits cannot be assessed using BIM.

Materials category

The materials category consists of two credits; sustainable materials and healthy materials and it aims to encourage using eco-friendly, responsibly sourced or reused materials. In addition, it recognizes minimising the Volatile Organic Compounds (VOCs) of the interior finishing materials. Points are awarded where at least 50% of the total materials are compliant with the assessment requirements. Revit demonstrates its ability to provide all the required data for achieving the Materials category points by extracting the materials bill using the “schedule” function in Revit (see Table 5.5).

BIM is an information management tool that contains the building materials and their type, specification, and quantities. However, it is recommended to establish a “materials” database for the materials certifications, eco-labels, Environmental Product Declarations (EPDs), and VOC content that can be integrated into BIM platforms to facilitate a fully automated assessment process for the Materials credits.

Table 5.5 Evaluation of Materials category

Assessment credit	Revit model	Analysis software	Additional data
MAT-1 Sustainable Materials	Fully		Materials certifications and eco-labels
MAT-2 Healthy Materials	Fully		VOCs content

Site category

The site category is the last assessment criterion in the Homestar rating system, it rewards the attributes of the site such as effective stormwater management, the contribution to local ecology, cycling facilities and the location of the neighbourhood amenities. Table 5.6 demonstrates that the majority of the required data for the assessment of the site category can be extracted from the architectural Revit model and the site plan. To achieve the Native Planting credit (STE-2), native plants need to be identified in the landscape areas using the "family" function in Revit. Using Geographic Information System (GIS) and Google Maps allows identifying travel distances from the building location to the public transportation stops and neighbourhood amenities. Since additional data such as public transport schedules cannot be available in a Revit model, BIM can partially assess the site category.

Table 5.6 Evaluation of the Site category

Assessment credit	Revit model	Analysis software	Additional data
STE-1 Stormwater Management	Partially		Effectiveness of onsite stormwater management system
STE-2 Native Planting	Fully		
STE-3 Neighborhood Amenities	Partially	GIS, Google Maps	Public transport schedule
STE-4 Cycling	Partially	GIS, Google Maps	Specification of parking facility

5.3.1.2 *BIM-based Homestar assessment*

Based on the analysis results, Table 5.7 presents an overview of the proportion of Homestar credits that can be directly and indirectly evaluated using Autodesk Revit and other supporting environmental analysis software for each assessment. The Density and Resources Efficiency (DRE) category and the Materials category can be fully evaluated using BIM tools. Other categories, namely, Energy, Water and Site can be partially evaluated using a Revit model and additional software such as IES, GIS and Green Building Studio, etc. using data exchange formats. Therefore, BIM can aid with 67% of the Energy points, 21% of the

Water points and 67% of Site points. However, Neighborhood Amenities credit requires modelling the whole neighbourhood to be assessed using a Revit model. Moreover, BIM can support %17 of the Waste points and 33% of the Management points. Overall, BIM tools can aid with calculating 76 points out of 120 points the total points available for the Homestar v4.1 rating system.

Table 5.7 BIM-based Homestar assessment results summary

Homestar Category	Points	Weighting	BIM-based Credits Points	Proportion
DRE	8	6%	8	100%
EHC	60	50%	40	66.7%
Water	14	12%	3	21.4%
Waste	6	5%	1	16.7%
Management	6	5%	2	33.3%
Materials	14	12%	14	100%
Site	12	10%	8	66.7%
Total	120	100%	76	63.3%

5.3.2 Integrating LCA and the carbon benchmarks into the BIM-based framework

Conducting LCA and auditing carbon emissions is not a part of the current version Homestar assessment system, version 4.1, which was released in April 2020. In August 2021, the NZGBC issued a pilot version of Homestar v5, which introduces a new assessment credit “EN2: Embodied Carbon”. This EN2 credit awards 1 point for conducting a whole building whole LCA and a maximum of 5 points for the reduction of the building embodied carbon emissions associated with the product and construction stages (A1-A5). In order to achieve the Embodied Carbon (EN2) credit in Homestar v5, the end-user has to manually enter the information on the building components and materials such as roofs, external walls, internal walls, windows, floors, and floor coverings (as shown in Figure 5.3).

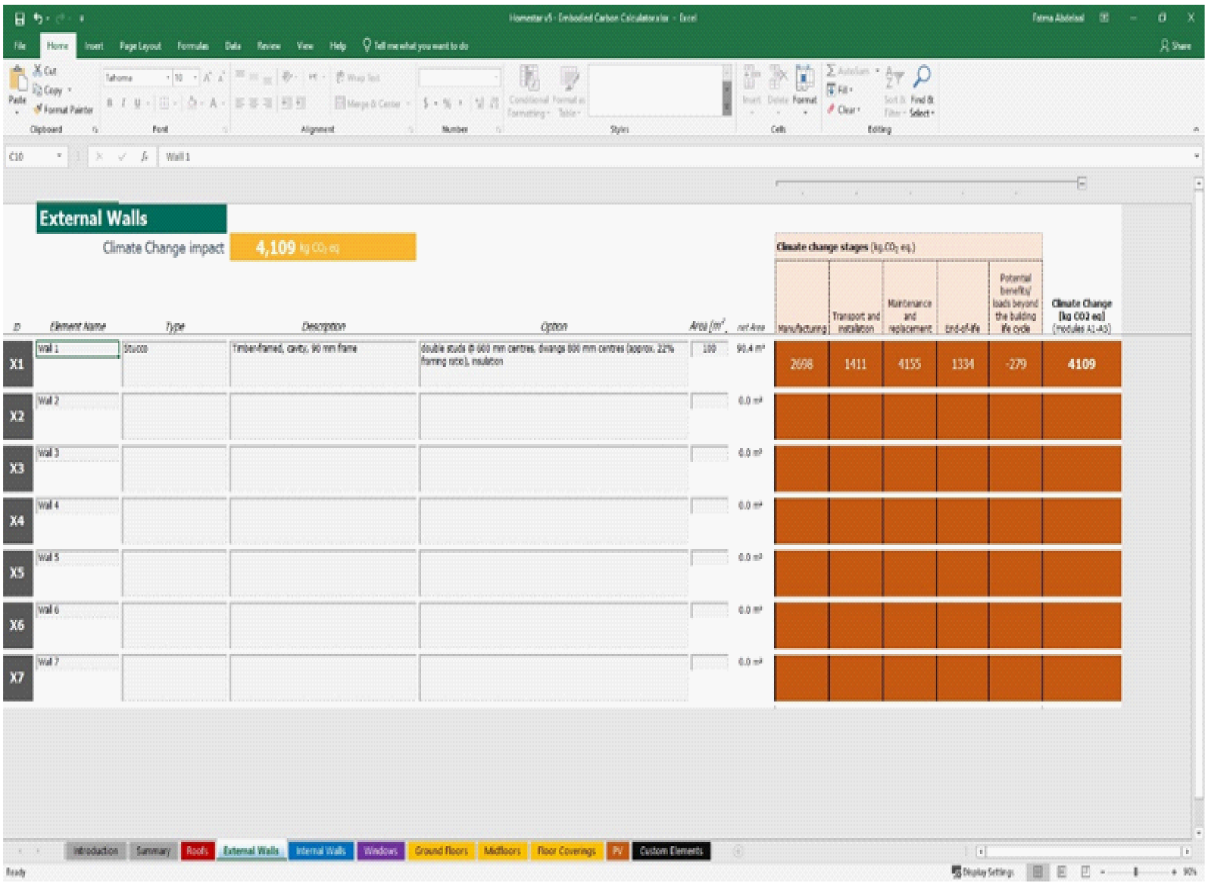


Figure 5.3 Embodied carbon calculator for Homestar v5

First of all, in order to perform LCA through a Revit model, materials ID mapping is required. Thus, the codes of the materials in the Revit materials schedules match the materials IDs in the LCA database software. Using the IFC format, the materials IDs and quantities can be extracted from the Revit model and imported into the LCA tool to do the calculations. For example, the use of an IFC file of the Revit model provides direct access to the model by avoiding the repetition of data insertion in a third party LCA tool. Figure 5.4 illustrates the procedure of integrating LCA and the embodied carbon benchmarks into the BIM-based Homestar framework, for the Materials category. This procedure can be achieved by assigning the same identification number (ID number) to the material in the Revit materials database, then the bill of quantities can be extracted from the Revit model and imported into the LCA tool using the IFC format. Building embodied carbon emissions can be imported from the LCA tool into the BIM-Homestar tool that incorporates the developed carbon emissions benchmarks. However, the Revit model maturity level or Level of Details (LoD) is crucial for accurate LCA results.

A similar process can be followed for improving the assessment requirements of the building operational phase as shown in Figure 5.5. Using the Revit model and its compatible simulation analysis tools such as GBS and Insight is a straightforward method to integrate BIM into the environmental assessment process, then the results can be imported into the BIM-based Homestar tool, using the gbXML format. l. The results, therefore, can be imported into the BIM-Homestar tool using gbXML as well. The BIM-based Homestar framework includes the developed operational carbon emissions benchmarks for the energy and water stages (B6 and B7) of the building LCA. Since few LCA tools support energy demand calculations, LCA cannot yet replace the energy modelling process.

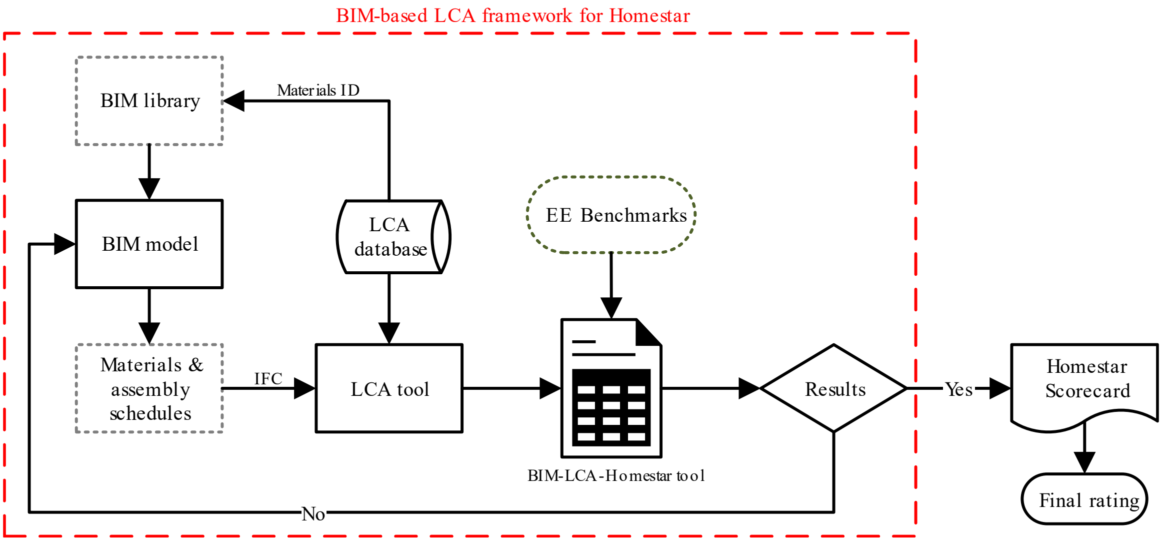


Figure 5.4 BIM-based LCA for Homestar for embodied carbon emissions

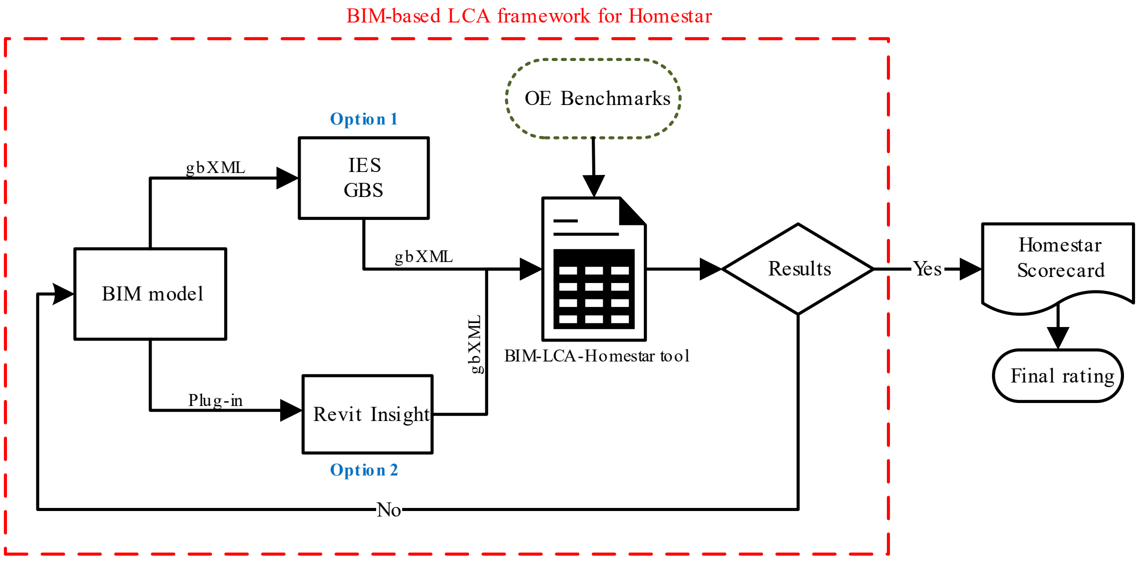


Figure 5.5 BIM-based LCA for Homestar for operational carbon emissions

Finally, Figure 5.6 shows the basis of the BIM-based LCA framework for Homestar assessment categories. The proposed framework consists of three main phases; the first phase is developing a Revit model with an adequate Level of Details (LOD) that includes the additional data required for the assessment such as efficacy ratings of the plumping fixtures, glazing data, lighting efficacy, etc. Moreover, the materials IDs in the Revit model library must match the materials codes in the chosen LCA database. Once the Revit model is developed, the data can be extracted from the model to the environmental analysis software (e.g. GBS, IES, Google Maps, LCA software) in phase 2 using the data exchange schemes in order to perform the thermal and daylight analysis and energy modelling. In phase 3, the data is extracted from the Revit model and the environmental analysis software to the developed BIM-based LCA framework that incorporates the carbon emissions benchmarks. Hence, the end-user can obtain the Homestar final achieved points and rating score for each assessment category, as well as, building embodied and operational carbon emissions compared to the developed science-based carbon emissions benchmarks.

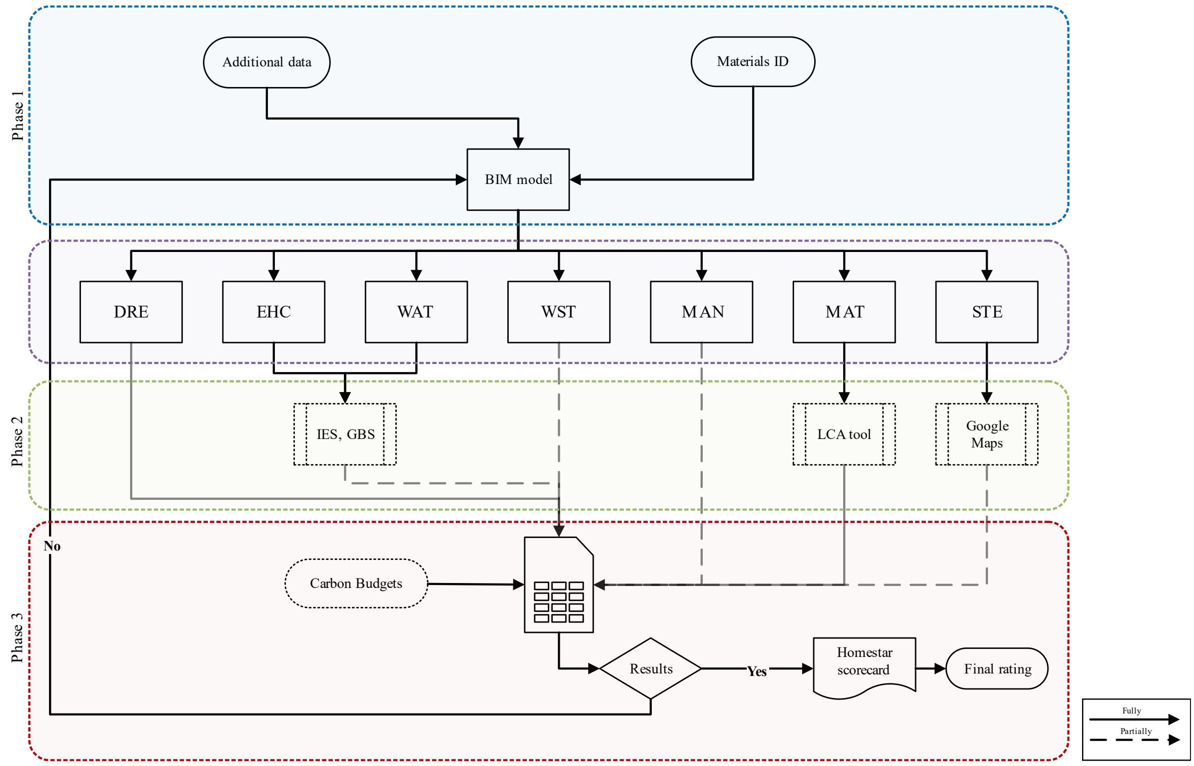


Figure 5.6 Summary of the BIM-based LCA framework for the Homestar rating system

This developed framework aims to optimize and facilitate the building environmental assessment by automating the GBRSs assessment process and improving the accuracy of the assessment results. At the same time, the framework supports end-user decision making and reduces manual data entry and the time of the assessment process. When integrating LCA and the developed carbon emissions benchmarks, the framework can measure and report building operational and embodied carbon emissions throughout its life stages against the remaining carbon budgets, therefore, the framework enhances the reliability and validity of Homestar as a green building rating system. This framework, as well, minimizes the manual entry of the data throughout the environmental assessment process compared to the conventional methods.

Based on the analysis results, the BIM-based LCA Homestar framework can improve the structure of the existing GBRSs by replacing a number of assessment categories with LCA.

For instance, the “Contractors Certifications” and “Construction Waste Minimization” requirements in the “Waste” category can be replaced with the LCA results for the construction stage (A3-A5). Similar, the “Management” category can be replaced with the Operation and Maintenance (B2-B4) stages of the building LCA. Noting that, the Waste and Management categories are the most challenging credits that can be assessed using BIM. Moreover, this chapter raises questions regarding the structure of Homestar and the other international GBRSs. For example, what is the purpose of the “Management” and “Waste” assessment criteria? How can these credits contribute to building environmental assessment? Furthermore, this chapter demonstrated that a fully automated BIM framework for GBRSs cannot be possible with the current structure and requirements of the rating systems.

5.4 Summary

Several building environmental assessment systems exist worldwide to assist with measuring and reporting building potential environmental impacts. Despite the wide implementation of these systems, environmental impacts associated with the building sector keep increasing. Therefore, the existing assessment systems and tools are considered insufficient, time-consuming and effort-intensive as demonstrated in Chapter 3. Efforts have been made to enhance building environmental assessment through integrating Building Information Modelling (BIM) into the building environmental assessment. However, these efforts have not presented a comprehensive investigation for BIM integration into each assessment criteria within the GBRSs. Similar, efforts have been conducted to develop integrated BIM and LCA frameworks. Nevertheless, the integration of BIM and LCA for the GBRSs has not been yet comprehensively investigated. To fill the research gaps, this chapter presented a novel approach that (1) investigated BIM capabilities for each assessment credit with the Homestar as a GBRSs, (2) developed a comprehensive BIM-based Homestar framework and identified additional data, analysis software and data exchange schemes that support the framework, (3) incorporated LCA and the science-based carbon emissions benchmarks into the tool and (4) developed an integrated BIM-LCA framework for Homestar.

The proposed BIM-based LCA framework can evaluate building environmental impacts throughout its lifecycle and reports the building embodied and operational carbon emissions. In addition, the framework contributes to improving the structure of Homestar by replacing several assessment credits such as the “Waste” and “Management” categories.

However, the results demonstrated that developing a fully-automated BIM framework for green building rating systems requires a critical improvement in the current structure of the green building rating systems. Furthermore, it requires a certain maturity level of the BIM model, adequate knowledge level and technical skills. This chapter proposes a conceptual framework for BIM and LCA integration that can facilitate achieving green building certifications. At this stage, there is no technical attempt has been made to develop a tool that implements and validates the BIM-based LCA framework for the Homestar rating system.

The following two chapters of this thesis investigate the influence of the stakeholders on green building practices that can determine whether the integrated BIM and LCA framework can be adopted in the building sector. Besides, it investigates the motivations and barriers to green building assessment tools from the stakeholders’ point of view.

Chapter 6. Stakeholders' knowledge, attitude and practice of green building design and assessment

6.1 Introduction

Buildings are responsible for 35% of global energy consumption and 38% of total direct and indirect energy-related CO_2 emissions (UNEP, 2020; N. Wang et al., 2017). As a result, the concept of green buildings has been introduced as an innovative approach to implementing and achieving sustainability in the building industry. A green building usually refers to a building that has less environmental impacts and high levels of indoor air quality, and energy and water use efficiency compared to a non-green building (Ali & Al Nsairat, 2009). Subsequently, Green Building Councils (GBCs) were established worldwide to monitor and accelerate sustainable development in the built environment (Medineckiene et al., 2015). Each GBC developed its own Green Building Rating System such as Leadership in Energy and Environmental Design (LEED) in the United States and Canada, Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom, Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan, Green Star in Australia, and the International Initiative for a Sustainable Built Environment (SBTool). The New Zealand Green Building Council (NZGBC) was established in 2006, as a member of the World Green Building Council (WGBC), to promote green buildings in New Zealand, and it operates several rating systems such as Green Star, Homestar, HomeFit, and the National Australian Building Environmental Rating System (NABERSNZ). Green Building Rating Systems provide "a way of structuring environmental information, an objective assessment of building performance, and a measure of progress towards sustainability" (Ding, 2008, p. 452), they have common criteria and are similar in terms of their evaluation of such factors as energy consumption, indoor environmental quality, water efficiency, waste management, and material use of a building (Solla et al., 2016).

Generally, there is a lack of studies that investigate multiple stakeholders' knowledge, attitude, and practices of green building design and assessment. In addition, different stakeholders may have distinct perceptions of green building design and assessment (Darko et al., 2017). Moreover, motivations and barriers identified in other studies cannot be transferrable to the New Zealand green building industry, and more attention is required to identify and acknowledge motivations and barriers that exist within the New Zealand context (Macgregor et al., 2018), in order to assist with developing effective engagement frameworks, thus improving collaboration and decision-making process in the green building industry. Hence, investigating the main stakeholders' knowledge, attitude and practices of green building design and assessment is essential to understand the dynamic interactions and promote coordination among them (Du Plessis & Cole, 2011).

According to a study conducted by the Building Research Association of New Zealand (BRANZ), there is a circle of blame exists that is stopping the transformation of the Architecture, Engineering and Construction (AEC) industry in New Zealand to make it more responsive to climate change. BRANZ study called for "system changes are needed to behaviours, attitudes, practices and policies especially around encouraging information flows within the building system to turn the circle of blame into a virtuous circle" (Macgregor et al., 2018). Thus, the complexity of stakeholders' collaboration and conflicts should never be underestimated. To the best of our knowledge, no similar study is available for the New Zealand context. Therefore, it is worthwhile to examine the green building KAP levels of multiple stakeholders in the New Zealand building industry and to investigate their motivations and barriers to adopting green building standards and certifications.

To fill the research gap, this chapter aims to (1) investigate and contrast the KAP levels of the major stakeholder groups who are involved in the green building design and assessment process in New Zealand, (2) understand the correlation between KAP levels among the multiple stakeholders, and (3) identify the motivations and barriers to green buildings in New Zealand as a country, and for each stakeholder group to implement green building design standards and assessment. The study contributes to the multiple stakeholders and policymakers for the New Zealand green building industry by providing a holistic picture of the green building industry in the country and proposing recommendations for enhancing collaboration, promoting green buildings, and implementing New Zealand green building rating tools.

6.2 Methodology

The Knowledge, Attitude, and Practice (KAP) framework is commonly used in medical and public health research, and it is usually used to facilitate evidence-based interventions to improve the situation or behaviour of a target group. The key component of a KAP study is a questionnaire survey (World Health Organization, 2008). Therefore, applying the KAP for green building research will help to identify the commonalities and differences among various stakeholders. A KAP study should enable a comprehensive understanding of the relationships between knowledge, attitude, and practices of multiple stakeholders, and it will generate insightful implications for sustainable development and green building implementation.

Questionnaire design

The KAP questionnaire survey was designed based on the aforementioned literature, the World Health Organization (WHO) guide on developing KAP surveys (World Health

Organization, 2008), and several discussions with experts and professionals in the green building industry in New Zealand. The purpose of the KAP questionnaire survey is to explore the knowledge, attitude and practice of key stakeholder groups who are involved in the green building design and assessment process in New Zealand such as architects, engineers, sustainability consultants, developers, contractors, and suppliers. The questionnaire (see appendix B) consists of 16 questions divided into four sections. Participants were allowed to enter text answers for most of the questions to express their opinion and share their knowledge and experience in more detail. The first section of the questionnaire is "general background" questions that cover the demographic characteristics such as the participant's role in the building industry, years of experience, the business size, and whether the participant has been involved in green building projects. The other three sections measured the KAP levels as follows:

Section A: Knowledge

The aim of this section is to test the green building knowledge of the different stakeholders by asking them about their main source of knowledge on green buildings (Che Ibrahim & Belayutham, 2020; Toh et al., 2017), whether they are green building certified professionals and their understanding of the green building standards and assessment requirements

Section B: Attitude

This section investigated the various stakeholders' attitudes in terms of their awareness and sense of responsibility towards green buildings (Banaji & Heiphetz, 2010; Pan & Pan, 2020). Furthermore, it asked the participants to identify their motivations and barriers to increasing the adoption rate of green building standards and certifications. The section also explored the stakeholders' perception regarding leading sustainable development in the country and improving current assessment tools' requirements.

Section C: Practice

The last section of the questionnaire looked into the frequency of participating in green building projects and the multiple stakeholders' experience with the New Zealand green building rating tools (Pan & Pan, 2020). In addition, this section investigated the participants' level of agreement with the current practices and whether it improves the built environment. In order to compare the KAP levels of the participants; "Rate your understanding of New Zealand green building rating tools" question was chosen to assess the stakeholders' knowledge and understanding of green building standards and assessment requirements since "understanding" implies a working knowledge of an idea, its importance, and it also involves appreciation (Roush, 2017). For attitude, "Who can lead the main role in promoting green building ratings in the AEC industry in New Zealand?" question was selected as it indicates the sense of awareness and responsibility toward promoting green buildings (Banaji & Heiphetz, 2010). To investigate the participants' practice level, their answers to "How frequently have you been involved in green building projects?" question indicated the actual application of green building standards and knowledge (Badran, 1995).

Data collection

The questionnaire survey was approved by the Human Ethics Committee (HEC) at the University of Canterbury, and it was administered using an online survey software tool, Qualtrics survey software. The anonymous link to the online survey was sent via email to NZGBC staff members and a number of experts in the green building industry to conduct pilot surveys. 5 pilot surveys were performed prior to administering the survey to assure face validity, improve the clarity of the instruction, and check the understanding and the length of the questionnaire (Goh & Chua, 2016; Toh et al., 2017). After integrating the feedback of these first participants, the questionnaire was distributed online among key stakeholder groups of the green buildings industry in New Zealand.

Potential participants were selected using random sampling to minimize error and bias in the sampling process (Fellows & Liu, 2015) in order to obtain a representative sample of the population that represents key stakeholders involved in the New Zealand building industry. The multiple stakeholders were defined as six (6) key stakeholder groups; architects, engineers, developers, sustainable building consultants, contractors, and suppliers, using the membership database of the supporting organizations and associations in New Zealand. Over hundreds of the industry professionals and different stakeholders were invited to the survey through emails, online platforms such as LinkedIn, relevant associations and organizations, and architecture and engineering companies that circulated the survey to their members and teams, in order to maximize the stakeholders' participation and achieve an effective response rate that represents the targeted population.

Data analysis

A total of 268 attempted responses were received. 53 out of 268 questionnaires were dropped due to missing and uncompleted responses. As a result, 215 of the valid and completed questionnaires were kept for data analysis (80% completion rate). A comparison with other relevant studies regarding the sample size was carried out, and the sample size of this research is considered appropriate compared to 219 (Pan & Pan, 2020), 77 (Berawi et al., 2019), 48 (Goh & Chua, 2016), and 257 (Toh et al., 2017). Furthermore, due to the relatively small market size of New Zealand, the sample size is considered representative of it. The collected responses were converted using SPSS software for conducting descriptive analysis; percentages and standard deviation to explore and measure the differences in KAP levels, and to determine if there are statistically significant differences in means between the multiple stakeholders' motivations and barriers.

Before conducting the statistical analysis, tests of Normality (Kolmogorov-Smirnov and Shapiro-Wilk) were performed and the results showed that the significance value p is less than 0.05, then the data do not follow a normal distribution, so the nonparametric analysis approach has been chosen for the study. A Kruskal-Wallis Test which is a nonparametric approach of the One-Way ANOVA Test was conducted since it has the ability to compare three or more groups of dependent variables that are measured on an ordinal level (Elliott & Hynan, 2011). Pairwise comparisons were performed using Post- Hoc Test where significant differences were identified. Nonparametric correlation coefficients (Pearson, Kendall’s tau-b and Spearman’s rho) were conducted to evaluate the association between the KAP levels of the multiple stakeholders with regard to green buildings design and assessment and to measure the significance of the relationship between KAP levels, the value of the correlation coefficient (p) varies between +1 and -1 (Liu et al., 2007).

6.3 Analysis and results

6.3.1 Background and demographic characteristics of questionnaire participants

The 215 participants who completed the valid questionnaires covered a wide range of the targeted stakeholder groups in the New Zealand green building industry. Descriptive statistics of the demographic characteristics of the participants are presented in Figure 6.1. The stakeholder groups consisted of architects (16.7%), engineers (19.5%), developers (5.1%), sustainable building consultants (14.8%), contractors (6.9%), suppliers (16.2%), the “other” stakeholder group (13.7%) includes project managers, government agents, academic researchers, etc.

Table 6.1 shows the professional background of the participants. Only 20% of the total participants have not ever been involved in green building projects. Among all, 33.3% of the contractor group had no prior experience in green building design and assessment, followed by the developers (27.3%) and the suppliers (24.2%). About 48% of the participants had over

15 years of experience in the New Zealand building industry. The majority of the participants (70%) work in small and medium-sized enterprises “SMEs”. This percentage fits the nature of the building industry in New Zealand as a small island country.

Figure 6.1 Role of the participants in the green building industry (n=215)

Table 6.1 Demographic characteristics of the questionnaire participants (n=215)

	Architect	Engineer	Developer	Consultant	Contractor	Supplier	Other
Years of experience							
1 – 4 years	11.4%	7.3%	9.1%	18.8%	13.3%	30.3%	20.5%
5 – 9 years	14.3%	29.3%	18.2%	15.6%	13.3%	18.2%	18.2%
10 – 15 years	14.3%	19.5%	9.1%	9.4%	20.0%	15.2%	20.5%
+ 15 years	60.0%	43.9%	63.6%	56.3%	53.3%	36.4%	40.9%
Business size							
1 – 10 employees	34.3%	22.0%	27.3%	21.9%	26.7%	24.2%	25.0%
11- 50 employees	34.3%	34.1%	36.4%	21.9%	6.7%	33.3%	20.5%
51 – 100 employees	17.1%	7.3%	0.0%	25.0%	53.3%	9.1%	20.5%
+ 100 employees	14.3%	36.6%	36.4%	31.3%	13.3%	33.3%	34.1%
Green Building Experience							
Yes	88.6%	80.5%	72.7%	87.5%	66.7%	75.8%	77.3%
No	11.4%	19.5%	27.3%	12.5%	33.3%	24.2%	22.7%

6.3.2 Green building design and assessment knowledge

Work experience is the main source of knowledge for the stakeholders except for the architects, training courses came as their first source of knowledge with 54.3% which is slightly higher than work experience (51.4%) as shown in Figure 6.2. Self-learning from online resources such as articles, webinars, podcasts, etc. was perceived as one of the most common sources of knowledge among the multiple stakeholders in New Zealand. Tertiary education and academic research were ranked as the last sources of knowledge according to the multiple stakeholders' responses. The following sources of information were also mentioned by the participants*; "conferences and affiliation with relevant organizations such as World Green Building Council (WGBC), New Zealand Green Building Council (NZGBC), Energy Efficiency & Conservation Authority (EECA), Passive House Institute of New Zealand (PHINZ), Living Building Institute"* and *"sharing information with colleagues."*

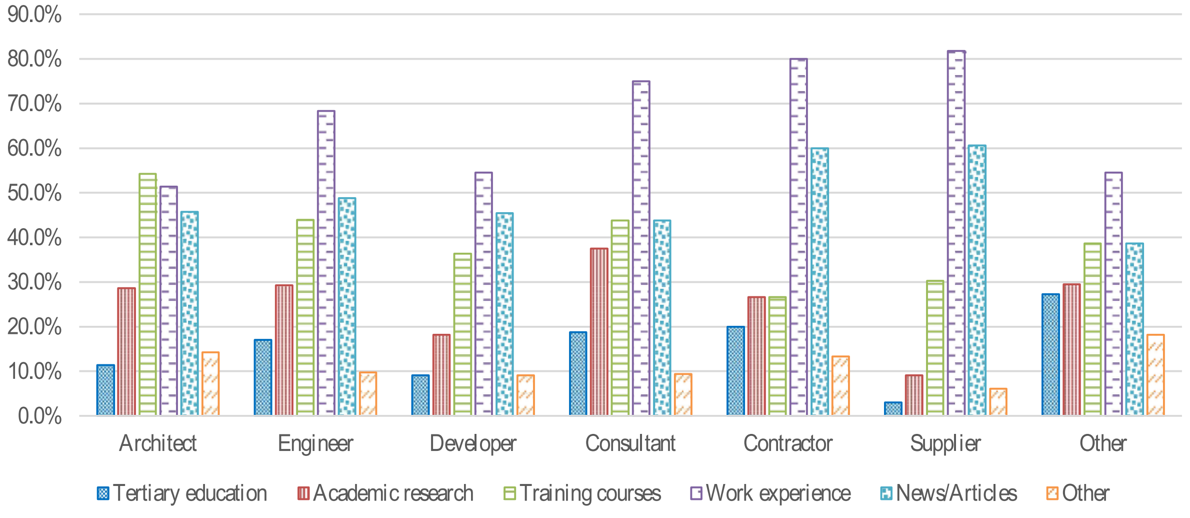


Figure 6.2 Stakeholders' main source of green buildings

Figure 6.3. shows the participants' self-rating of their understanding of the green building rating tools such as Green Star NZ, Homestar, Passive House standards, and the National Australian Built Environment Rating System New Zealand (NABERSNZ). Almost half of the respondents perceived their understanding of the green building tools as "Excellent" and "Good" with 12% and 40% respectively. Among the groups, architects rated their understanding of the rating tools as the highest, while the contractors' and suppliers' understanding level was the lowest. This suggests providing tailored training courses for these two groups to improve their understanding of the rating tools and certification requirements. In this regard, a participant suggested that *"more information should be sent out to contractors when working on their green building projects from the consultants so it can be discussed at a toolbox talk to spread the wider knowledge of what subcontractors onsite are building."*

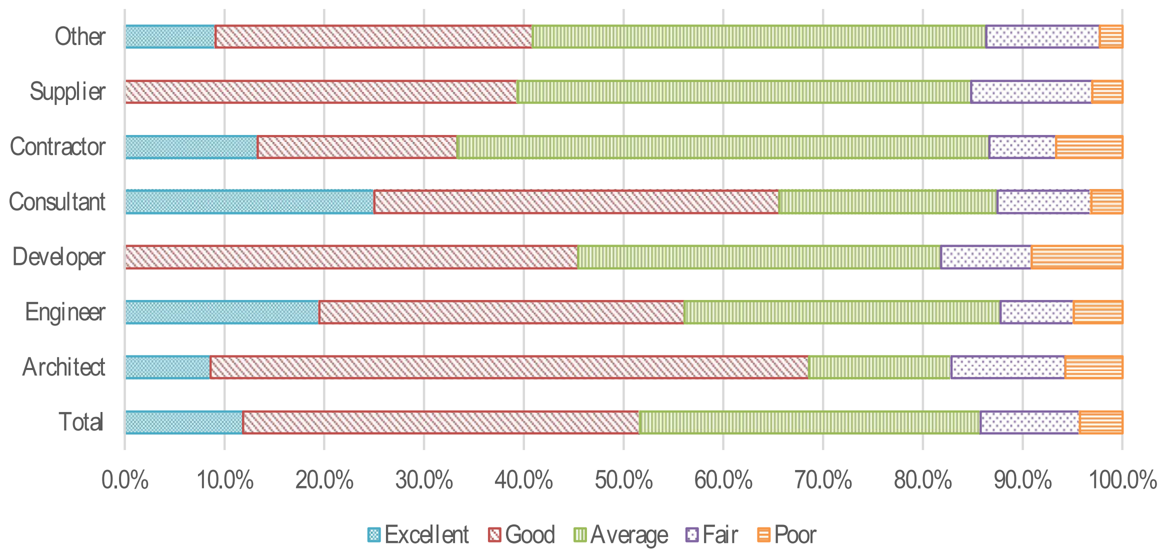


Figure 6.3 Stakeholders' understanding of the green building standards and rating tools

Although 62% of the participants claimed to have an "Excellent" or "Good" understanding of the green building rating tools, almost 67% of the total participants have not achieved the

Accredited Professional qualifications (Table 6.2). The architect group had the highest proportion of Green Building Accredited Professionals (53%) which can explain their high level of knowledge of green building design and assessment requirements. A participant made the following statement: *"In my opinion, industry knowledge and skills around green building, building science, and the calculation of energy, Indoor Environmental Quality (IEQ), and environmental impact is a large obstacle to increased update. Most of this is concentrated in building science and engineering disciplines."*

Table 6.2 Percentage of Green Building Accredited Professionals (GBAPs) among the multiple stakeholders

	Total	Architect	Engineer	Developer	Consultant	Contractor	Supplier	Other
Yes	33.2%	54.3%	31.7%	27.3%	50%	26.7%	15.2%	22.7%
No	66.8%	45.7%	68.3%	72.7%	50%	73.3%	84.8%	77.3%

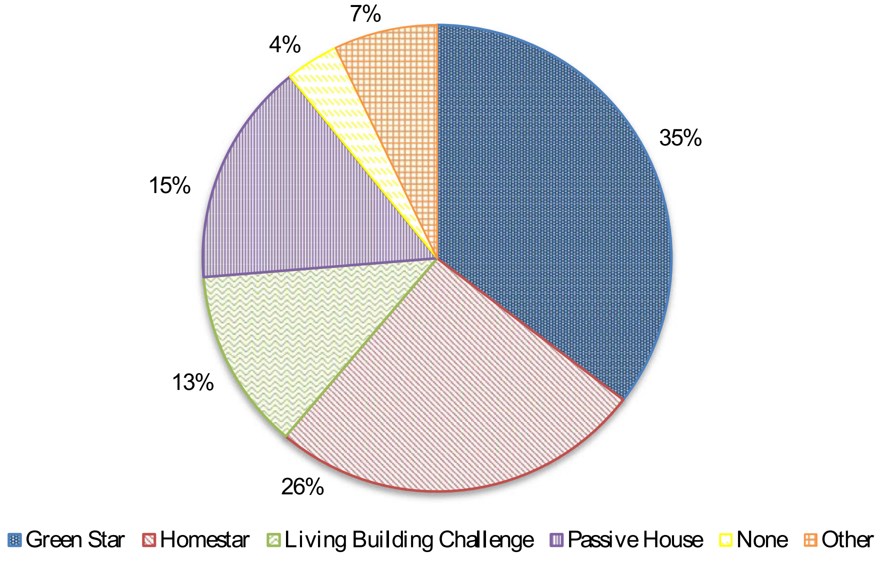


Figure 6.4 Green building rating systems used in New Zealand

The last question in the knowledge section was about what green building standards and rating tools the participants have experience with. As shown in Figure 6.4, Green Star NZ was the most used rating tool in the country with 35%. Around 26% of the participants had experience working with Homestar, followed by Passive House Standards with 15%. Regarding the international standards and rating tools, Living Building Challenge was fairly used in New Zealand (13%). LEED, BREEAM, WELL Building Standard, and Green Star Australia were mentioned under "other".

6.3.3 Attitude towards green building design and assessment

6.3.3.1 *Stakeholders' motivations for green buildings*

The questionnaire results indicated that the biggest motivation for the stakeholders, regardless of their role in the industry, was reducing building environmental impact (80%), followed by improving quality of life (58%), and low running cost (48%), as represented in Table 6.3.

Table 6.3 Stakeholders' motivations for green buildings

Motivations	Total	Mean	SD	Rank
Reduce environmental impacts	29.7%	24.1	9.9	1
Improve quality of life	21.4%	17.4	8.1	2
Low running cost	17.7%	14.4	7.4	3
Government regulations	4.5%	3.7	2.7	6
Client demand	11.7%	9.6	5.2	5
Organization image	12.1%	9.9	4.0	4
Other	2.6%	2.1	1.0	7

The first three main motivations cover the three pillars of sustainability: environmental, social, and economic. Except for developers, they identified the organization's image and reputation as their first motivation for green buildings for *"sales advantage"* as explained by one of the participants. Improving the quality of life and reducing running costs ranked as the least motivations for green buildings in the developers' perspective (Figure 6.5). "*Reducing carbon footprint"* was highlighted as a significant motivation by participants. Considering that client demand, government regulations, and organization image were ranked as the lowest motivations for the majority of the multiple stakeholders involved in the green building sector in New Zealand, it demonstrates a positive attitude towards green building standards and rating tools. It also represents a high level of awareness of building environmental impacts.

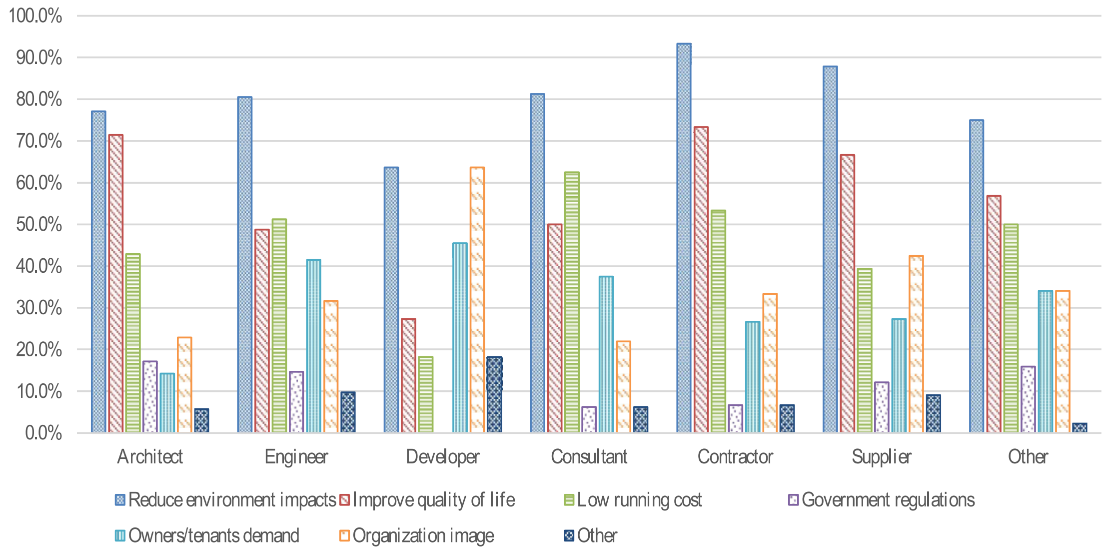


Figure 6.5 Each stakeholder group's motivations for green buildings

6.3.3.2 *Barriers to green buildings design and assessment*

Table 6.4. illustrates that a significant number of the participants (65%) considered the upfront cost that is associated with the green building design and assessment process as the major barrier that slowed the adoption of green building concepts and rating tools in New Zealand, followed by the lack of government support (44.5%). One of the participants concluded that "*It needs further development and driven further by government and by industry leaders. It is hard to implement green buildings due to the often-extensive higher costs compared to the building code alternative. Require subsidy or better availability and market competition for "greener" materials and products to make it more affordable to build more sustainable support.*"

Building codes and clients were ranked by the multiple stakeholders as the third and fourth barriers with (37.4%) and (36%) respectively. However, the engineer, consultant, and contractor groups rated the lack of clients' demand as the third barrier, overriding outdated building codes. Clients are defined as the end-users with funds who are responsible for financing green building projects (Chan et al., 2017; Love et al., 2012). A participant who belongs to the engineers' group stated that *"Often design professionals specify good quality green products and systems but building owner /client take them out for cost-cutting*".

Table 6.4 Barriers to green buildings identified by the stakeholders

Barriers	Total	Mean	SD	Rank
Lack of government support	44.5%	13.4	6.4	2
Assessment process timeframe	20.4%	6.1	3.1	7
Cost	65.4%	19.7	7.1	1
Technical skills	27.5%	8.3	4.3	5
Data availability	15.2%	4.6	2.5	8
Building codes	37.4%	11.3	6.1	3
Market limitations	20.9%	6.3	3.0	6
Clients	36.0%	10.9	4.9	4
Other, please specify	10.0%	3.0	2.1	9

The architects considered the lack of technical skills as one of the major barriers to achieving green building standards and ratings (Figure 6.6), this barrier can be associated with another barrier *"complexity of the rating tools"* which was mentioned by many participants. *"Outdated construction methods compared to Europe"* was also mentioned as another barrier. Data availability, market limitations, and time required for the green building assessment process were ranked as the least obstacles in the New Zealand green building industry. However, a participant argued that *"the industry mindset and the lack of consistency"* is the first barrier to increasing the current uptake of green building standards and certifications.

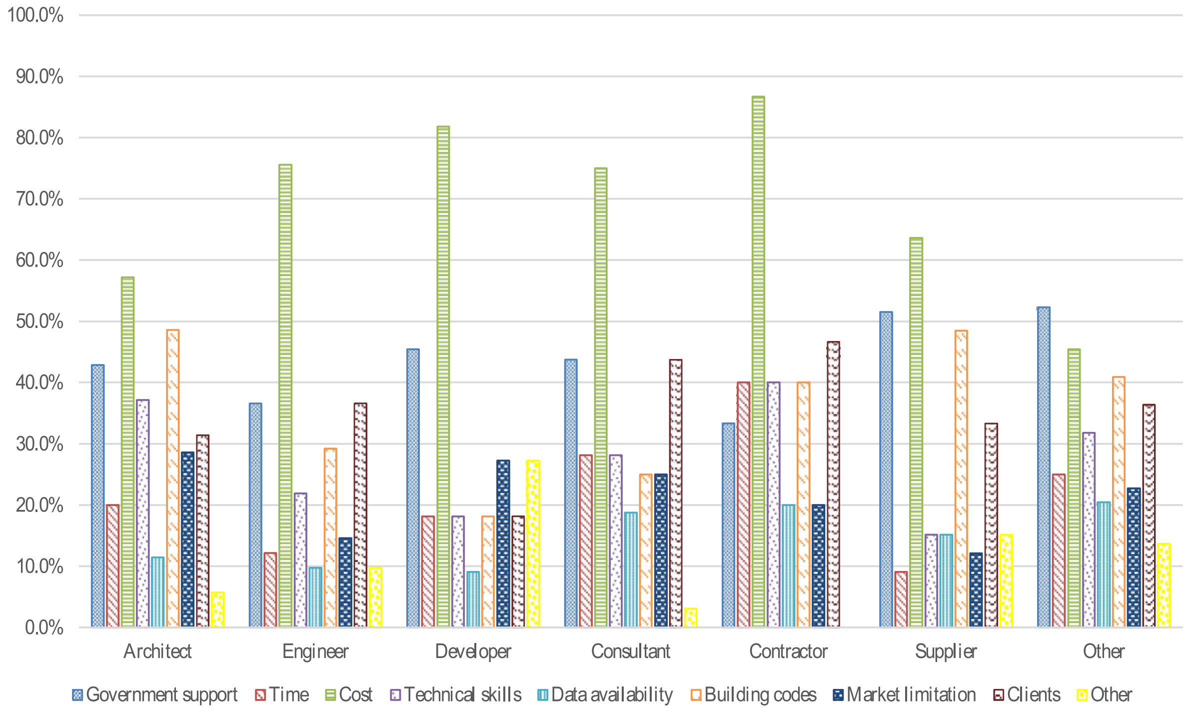


Figure 6.6 Barriers to green buildings according to each stakeholder group

6.3.4 Stakeholders' perspective on promoting green building standards and certifications

The participants were asked about their perception of the further actions that need to be taken and who should lead the sustainable development in the New Zealand green building industry. As shown in Table 6.5, 53% of the stakeholders agreed that the New Zealand government should lead sustainable development in the built environment. The following statements made by the participants emphasize the role the government should play:

- *"Uptake of green rating tools is largely dependent on local and central government support and mandate. Until there are volume and brand profile in the market, I think voluntary demand for ratings from the public and construction industry will be limited."*

- *"It is too expensive for New Zealand and the industry needs the government procurement model to push sustainability harder"*

- *"Government needs to follow the Australian lead to get more NABERS and Green Star rated projects using mandates or incentives. We have fallen behind the rest of the world in this area. The NZGBC needs to work hard with developers and industry to flush out the theory that green buildings are too expensive or do not make financial sense."*

- *"If tax benefits are designed to benefit developers for green buildings- It will work."*

Table 6.5 Leading sustainable development

Leadership and responsibility	Total
Government and local authorities	53.1%
Academic institutions	0.5%
Industry professionals	13.7%
Material suppliers	1.9%
Developers/Clients	25.6%
Other	5.2%

25% of participants agreed that developers and clients can improve the green building industry, and this result supports the previous finding which ranked clients as one of the biggest barriers to increasing green building certification uptake in the country. A participant suggested, *"if green building ratings are required for all leases, it would force landlords/developers to obtain it"*. Around 36% of the developers and clients admitted that their group should lead the green building industry (Figure 6.7). However, many responses stated that it has to be a coordinated approach across the sector by all stakeholders and authorities.

54% of the respondents declared that building actual performance is the most significant factor that should be considered when reviewing and updating the current green building standards and rating systems in New Zealand. The industry professionals' feedback came next with almost 30% (Table 6.6).

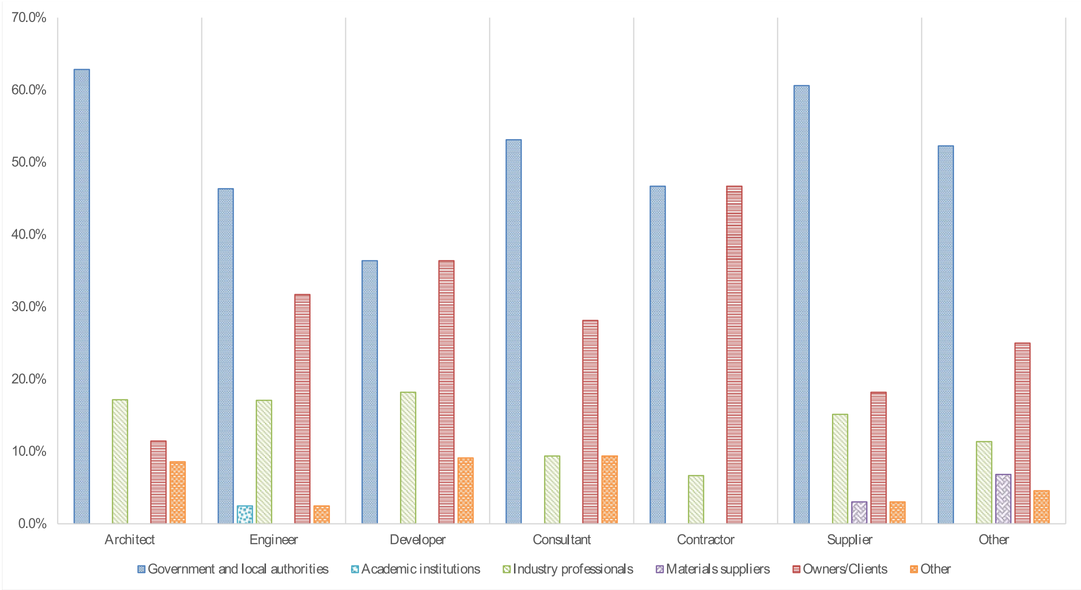


Figure 6.7 Stakeholders' perception of leading the green building industry development

Table 6.6 Preferred factors when improving rating tools

Preferred factors	Total
Industry professionals' feedback	30.3%
Occupants feedback	3.8%
Academic research	3.8%
Building actual performance	53.6%
International rating tools	4.7%
Other	3.8%

In contrast, the occupants' feedback was chosen as the last factor that should be considered when improving green building standards. None of the engineers and contractors who participated in this study believed that occupants' feedback is a key factor as shown in Figure

6.8. Surprisingly, the questionnaire results showed that academic research has the least support from all stakeholders regarding improving green building standards and rating tools and leading the sustainable development process. Only 2.4% of the engineers think academic research can lead to improving the green building industry, and one of them suggested that *"following overseas academic research as we are about 25 years behind Europe in New Zealand, so leveraging this knowledge and then adopted here would be the most productive and efficient way to move forward"*.

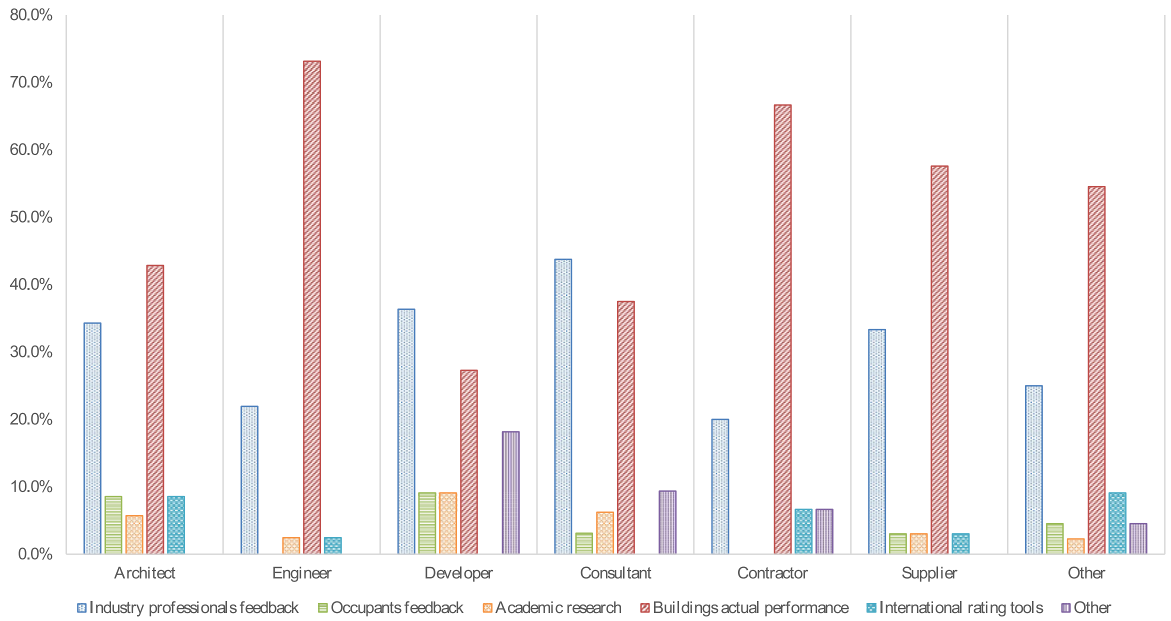


Figure 6.8 Factors to be considered when updating green building standards and rating tools

6.3.5 Green building practices

As shown in Table 6.7, only 10% of the respondents have always been participating in green building projects. Over one-third of the respondents have never or rarely participated in green buildings. When the frequency is broken down by stakeholder groups, architects, engineers, and consultants are the most involved in green building projects.

Table 6.7 Stakeholders' participation in green building projects

	Total	Architect	Engineer	Developer	Consultant	Contractor	Supplier	Other
Always	10.4%	14.3%	17.1%	9.1%	18.8%	0.0%	3.0%	4.5%
Often	20.4%	17.1%	26.8%	9.1%	21.9%	6.7%	24.2%	20.5%
Occasionally	33.6%	37.1%	31.7%	45.5%	25.0%	26.7%	36.4%	36.4%
Rarely	24.6%	25.7%	14.6%	36.4%	25.0%	46.7%	21.2%	25.0%
Never	10.9%	5.7%	9.8%	0.0%	9.4%	20.0%	15.2%	13.6%

When the participants were asked about what rating they target, Figure 6.9 shows that stakeholders who usually participate in green building projects prefer to target the "Built Rating". In addition, the figure represents the inverse relationship between frequency and the preferred rating. "Built Rating" was preferred by professionals who were more often engaged in green building projects while professionals who were occasionally or rarely involved in green building projects tend to target the "Design Rating". In general, the "Performance" rating is the least targeted in the green building industry in New Zealand.

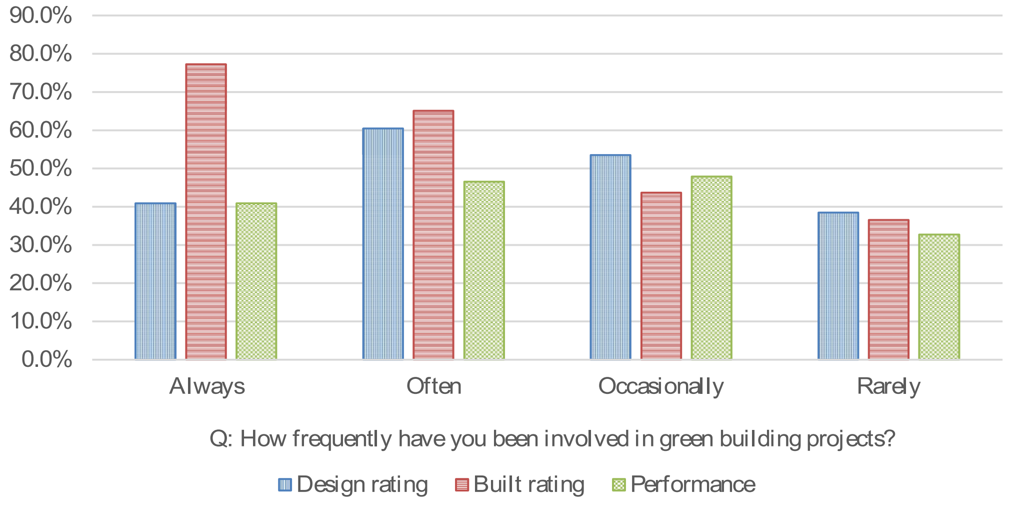


Figure 6.9 Relationship between participating in green building projects and preferred rating

The last two questions in the practice section aimed to investigate the multiple stakeholders' perspectives on the relation between green building current practice in New Zealand and its impact on improving building environmental performance. Figure 6.10 demonstrates this relationship; 65% of the participants agreed that current green building practices in New Zealand can lead to improving the built environment. 89% of them confirmed that implementing green building standards and assessment requirements at the early design stages "planning and pre-design" improves building environmental performance and facilitates achieving green building certificates. However, a participant argued that *"we consider sustainability from planning & pre-design initially but not in detail until developed design phase."* and another participant explained, *"too often in the New Zealand industry "sustainability" is seen as something to add after the design has been developed"*.

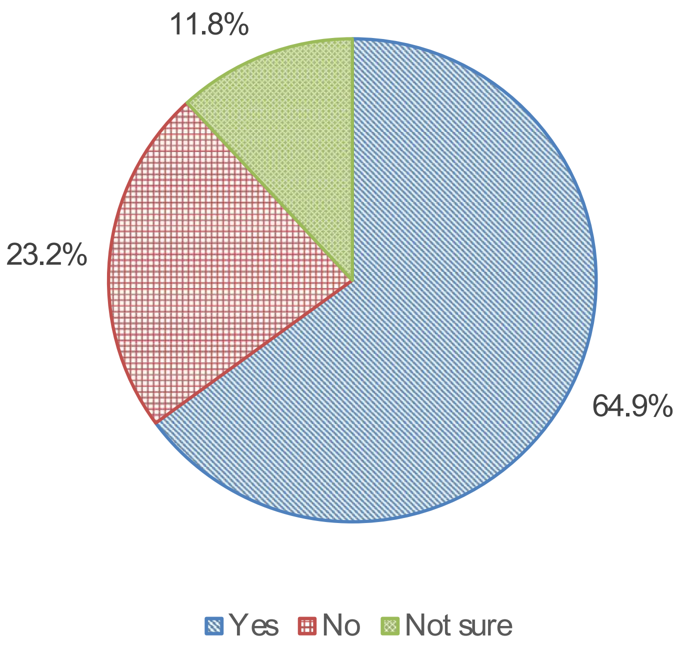


Figure 6.10 The relationship between current practices and improving buildings performance

6.3.6 Differences between Knowledge, Attitude, and Practice among the stakeholder groups

Table 6.8 Differences in KAP among participant groups

	Knowledge	Attitude	Practice
Kruskal-Wallis H	11.212	5.682	13.371
Df	6	6	6
Asymp. Sig.	.082	.460	.038

As presented in Table 6.8, there was not a statistical difference in knowledge and attitude towards green building design and assessment among different stakeholder groups. However, there was a statistically significant difference between the stakeholder groups in practice ($p = .038$, $p \leq .05$). Pairwise Comparison Tests were then performed between each pair of the stakeholder groups to identify that difference. It has been found a statistically significant difference in green building practice between engineers and contractors ($p = .025$, $p \leq .05$) as shown in Table 6.9.

Table 6.9 Pairwise comparison

Sample 1 - Sample 2	Sig.	Adj. Sig.
Engineer - Contractor	.001	.025

Asymptotic significances (2-sided tests) are displayed. The significance level is .05

6.3.7 Relationships between Knowledge, Attitude, and Practice of the multiple stakeholders

Correlation tests were conducted to evaluate the association and measure the significance of the relationships between knowledge, attitude, and practice levels, correlated to the stakeholders' role in the building industry as the independent variable. Table 6.10 shows statistically positive and significant correlations were observed between knowledge and practice (*p* = .001, p ≤ 0.01). Knowledge, as well, was positively and moderately correlated with attitude (p = .003, p ≤ 0.01) in both Kendall' tau and Spearman's rho coefficients, and Pearson Correlation coefficient (p = .004, p ≤ 0.01). In contrast, there was no statistically significant correlation between attitude and practice (*p* = .016, p ≤ 0.05) for Pearson Correlation coefficient, (*p* = .027, p ≤ 0.05) for Kendall's tau coefficient, and (*p* = .026, p ≤ 0.05) for Spearman's rho coefficient.

Table 6.10 Correlations between Knowledge, Attitude, and Practice (KAP)

			Knowledge	Attitude	Practice
Knowledge	Correlation	Pearson Correlation	1	.196**	.433**
		Sig. (2-tailed)		.004	.001
	Kendall's tau_b	Correlation Coefficient	1	1.77**	.380**
		Sig. (2-tailed)		.003	.001
	Spearman's rho	Correlation Coefficient	1	.201**	.442**
		Sig. (2-tailed)		.003	.001
Attitude	Correlation	Pearson Correlation	.196**	1	.165*
		Sig. (2-tailed)	.004		0.16
	Kendall's tau_b	Correlation Coefficient	1.77**	1	.129*
		Sig. (2-tailed)	.003		.027
	Spearman's rho	Correlation Coefficient	.201**	1	.151*
		Sig. (2-tailed)	.003		.026
Practice	Correlation	Pearson Correlation	.433**	.165*	1
		Sig. (2-tailed)	.001	.016	
	Kendall's tau_b	Correlation Coefficient	.380**	.129*	1
		Sig. (2-tailed)	.001	.027	
	Spearman's rho	Correlation Coefficient	.442**	.151*	1
		Sig. (2-tailed)	.001	.026	

**Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

6.4 Discussion

6.4.1 Interpretation of the results

Although the majority of the stakeholders showed good knowledge, positive attitude and strong motivations toward green building design and assessment, green building practices are still immature in the New Zealand building industry. The results first revealed that despite the weak practice and the modest number of certified green buildings in the country, participating in green building projects was considered the prime source of knowledge among the stakeholder groups. This emphasizes the statistically positive and significant correlation that was found between knowledge and practice. Autodidacticism or self-learning from online resources was the second main source of the stakeholders' knowledge of green building design and assessments. Although, most of the participants have not received structured education or training courses on green buildings, around 50% claimed that their understanding of green building requirements is at least good. Among the multiple stakeholders, architects claimed to have better knowledge and understating of green building standards and assessment requirements as green building training courses are their main source of knowledge. The architect group also contained the largest number of Green Building Accredited Professionals. On the other hand, contractors and suppliers were having the lowest level of understanding of green building standards and requirements. These differences in the knowledge level can lead to potential knowledge and practice gaps in green building applications and technologies between architects on one side and contractors and suppliers on the other side.

The results also indicated a positive attitude between the multiple stakeholders towards green buildings in New Zealand. Generally speaking, the multiple stakeholders' drivers for green building lean towards "intangible motivations" such as reducing building environmental impacts and improving the quality of life regardless of the absence of “tangible motivations” such as incentives and financial rewards. That demonstrates a high level of environmental and social awareness. In contrast, developers pursued green building certifications to improve the company’s public profile and attract clients, while improving the quality of life and reducing the operational cost were their least drivers for green buildings.

For the promotion of green buildings, the lack of government and local authorities' support was considered the major barrier to improving green building uptake. Therefore, the majority of the stakeholders agreed that the government could effectively lead the industry towards sustainable built development. Besides this, the results showed that promoting green buildings in New Zealand depends on external factors such as cost and building codes which also represent the main barriers to green buildings, rather than the stakeholders’ attitude. Engineers and consultants identified ‘client demand’ as another major challenge in implementing green building standards, while architects believed that the lack of technical skills is a key barrier to improving the green building industry in New Zealand.

The results further identified an attitude-practice gap in the green building industry in New Zealand as only 30% of the participants have frequently participated in green building projects. Participants’ experience in green building design and assessment had no observed correlations with their attitude and level of awareness, which can be perceived as it is still difficult to adopt green building standards despite the positive attitude towards sustainability. The attitude-practice gap has received much attention in the fields of medical and environmental psychology and it explains the gap between intentions and actual practices (Kaiser et al., 1999) and (Ghalandarpoorattar et al., 2012). Furthermore, a statistically significant difference was found between the engineers and contractors in terms of their practice levels and participation in green building projects. Engineers, compared to the other stakeholder groups, showed a leading practice level in the green building design and assessment process while contractors were the least group participating in green building projects.

Additionally, the analysis demonstrated that there is an inconsistency lie in the stakeholders' perspective on developing green building assessment requirements and the current practices in the green building industry in New Zealand. While the stakeholder groups agreed that building actual performance should be considered as the crucial factor when improving green buildings assessment requirements, performance rating tools are the least achieved certifications in New Zealand. Performance rating tools such as Green Star Performance and NABERSNZ assess building operational performance like energy and water consumption on an annual basis. According to the NZGBC's recent records, 20 buildings achieved Green Star Performance certification and 40 buildings achieved NABERSNZ certification (NZGBC, 2021).

The results as well bring to light that academic research had no support from the participants regarding its role in improving green building design standards and rating tools, and leading sustainable development in New Zealand. One of the reasons can be the low number of research studies that have been done to investigate sustainability and green building in the New Zealand context. This also can explain the reason behind ranking tertiary education and academic research as the least sources of green building knowledge among the stakeholder groups.

6.4.2 Practical implications

The government, as most of the participants agreed, can play a leading role in improving green building practices. Green building assessment is still voluntary in New Zealand compared to Australia and Europe. Research shows that mandating energy certifications in

Australia contributed to improving building performance in terms of energy consumption and carbon reduction (Kim & Lim, 2018). Therefore, introducing regulations that mandate green building certifications, for both public and private sectors, can be the most effective tool to promote sustainability in the building industry. Furthermore, there is a strong need to update building codes since its current requirements are below green building standards. Financial incentives are also important to encourage building owners and developers to pursue green building certifications (Olubunmi et al., 2016). These actions can improve the poor practices, bridge the gap between attitude and practice, and so motivate the multiple stakeholders to align their practices with their attitudes toward green buildings.

The research results revealed knowledge gaps between multiple stakeholders. While training courses were considered the main source of green building knowledge for architects, it is the opposite for contractors. Also considering the contractors' group self-rated their knowledge in green building design and assessment as low, therefore, designing tailored training courses that target each stakeholder group can reduce the knowledge gap between the multiple stakeholders participating in green building projects.

From the results, it was evident that there is a lack of collaboration between academic research institutes and the green building industry in New Zealand. Only 0.5% of whole participants supported academic research to play a leading role in promoting green buildings. 3.8% agreed that academic research can be considered while updating green building standards and assessment requirements. Therefore, the study recommends developing engagement strategies that lead to effective collaboration between academic research and the green industry in New Zealand. Academic institutions need to link their research with the green building industry needs and practices in order to suggest practical solutions that overcome challenges and enhance sustainability in the built environment.

Tertiary education represents only 16% of the multiple stakeholders' sources of green building knowledge. It is therefore recommended to develop modules and courses in architecture and engineering faculties in New Zealand universities, that cover theoretical and technical aspects of green building design and assessment requirements in collaboration with the industry experts.

6.5 Summary

Green building design and assessment have drawn significant attention from researchers over the past decades. Despite the advancements in this research area, multiple stakeholder analysis, as a social and non-technical research area, has been left uninvestigated in green building and sustainable development research. To fill the research gap, this chapter aimed to (1) examine the knowledge, attitude, and practice (KAP) of multiple stakeholders towards green building design and assessment process in the New Zealand building industry, (2) explore motivations and barriers to green buildings on the national level, and (3) identify and contrast each stakeholder group's motivations and barriers to adopt green building standards and certifications. Data were collected from 215 multiple stakeholders (i.e., architects, engineers, sustainability consultants, developers, contractors, and suppliers) in New Zealand using a KAP questionnaire survey. To explore the relationships and differences between the stakeholder groups' KAP levels, the Kruskal-Wallis H test and Correlation tests (Pearson, Kendall, and Spearman) were conducted. The results indicated that the multiple stakeholders had a good level of self-perceived knowledge and a positive attitude towards green building design and assessment. However, practices of green building design and assessment were still limited. The stakeholders' knowledge level was significantly and positively correlated with their attitude and practice. Note that an attitude-practice gap was identified among the multiple stakeholders and it needs to be bridged.

The research examined the KAP of multiple stakeholders towards green building standards and rating tools in New Zealand, as a small country. Although the a small number of developers and contractors in the country who usually participate in green building projects, both stakeholder groups might be underrepresented in this study. Therefore, further studies that target these two groups with a larger sample size would help in understanding their perspective, motivations, and challenges. In addition, it is recommended to conduct cost-analysis research using case studies of certified green buildings in New Zealand to compare green building upfront cost and operational cost throughout the building service life in order to demonstrate the long-term benefits of green buildings.

Chapter 7. Stakeholders' perspectives on BIM and LCA for green buildings

7.1 Introduction

Buildings are responsible for approximately 35% of global energy consumption and 38% of total direct and indirect energy-related CO_2 emissions (UNEP, 2020). The building industry, therefore, has attempted to enhance sustainability in its practices through implementing various building technologies and environmental assessment methods to mitigate building environmental impacts on climate change.

Building Information Modelling (BIM) is considered a revolutionary technology that brings a significant opportunity to the building industry (Lu et al., 2017). Recently, "Green BIM" has become a technical term with the idea of integrating BIM with green building assessment systems such as LEED and BRAEEM (Azhar et al., 2011; Jalaei & Jrade, 2015; Wong & Kuan, 2014). It has been demonstrated that BIM affords great potential for optimizing the green building assessment process (Carvalho et al., 2019; Yahya et al., 2016).

Within building environmental assessment, Life Cycle Assessment (LCA) is scientifically acknowledged as a holistic method for evaluating the environmental impacts of a building throughout its lifecycle (Nwodo & Anumba, 2019; Sibiude et al., 2014). According to the ISO 14040-14044 standards, LCA is defined as the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product, process or system throughout its lifecycle (International organization for standardization, 2004). Existing studies on LCA demonstrated its significance when incorporated into the building environmental assessment process (Dekkiche & Taileb, 2016; Humbert et al., 2007).

As BIM and LCA both continuously gain momentum as the most powerful tools that can achieve sustainability in the built environment (Bruce-Hyrkäs et al., 2018), a framework that integrates a BIM model and LCA method is needed because it would have the potential to enhance and streamline the environmental design and assessment process of buildings (Jrade & Jalaei, 2013; Soust-Verdaguer et al., 2017). Thus, BIM and LCA integration has generated considerable interest in academic research worldwide. Recent studies have shown that an integrated LCA-BIM workflow can significantly reduce the time and effort needed for building environmental design and assessment (Veselka et al., 2020; Nizam et al., 2018; Nwodo & Anumba, 2019). Efforts have been made to develop and present frameworks and workflows for BIM-LCA integration in green building literature (Carvalho et al., 2020; Horn et al., 2020; Marrero et al., 2020; Naneva et al., 2020; Santos et al., 2019), these attempts mainly focused on BIM functions that can simplify building data input, estimate environmental impacts and optimize output data during the LCA application in buildings (Soust-Verdaguer et al., 2017). Despite these advancements, no study has investigated the stakeholders' perspective on the BIM and LCA integration and its applicability to green building practices.

Apart from the technical aspects, the implementation of an integrated BIM-LCA framework for green buildings will be significantly affected and shaped by the stakeholders' (i.e. architects, engineers, clients, contractors, developers, etc.) perspectives (Linderoth, 2010). Worldwide, there has been increasing recognition of the importance of stakeholders' role in the building industry (Abdelaal & Guo, 2021; S. C. Wong & Abe, 2014), since every construction project is a combination of social interaction between various stakeholders (Chinowsky et al., 2008). Furthermore, a decision of whether individuals will adopt a particular technology has been a long source of research across multiple disciplines (Sträub, 2009). Therefore, an adequate understanding of collaboration among stakeholders is essential for a successful BIM and LCA integration (Wang et al, 2020).

Stakeholders' analysis research is still underestimated and overlooked in green building literature (Abdelaal & Guo, 2021; Herazo & Lizarralde, 2016; Karatas & El-Rayes, 2015; Pan & Pan, 2020). Previous research has been conducted to investigate stakeholders' perspectives on using BIM in the building industry (Lewis et al., 2019; Solla et al., 2019; Travaglini et al., 2014; A. K. D. Wong et al., 2013). On the other hand, very few studies investigated the stakeholders' views on LCA applications (Jusselme et al., 2020; Schlanbusch et al., 2016). To our knowledge, no study has yet been conducted to explore the stakeholders' perspectives on the integration of BIM and LCA for the building environmental design and assessment process. To fill the research gap, this research explores current BIM and LCA applications for green building design and environmental assessment, and it investigates multiple stakeholders' levels of awareness and agreement on the integration of BIM and LCA. The research provides unique user-centred knowledge of BIM and LCA applications for green buildings. Besides, it investigates the suitability and applicability of a potential BIM-based LCA integrated framework.

7.2 Methodology

Questionnaire design

The questionnaire survey was designed to investigate the current BIM and LCA applications for green buildings in the New Zealand building industry from the stakeholders' perspective. The questionnaire (see appendix C) consists of 16 questions and was divided into three sections. The first section of the questionnaire is general background questions that cover the demographic characteristics such as the participant's role in the building industry, years of experience, the business size and whether the participant has experience in green building projects. The other two sections aim to explore BIM and LCA applications and to investigate the stakeholders' level of agreement on BIM and LCA value for improving green building design and facilitating the environmental assessment process using a 5-point Likert scale. Additional text boxes were provided in the questionnaire to allow participants to provide further comments in relation to the question.

Participant sampling and data collection

Potential participants were selected using random sampling to minimize error and bias in the sampling process (Fellows & Liu, 2015) and to obtain a representative sample of the population that represents key stakeholders involved in the New Zealand building industry. The multiple stakeholders were defined as six (6) key stakeholder groups; architects, engineers, developers, sustainable building consultants, contractors and suppliers, using the membership database of the supporting organizations and associations in New Zealand. The questionnaire was administered using an online survey software tool, Qualtrics survey software, an anonymous link to the online survey was sent via email to several experts in the building industry to conduct pilot surveys. 5 pilot surveys were performed to check the understanding and the length of the questionnaire, assure face validity and improve the clarity of the instruction (Goh & Chua, 2016; Toh et al., 2017). After integrating the feedback of these first participants, the questionnaire was distributed online among stakeholder groups of the building industry in New Zealand through online platforms such as LinkedIn, relevant associations, organizations and architecture and engineering companies.

Data analysis

A total of 268 attempted responses were received. 53 out of 268 questionnaires were dropped because of missing and uncompleted responses. As a result, 215 of the valid and completed questionnaires were kept for data analysis using SPSS software for descriptive analysis to explore the current practices of using BIM and LCA for green buildings. Due to the relatively small market size of New Zealand, the sample size is considered representative. The participants were invited to indicate the relative significance of BIM and LCA tools for building environmental design and assessment process based on a 5-point Likert scale weighing from 1 to 5 ranging from “strongly disagree” to “strongly agree”. Normality tests were performed before conducting the statistical analysis and the results showed that the significance value *p* is less than .05, then the data is not normally distributed. Therefore, Spearman’s Rho correlation which is a nonparametric statistic approach that can be used with Likert data has been chosen for the study (Murray, 2013) to measure the strength between the stakeholders’ level of agreement on the significance of BIM and LCA for green buildings. , The survey covered a diverse range of stakeholders in the New Zealand building industry, the participants consisted of architects (16.7%), engineers (19.5%), developers (5.1%), sustainability consultants (14.8%), contractors (6.9%), suppliers (16.2%) the “others” group (13.7%) included project managers, government agents, researchers, etc. The majority of the participants (48.3%) had over 15 years of experience in the building industry. Almost 14% of the participants have never been involved in green building projects, and 65% have participated in less than 10 green building projects throughout their career life.

7.3 Analysis and results

7.3.1 BIM applications in green buildings

Only 77 of the participants out of 215 claimed to have previous experience with BIM tools. As shown in Figure 7.1 Although BIM is a data-rich and intelligent building information management tool (Ansah et al., 2019), 27.4% of the participants often use it for 3D modelling and visualization purposes. 20% of the participants used BIM for clash detection, while 13% used BIM for environmental assessment such as energy modelling to meet the requirements of green building rating systems in New Zealand such as Green Star and the National

Australian Built Environment Rating System New Zealand (NARESNZ). Further evidence that BIM potentials are not fully used in the New Zealand building industry is that only 11.5% of the stakeholders used BIM-based quantity take-off functions, 6% for cost estimation and 6% used BIM software as a project management tool. One of the participants stated that *"There is not enough uptake of BIM through the entire supply chain, it often stops at the developed design stage".*

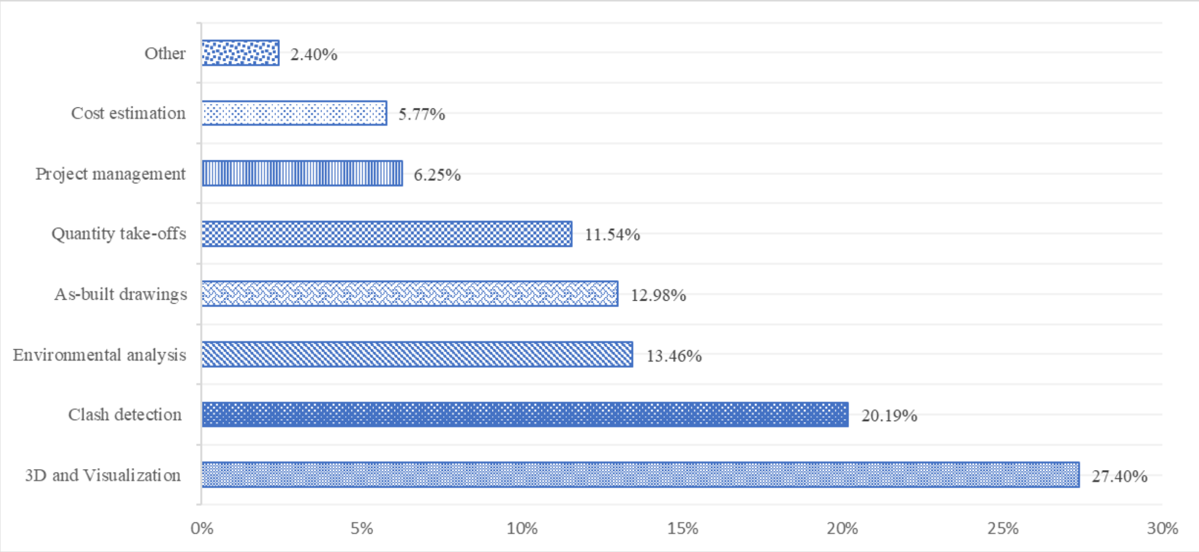


Figure 7.1 BIM applications in green building projects (n=77)

Regarding BIM software, Autodesk Revit is the most used BIM application in the New Zealand building industry with 66%, followed by ArchiCAD with 26%. 14% of the participants used Navisworks for coordination and clash detection, and only 4% of the participants used environmental analysis applications such as Integrated Environmental Solutions (IES).

7.3.2 LCA applications for building environmental assessment

First of all, the participants were asked about the building LCA stages and their responsibility for building environmental impacts. The majority of the participants (58.6%) stated that the construction phase of the building lifecycle (A4-A5) has the largest environmental impact on buildings. 20.5% of the participants stated that the use stage (B1 – B7) is the largest contributor to building environmental impact. While less than 1% of the stakeholders associated building environmental impact with the end-of-life stage (C1-C4) (see Figure 7.2).

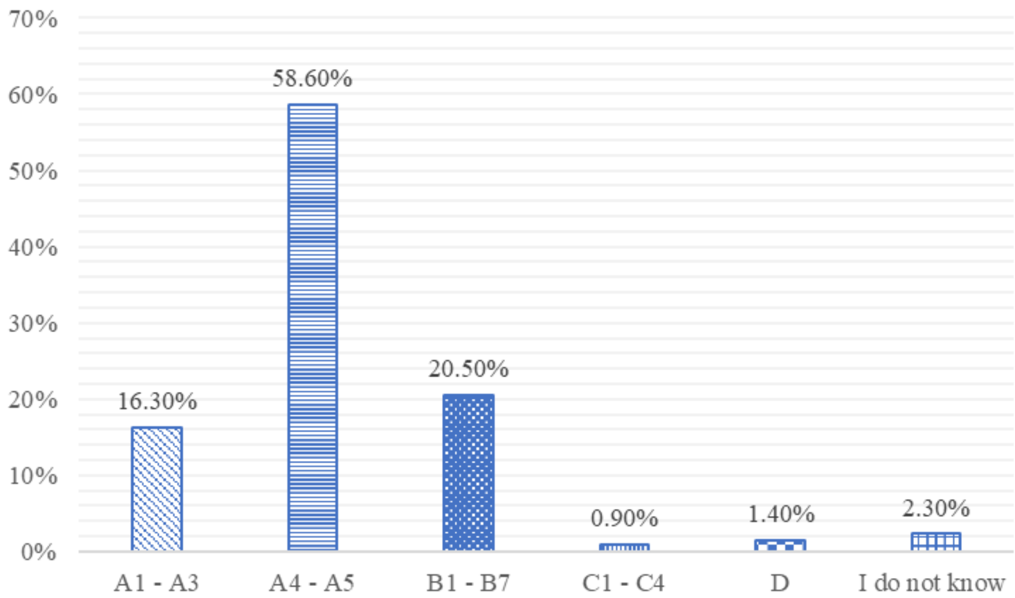


Figure 7.2 Building performance for LCA stages (n=215)
Product stage (A1-A3); Construction stage (A4-A5); Use stage (B1-B7); End of life stage (C1-C4); Benefits and loads beyond the system boundary stage (D)

Second, as shown in Figure 7.3, around 30% of the participants claimed that they conducted LCA to evaluate construction materials' impact on building environmental performance. 22.6% of the respondents stated that they performed LCA for calculating the operational emissions during the use stages. On the other hand, 15% used LCA tools to calculate the embodied emissions of buildings. 20.7% used the whole-building LCA approach to evaluate building environmental performance throughout its whole lifecycle. Life Cycle Cost Assessment (LCCA) as an LCA application was not commonly used in the New Zealand building industry.

Regarding LCA tools, most of the participants (45%) claimed using the LCAQuick tool to perform LCA for New Zealand green building projects, LCAQuick was developed by Building Research Association New Zealand (BRANZ) and it is tailored for the New Zealand building market. 16% of the participants used eTool which is a web-based LCA tool developed in Australia. GaBi is used by 10% of the participants. Other tools were mentioned such as SimaPro, and some participants stated that they used in-house tools which were developed and used to perform LCA in their organizations and companies.

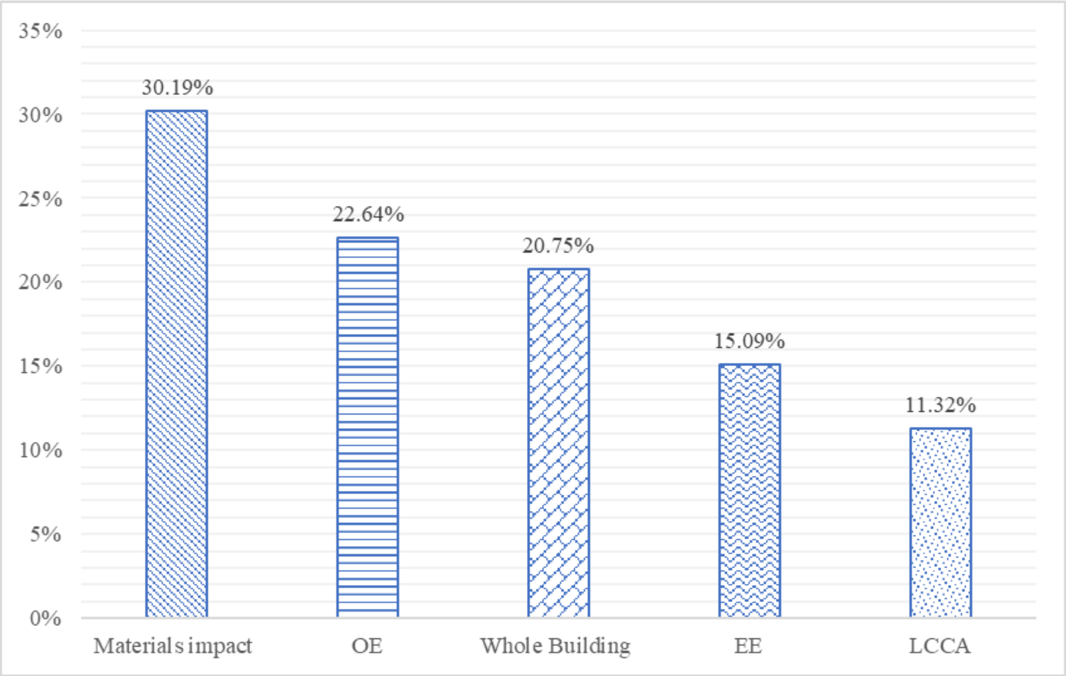


Figure 7.3 LCA applications in green building projects (n=51)

7.3.3 Stakeholders' agreement on the significance of BIM and LCA for green buildings

The results demonstrated that, among all participants, the majority have a positive perception of BIM and LCA as useful tools for building environmental design and assessment. As presented in Table 7.1, around 72% of the stakeholders who participated in the study agreed that LCA can improve the environmental analysis process compared to the existing green building rating systems. A participant explained that *"most of the rating tools give boxes to tick without good tools for calculating the embodied carbon of buildings. Proper LCA should be used"*.

Table 7.1 Stakeholders' level of agreement on BIM and LCA for green buildings

		BIM		LCA	
		Frequency	Percent	Frequency	Percent
Valid	Strongly agree	38	17.7	52	24.2
	Agree	94	43.7	102	47.4
	Neutral	71	33.0	55	25.6
	Disagree	8	3.7	1	0.5
	Strongly disagree	4	1.9	1	0.5
Missing		0	0	4	1.9
Total		215	100	215	100

For BIM, 61% of respondents agreed that BIM can facilitate the green building design and assessment process compared to the traditional tools. 33% and 26% of the participants had a neutral opinion regarding BIM and LCA tools, respectively. Around 6% of the total respondents doubted BIM potential for enhancing the green building design process and less than 1% disagreed that LCA can improve building environmental assessment.

Figure 7.4 illustrates the impact of participation in green building projects and the frequent adoption of BIM on the stakeholders' level of agreement on the value of BIM for green buildings. It was observed that the frequent use of BIM tools has a large impact on the users' perspective on its value as a green building design and environmental analysis tool. Participants who always or often use BIM for green building projects are the most agreed that BIM can facilitate and improve green building practices. On the other hand, Figure 7.5 shows that neither the participation in green building projects nor the frequent implementation of LCA has an observed impact on the stakeholders' perspectives. Participants who occasionally use LCA tools for green building projects are the majority who strongly agreed on its significance for enhancing building environmental assessment. That can be explained by the limited uptake rate of LCA tools in the New Zealand building industry.

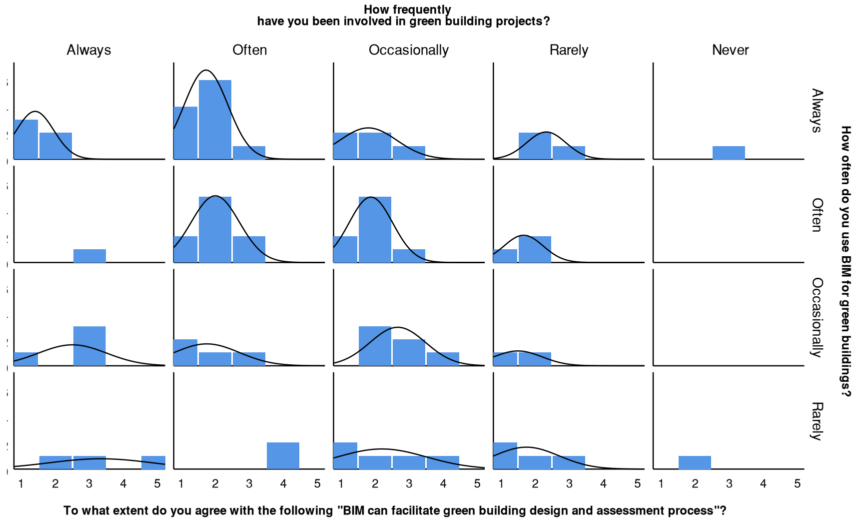


Figure 7.4 Stakeholders' perception of BIM significance for green buildings (n=215)
1 = Strongly agree, 2 = agree, 3 = Neutral, 4 = Disagree, 5 = Strongly disagree

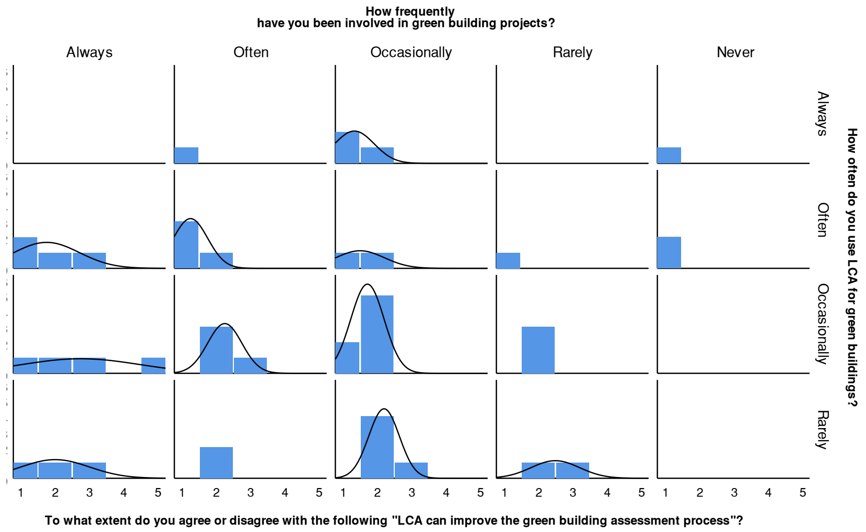


Figure 7.5 Stakeholders' perception of LCA significance for green buildings (n=215)
1 = Strongly agree, 2 = agree, 3 = Neutral, 4 = Disagree, 5 = Strongly disagree

7.3.4 BIM and LCA integration for green buildings

As shown in Table 7.2, over half of the participants (52.5%) have not used either BIM or LCA for green buildings in green building projects. Only 12% of the participants have used both tools for green building design and assessment. BIM is commonly implemented in green buildings in the New Zealand building industry compared to LCA with 24% and 12% respectively.

Table 7.2 BIM and LCA implementation in New Zealand (n=215)

		BIM	
		Yes	No
LCA	Yes	12%	11.6%
	No	23.7%	52.5%

Spearman's rho correlation test was conducted to measure the strength of the stakeholders' level of agreement on the significance of BIM and LCA for green buildings. Table 7.3 presents the correlation coefficient (*r*) of BIM and LCA significance for building environmental design and assessment from the stakeholders' perspective. The correlation coefficient (*r*) is almost .4 (r = .397) which represents a positive correlation (Akoglu, 2018), with a statistical significance p-value of less than 0.001 (p = <.001, p = .01).

Table 7.3 Spearman correlation (n=215)

			BIM significance	LCA significance
Spearman's rho	BIM significance	Correlation Coefficient	1.000	.397**
		Sig. (2-tailed)	.	<.001
	LCA significance	Correlation Coefficient	.397**	1.000
		Sig. (2-tailed)	<.001	.

**. Correlation is significant at the 0.01 level (2-tailed).

7.4 Discussion

The results have manifested that the adoption of BIM technology and LCA tools for green buildings in New Zealand is still immature since over 50% of the industry stakeholders have no previous experience with either BIM or LCA. On the contrary, when the stakeholders' level of agreement of BIM and LCA significance was examined using a 5-point Likert scale as part of the questionnaire survey, the results revealed that the stakeholders' level of agreement is not associated with the low level of BIM and LCA implementation. Stakeholders who occasionally perform LCA for building environmental assessment are the most agreed on the value of LCA to improve the building environmental assessment process. For BIM significance, participants who often use BIM for green buildings agreed with its potential to facilitate green building design and assessment process compared to the stakeholders who are always using BIM for green projects. The stakeholders' level of agreement on the significance of BIM and LCA for green buildings can be associated with the BIM and LCA applications in the New Zealand industry since the results revealed that BIM and LCA potentials for green buildings are not yet fully discovered and utilized in New Zealand. The majority of the stakeholders still perceive BIM as a visualization tool, therefore, BIM potential as an environmental analysis tool are underestimated in New Zealand. 13% of the participants take advantage of BIM potentials for environmental analysis which aligns with the results of a survey conducted by the New Zealand BIM Acceleration Committee in 2020, the results showed that 18% of the multiple stakeholders use BIM for sustainability analysis (Eboss, 2020), considering that the total number of the participants in Eboss survey was 40.

There is an inconsistency between the stakeholders' perspectives and the current applications of LCA for building environmental assessment in New Zealand. LCA is commonly performed to calculate the operational impacts and meet the green building rating systems requirements. Although the majority of the participants considered that the embodied emissions associated with the construction stage have the most significant environmental impacts throughout the building lifecycle, only 15% of the participants conducted LCA to calculate building embodied carbon. Furthermore, LCA is used to identify the environmental impacts of the construction materials in order to issue the Environmental Product Declarations (EPDs) that usually report the embodied emissions for the production stage of LCA.

The statistical analysis results demonstrated that the stakeholders have a positive perception of the value associated with using BIM and LCA for green buildings, separately. Moreover, a significant correlation exists between the value of BIM and LCA integration from the stakeholders' perspective. Regardless of the stakeholders' positive attitude towards BIM and LCA, the New Zealand industry is not yet ready for a wide implementation of an integrated BIM-LCA framework since only 12% of the stakeholders can use both tools. Therefore, efforts from the public and private sector and educational institutions are encouraged to promote BIM and LCA and enhance their applications for green buildings.

7.5 Summary

There is growing concern about the environmental impacts of buildings on climate change. In this regard, the concept of integrating building technology and environmental assessment methods, namely Building Information Modelling (BIM) and Life Cycle Assessment (LCA), has arisen as an innovative approach to improve building environmental assessment at the design phase. Recent studies made attempts to develop frameworks for BIM and LCA integration focusing on the technical aspects and challenges of this integration. However, the stakeholders' perspectives on this integration of BIM and LCA for building sustainability assessment have been overlooked. Therefore, there is a pressing need to understand the stakeholders' perspectives on BIM and LCA and their perceived usefulness to improve their adoption rate. To this end, this chapter investigated (1) the perspectives of stakeholders on

BIM and LCA applications for green buildings and (2) the stakeholders' level of awareness and agreement on the significance of BIM and LCA for building environmental design and assessment. In order to achieve this aim, a national survey was conducted among multiple stakeholders in the New Zealand building industry. The results indicated that BIM and LCA applications for green buildings are still immature. A statistically significant correlation was observed between the importance of BIM and LCA applications for green buildings. The stakeholders perceived BIM and LCA potential and their integration positively. However, the current practices and applications of BIM and LCA do not align with the stakeholders' perceptions. Massive efforts are still required for a wide implementation of BIM and LCA and their potential integration for green buildings. For future research, the study suggests an in-depth investigation of the barriers to implementing LCA and BIM widely in the New Zealand building industry.

Chapter 8. Conclusion, recommendations and future research

This chapter presents the review of the research objectives and the contribution to knowledge in relation to each research objective. Furthermore, it proposes a number of recommendations and suggests future research pathways that are relevant to the research objectives and limitations.

8.1 Review of the research objectives

Objective 1: develop science-based carbon emissions benchmarks for buildings using an integrated Whole Building LCA (WBLCA) and Distance to Target (DTT) approach, the developed carbon emissions benchmarks can be incorporated into the GBRSs to enhance their validity and reliability as building environmental assessment tools.

In order to address the pressing issue of carbon emissions reduction in the building sector that limits global warming at 1.5 °C, the research, first, analysed and compared five established international green building rating systems, i.e. BREEAM, LEED, BEAM Plus, Green Star and Homestar from LCA perspective. The research aimed to investigate the recognition and weightings of the LCA and building operational and embodied carbon emissions in the rating systems. The results showed that LCA is barely recognised in the studied GBRSs. Moreover, measuring and auditing building carbon emissions is not a part of the environmental assessment process. Although these rating systems require reporting the building operational emissions as a part of building energy performance, operational carbon emissions associated with the water use stage (B7) are neglected. Therefore, the GBRSs are not yet sufficient to address and report the building carbon emissions, embodied and operational, accurately. The

research findings in Chapter 3 demonstrated that the GBRSs require a critical improvement in order to enhance their validity and reliability as building environmental assessment tools.
To contribute to the improvement of the rating systems and building environmental assessment, this research developed science-based short-term and long-term carbon emissions benchmarks based on an integrated LCA-DTT approach (Chapter 4). The Distance to Target (DTT) method calculates the weighting factors of an LCA impact category to identify the distance from the current environmental situation to a defined environmental target. The climate targets used for that purpose are the global targets set by the IPCC and the UNEP latest reports. The DTT approach was applied to the New Zealand residential buildings to develop carbon emissions benchmarks for (1) New Zealand detached housing sector, (2) the embodied carbon emissions and operational carbon emissions and (3) carbon emissions for each LCA stage of the whole building lifecycle from cradle to grave. The results showed that massive carbon emissions gaps exist in New Zealand buildings between the current emissions and the 2030 and 2050 targets, in particular, in the embodied carbon emissions during the construction stage and end-of-life stage. However, the efforts and climate policies largely focus on operational carbon emissions and there is no clear policy for reducing the embodied carbon emissions in the building sector. The results, therefore, demonstrate the importance of incorporating carbon emissions benchmarks into the GBRSs to enhance the reliability and validity of the building environmental assessment process.

Objective 2: develop an integrated BIM-based LCA framework for GBRSs that incorporates the science-based carbon emissions benchmarks.
This research represented a novel approach to an integrated BIM, LCA and the carbon emissions benchmarks framework in order to optimize the environmental assessment of the building and promote digitalization in the building sector (Chapter 5). First, the research

investigated the potential of integrating BIM into each assessment category of the Homestar rating process through analysing, comparing and presenting the relationship between the required data for the Homestar assessment and the data available in a BIM model using Autodesk Revit as the BIM platform. The findings indicated that 67 of 120 points can be achieved by integrating BIM into the assessment process. This study is the first study to investigate the feasibility of integrating BIM technology and green building assessment systems in New Zealand and the first study to develop a comprehensive BIM-based Homestar framework. The research, furthermore, integrated LCA and science-based carbon emissions benchmarks into the BIM-based Homestar framework in order to produce accurate and reliable results regarding building environmental performance throughout its whole lifecycle thus enhancing the environmental assessment process for buildings. This integration can improve the structure of the existing international GBRSs and enhance the validity and reliability of their assessment process.

Nevertheless, a few restrictions need to be considered in order to fully automate the environmental assessment process of buildings. For example, the BIM model should be modelled with accurate geometric information, material properties and additional information required for the assessment. In addition, neighbourhood modelling is required for evaluating the “Site” category. For some assessment credits such as the “Management” and “Waste”, the current requirements represent a challenge to the automation process since the required documentation cannot be integrated into the BIM model. However, the research recommends replacing these credits with the LCA approach.

Objective 3: conduct stakeholders’ analysis that investigates the influence of the stakeholders’ perspectives on green building practices and BIM and LCA applications for building environmental assessment.

First, as presented in (Chapter 6) a national questionnaire was conducted to explore the levels of Knowledge, Attitude, and Practice (KAP) of multiple stakeholders towards green building design and assessment, and to identify their motivations for green buildings and barriers that slow down sustainable development in New Zealand. Data were collected from 215 participants from the New Zealand building industry. The results of this study provided a holistic picture of current green building design and assessment in New Zealand from a multiple-stakeholders perspective. The results, as well, identified knowledge gaps and behavioural patterns of various stakeholders that can enhance their collaboration and engagement, in addition, to assisting policymakers plan and implementing system interventions. In general, the results indicated that the multiple stakeholders have a good level of knowledge, positive attitude and immature practices with regard to green building design standards and assessment in New Zealand. Reducing environmental impacts and improving quality of life are the main motivations that drive the stakeholder groups; however, the cost associated with green buildings design and assessment process green buildings and the lack of government support prevent the stakeholders from implementing green building requirements in construction projects. The correlation analysis revealed that knowledge has a significant influence on attitude and practice while there is no significant correlation between attitude and practice, and so the attitude-practice gap was identified. Moreover, the results highlighted a statistically significant difference in green building practices among the stakeholder groups, in particular, between engineers and contractors. The study findings have useful implications for future practices in the green building industry and academic research. Second, as in (Chapter 7), due to the importance of the stakeholders' role in promoting BIM and LCA in the building industry, another national survey was conducted to explore BIM and LCA applications for green buildings in New Zealand from the stakeholders' view. Besides, the study investigated the stakeholders' level of agreement on the significance of BIM and

LCA for green buildings, and the association with the current practices. The results of this study provided a holistic picture of the BIM and LCA current practices in the New Zealand building industry from the stakeholders' perspectives. Regardless of the weak implementation of BIM and LCA in the New Zealand building industry, the stakeholders have demonstrated a positive perception of LCA and BIM for green buildings. However, the thesis outcomes revealed that the integrated BIM and LCA framework for building environmental assessment will not be adopted since over 50% of the stakeholders in New Zealand have no experience using BIM and LCA and therefore, the stakeholders lack the required knowledge and skills to implement such framework.

8.2 Research contributions

Despite the existence of various tools and systems that evaluate the environmental impacts of buildings, none of these tools, on their own, succeeded to provide holistic and reliable results on building carbon emissions and environmental performance throughout the building lifecycle. Therefore, the outcome of this PhD thesis presents a novel contribution to the scientific knowledge as well as to the practices of the building industry.

First, the comparison study presented in Chapter 2 provides scientific evidence on the insufficient performance of the existing Green Building Rating Systems. Second, this research develops science-based carbon emissions benchmarks for buildings that can be incorporated into the rating systems to improve their validity and reliability. This research adopts a novel approach to integrate LCA and the Distance to Target (DTT) methods in order to develop science-based benchmarks for Whole Building Life Cycle Assessment (WBLCA) that contribute to achieving the 2030 and 2050 international carbon reduction targets and limiting global warming to 1.5 °C. Furthermore, the research identifies the current carbon emissions gaps for the New Zealand residential buildings throughout the lifecycle stages from cradle to grave. The largest emissions gap was identified in the embodied emissions stages instead of the operational stages. Considering the technological developments that reduce building operational emissions, the embodied emissions gaps are expected to continue increasing in the upcoming years.

Previous academic attempts have been made to integrate BIM and GBRSs, LCA and GBRSs or BIM and LCA. However, very limited studies have explored the feasibility of integrating the three approaches and these previous attempts, these efforts have not presented a comprehensive investigation for BIM integration into each assessment criteria within the GBRSs. Therefore, this thesis develops an integrated framework that integrates BIM, LCA and Homestar rating system. The novelty of this framework is that it (1) presents a comprehensive BIM integration into each assessment criteria of the rating systems, (2) integrates LCA into the assessment process and (3) incorporates the carbon emissions benchmarks into the assessment framework (4) improves the structure of the existing rating systems. Hence, the framework addresses the scientific and technological attributes of building environmental assessment.

Beyond the scientific and technological aspects, this thesis recognizes the social factor that influences green building practices. It highlights the significance of the stakeholders' perspective on adopting and implementing building environmental assessment tools and technologies, which has been overlooked in the green building literature. This thesis is the first that investigates multiple stakeholders' perspectives and attitudes towards green buildings and building environmental assessment in the New Zealand building sector. Moreover, it is the first research that investigates the stakeholders' perspectives on BIM and LCA applications and their potential integration for building environmental assessment. The thesis results provide a holistic picture of green building practices in New Zealand and contribute to bridging the research-industry gap. The thesis, moreover, proposes a number of practical recommendations that aim to enhance the collaboration and decision-making process in the building sector.

From a practical standpoint, New Zealand currently faces enormous challenges to limit its carbon emissions and achieve the Paris Agreement goals. Moreover, there is a lack of national policies that tackle and reduce carbon emissions in the industrial sectors, including buildings and construction. Therefore, the research aims to guide the emissions reduction plan and bridge the current gap between academia and policymaking.

8.3 Research limitations

The research limitations of each objective are discussed as follows:

First, due to the absence of official data on the carbon emissions in the New Zealand building sector, the developed carbon emissions benchmarks in Chapter 4 relied on the BRANZ published studies that calculated the carbon emissions of the residential buildings in 2018. As aforementioned, the New Zealand government has not yet reported the carbon emissions for the building sector. However, the absence of official data does not violate the novelty of the integrated LCA and DTT approach presented in this research. It is a generic methodology for developing carbon emissions benchmarks that can be applied to any set of data.

In terms of the second objective, the integrated BIM and LCA framework for Homestar rating systems that incorporates the carbon emissions benchmarks is a conceptual framework. The developed framework in Chapter 5 presents the relationship between BIM tools and each assessment criteria in the rating system. In addition, it presents a method to integrate LCA and the carbon benchmarks into the BIM-based framework for Homestar as a Green Building

Rating System. However, no technical attempt has been made yet to develop a physical tool that implements and validates the framework.

Finally, the research conducts a national survey to examine the knowledge, attitude and practice of multiple stakeholders toward green buildings in New Zealand (Chapter 6). Although the relatively small size of the New Zealand building sector and the small number of developers and contractors in the country usually participate in green building projects, both stakeholder groups might be underrepresented in this research.

8.4 Recommendations and future studies

Based on the abovementioned research limitations and the research outcomes, the following recommendations are suggested:

In terms of improving building environmental assessment, the research recommends shifting focus from efficiency in operation towards a whole LCA perspective. The existing GBRSs must incorporate a reliable Whole Building LCA assessment approach with proper weightings. Moreover, integrating the carbon emissions benchmarks into the building environmental assessment is urgently needed to measure and tackle building total carbon emissions, in particular, the embodied emissions to achieve the carbon reduction targets, especially, in New Zealand which needs to take urgent and enormous actions in order to mitigate its carbon emissions and meet its commitment to Paris Agreement targets.

The New Zealand government, building sector and academic institutes must collaborate on reporting the environmental impacts, including the carbon emissions, of the built environment. The government's official carbon emissions data can assess academics to provide accurate and practical solutions that reduce building environmental impacts in New Zealand. As well, it can guide the climate change policies that achieve the country’s international obligations.

In addition, the thesis recommends (1) introducing regulations that mandate green building certifications and provide financial incentives for the stakeholders, (2) designing tailored training programs for each stakeholder group to enhance their green building knowledge, (3) building effective collaboration between green buildings research and the industry, and (4) developing green building courses for tertiary education.

For future research, this study suggests the following:

- This research examined the KAP of multiple stakeholders towards green building standards and rating tools in New Zealand, as a small country. Although a small number of developers and contractors in the country usually participate in green building projects, both stakeholder groups might be underrepresented in this study. Therefore, further studies that target these two groups with a larger sample size would provide a better understanding of their perspectives, motivations and barriers to green buildings.

- It is recommended to conduct an investigation and semi-structured interviews with LCA professionals in New Zealand to understand the barriers to the wide implementation of LCA for green buildings.

- It is also recommended to conduct cost-analysis research using case studies of certified green buildings in New Zealand to compare green building upfront cost and operational cost throughout the building service life can promote green building long-term benefits in the New Zealand market.

- Extend the BIM-based LCA framework to integrate the Life Cycle Cost (LCC) of buildings and other LCA environmental impacts.

- Finally, this research encourages future attempts to develop a software, Revit plug-in or web-based tool for the integrated BIM-based LCA framework for the Homestar rating system to facilitate residential building environmental assessment in New Zealand.

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Appendices

Appendix A: Human Ethics Committee (HEC) Approval Letter

UNIVERSITY OF CANTERBURY

HUMAN ETHICS COMMITTEE
Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2019/45/LR-PS

2 December 2019

Fatma Abdelaal
Civil and Natural Resources Engineering
UNIVERSITY OF CANTERBURY

Dear Fatma

Thank you for submitting your low risk application to the Human Ethics Committee for the research proposal titled "Integrating Building Information Modeling (BIM) and Whole-Building Life Cycle Assessment (WB-LCA) for Green Building Rating Systems".

I am pleased to advise that this application has been reviewed and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your emails of 18th and 26th November 2019.

With best wishes for your project.

Yours sincerely

Dr Dean Sutherland
Chair, Human Ethics Committee

Appendix B: Knowledge, Attitude and Practice (KAP) questionnaire

A. Information of Participants

Q1. What is your role in the Architecture, Engineering, and Construction (AEC) industry?

Architect; Engineer; Developer; Consultant; Contractor; Supplier; Other, please specify

Q2. How many years of experience do you have in the AEC industry?

1 – 4; 5 – 9; 10 – 15; Over 15 years

Q3. What is your company size?

1 – 10; 11 – 50; 51 – 100; Over 100 employees

Q4. Have you ever participated in green buildings projects?

Yes; No

B. Knowledge of Green Building Design and Assessment

Q5. What is your main source of information on green buildings? (multiple choice)

Tertiary education; Academic research; Training courses; Work experience; News/Articles; Other, please specify

Q6. Rate your understanding of the New Zealand green building rating tools? e.g. Green Star, Homestar, etc.

Excellent; Good; Average; Fair; Poor

Q7. Are you a Certified Green Building Professional? e.g. Green Star Accredited Professional (GSAP)

Yes; No

Q8. Which rating tool do you have experience with? (multiple choice)

Green Star; Homestar; Living Building Challenge; Passive House; None; Other, please specify

C. Attitude towards Green Building Design and Assessment

Q9. What is your main motivation for green buildings? (multiple choice)

Reduce environment impacts; Improve the quality of life; Low running cost; Government regulations; Clients demand; Organization image; Other, please specify

Q10. What are the barriers to increasing green building rating tools uptake in New Zealand? (multiple choice)

Lack of government support; Assessment process timeframe; Cost; Technical skills; Data availability; Building codes; Market limitation; Clients demand; Other, please specify

Q11. In your opinion, who can lead the main role in promoting green building standards and certifications in the AEC industry in New Zealand?

Government and local authorities; Academic institutes; Industry professionals; Material suppliers; Developers/Clients; Other, please specify

Q12. What is the most important factor that should be considered while updating the current versions of green building rating tools?

Industry professionals' feedback; Occupants feedback; Academic research; Buildings actual performance; International rating tools; Other, please specify

D. Practice in Green Building Design and Assessment Process

Q13. How frequently have you been involved in green building projects?

Always; Often; Occasionally; Rarely; Never

Q14. What type of rating do you target for your projects? (multiple choice)

Design rating; Built rating; Performance; None; Other, please specify

Q15. Based on your practical experience in the New Zealand AEC industry, what stage the sustainability concepts are considered at?

Planning & Pre-design; Concept design; Developed design; Detailed design; Construction documents; Other, please specify

Q16. Based on your previous answer, do you agree that it is the best stage to improve the building environmental performance?

Yes; No; Not sure

Appendix C: BIM and LCA applications for green buildings questionnaire

Background section

Q1. What is your role in the Architecture, Engineering, and Construction (AEC) industry?

(Architect; Engineer; Developer; Consultant; Contractor; Supplier; Other, please specify)

Q2. How many years of experience do you have in the industry?

(1 – 4; 5 – 9; 10 – 15; Over 15 years)

Q3. What is your company size?

(1 – 10; 11 – 50; 51 – 100; Over 100 employees)

Q4. Have you ever participated in green building projects?

(Yes; No)

Q5. How many green building projects have you been involved in?

(0; 1-5; 6 – 10; +10 projects)

BIM section

Q6. Have you ever used Building Information Modelling (BIM) technology for green building projects?

(Yes; No)

Q7. How often do you use BIM for green buildings?

(Always; Often; Occasionally; Rarely)

Q8. What purpose do you use BIM for? (multiple choice)

(3D & Visualization; Environmental analysis (i.e. energy, thermal, daylight, etc); Clash detection; Quantity take-offs; Cost estimation; As-Built drawings; Project management; Other, please specify)

Q9. What is BIM software do you use? e.g. Revit, ArchiCAD, Naviswork, etc.

Q10. To what extent do you agree with the following "BIM can facilitate green building design and assessment process"?

(Strongly agree; Agree; Neither agree nor disagree; Disagree; Strongly disagree)

LCA section

Q11. Have you ever conducted Life Cycle Assessment (LCA) for green building projects?

(Yes; No)

Q12. How often do you use LCA for green buildings?

(Always; Often; Occasionally; Rarely)

Q13. What purpose do you use LCA for?

(Materials impact; Embodied emissions; Operational emissions; Life Cycle Cost Analysis; Whole Building)

Q14. What LCA tool do you use? e.g. LCAQuick, eTool, GaBi, etc.

Q15. Which LCA stage of building has the largest environmental impact?

(Product stage (A1-A3); Construction stage (A4-A5); Use stage (B1-B7); End of Life stage (C1-C4); Benefits and loads beyond the system boundary stage (D); I do not know)

Q16. To what extent do you agree or disagree with the following "LCA can improve the green building assessment process"?

(Strongly agree; Agree; Neither agree nor disagree; Disagree; Strongly disagree)