Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

Time-Differentiated Life Cycle Assessment and Dynamic Carbon Budgeting for Decarbonising the Aotearoa New Zealand Building Sector

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

in

Natural Resource Management

at Massey University, Palmerston North, New Zealand.



Sachini Nidusha Weerasinghe

2026

Abstract

The building sector is a major contributor to global greenhouse gas (GHG) emissions, and is characterised by the long service lives of buildings and associated whole-of-life building GHG emissions. Despite the increasing policy emphasis in countries around the world on achieving net-zero emissions within specified time horizons, and setting carbon budgets for specific years, existing conventional life cycle assessment (LCA) climate change assessment methods are based on static assumptions and aggregating emissions over time. This limits their usefulness in informing timely and effective mitigation strategies. The thesis therefore addresses the challenge of aligning building sector GHG emissions with time-differentiated climate change targets and associated carbon budgets - where the aim is to support more effective decision-making for building sector decarbonisation.

The thesis is focused on two major research areas. First, it applies two time-differentiated LCA approaches - dynamic and prospective LCA - to assess the timing and evolution of GHG emissions across building life cycles. Two industry case studies are used to test different time-differentiated LCA methods: (i) a steel eccentric braced frame representing a structural system in a multi-storey building subject to temporal dynamics (such as potential seismic-related reconstruction and technology changes at end-of-life treatment), and (ii) an office fit-out case study with recurring emissions associated with interior refurbishment over the service life of a multi-tenant building. The results demonstrate that dynamic - as opposed to static - LCA provides additional insights on emission profiles over time, and in particular highlighting the relevance of early-stage mitigation actions. The case studies further show that circular economy strategies, including reuse and design for disassembly, can substantially mitigate climate change impacts, alongside prospective technological and socio-economic developments that may deliver additional progressive reductions in emissions over time. Secondly, a dynamic carbon budget allocation approach is developed for the national and building sectoral level in Aotearoa New Zealand. The method enables the quantification of annual remaining carbon budgets (RCBs) and carbon debts up to year 2050 to stay below the Paris Agreement 1.5 ºC warming levels, incorporating temporal dynamics that influence emissions over the years. It provides a

range of RCBs by accounting for the influence of different sharing approaches and non-CO_2 emission global warming on the RCBs. This approach improves the robustness of dynamic RCBs and debts by: (a) avoiding reliance on a single allocation principle that may result in either overly restrictive or insufficiently ambitious mitigation pathways, and (b) addressing uncertainties associated with assumptions that future emissions will align with stringent non-CO_2 emission global warming levels.

In addition to these two main research areas, the thesis also explores alternative decarbonisation strategies for the office building sector in the context of the Construction 4.0 concept. Although the technology improvements and data management techniques promoted in Construction 4.0 offer significant potential to reduce emissions over the lifetime of buildings, research on current applications is largely limited to studying the construction phase. This research demonstrates how integrating (i) Construction 4.0 themes - such as the circular economy and digital technologies - with (ii) a whole-of-life perspective informed by time-differentiated assessment approaches provides additional insights. In particular, it highlights the need to prioritise reuse of building materials and elements in the near-term future.

The thesis contributes methodological, conceptual, and practical advancements in the practice of LCA by integrating the timing of GHG emissions into prospective climate change impact assessment informed by the Intergovernmental Panel on Climate Change (IPCC) shared socio-economic pathways (SSPs) and downscaled RCBs. This approach provides new insights into how time-differentiated LCA approaches can support the development of effective decarbonisation pathways for the building sector using Construction 4.0 strategies.

Acknowledgements

The journey behind this thesis did not start with my PhD enrolment, but with a single email that opened the door to everything that followed. It starts with the very first email I wrote to my primary supervisor, Prof Sarah McLaren, who has since guided and shaped me into the researcher I am today.

First and foremost, I would like to sincerely thank Sarah, for her continuous support, encouragement, and guidance over the past few years. Most importantly, I am deeply grateful to her for believing in me from the very beginning and for giving me the opportunity to pursue this PhD under her supervision. I am especially thankful for the many opportunities she provided to work on the Construction 4.0 and IEA EBC Annex 89 projects alongside my doctoral research. Beyond supervision, her support has been personal as well as academic, and I will always value that greatly.

I would also like to show gratitude my co-supervisor during the first year, Dr Nihal Jayamaha, who introduced me to Sarah and supported me through the early stages of my PhD. His advice and guidance during that time were invaluable. I am equally grateful to my co-supervisor from the second year onwards, Dr Mikael Boulic, for his thoughtful guidance, encouragement, and support in helping me complete this journey.

I would like to extend my sincere thanks to my industry advisors, Dr David Dowdell and Dr Chanjief Chandrakumar. Despite the challenges of aligning schedules, I truly appreciate your commitment to attending progress meetings - often across different time zones - and for your valuable input into our publications and discussions. Your industry insights have been extremely beneficial to this research.

I gratefully acknowledge the Massey University Doctoral Scholarship, which supported me over the past three years and allowed me to focus fully on my research without financial burden. I also appreciate the Massey doctoral conference grant and the Construction 4.0 project funding, which enabled my travel and participation in international conferences.

My sincere thanks go to the Construction 4.0 project team including Heavy Engineering Research Association (HERA) for their support with case studies and for the many insightful discussions. I would also like to thank Building Research Association New Zealand (BRANZ), especially Jarred Butler, for providing case study data and valuable guidance. I am also grateful for the opportunity to undertake PhD placements abroad. At Aalborg University, within the BUILD department, I would like to thank Harpa, Endrit, Maria, and the wider team for their support. I am equally thankful to the Paul Scherrer Institute (PSI) for hosting me, particularly Romain and the Technology Assessment group, for their guidance and collaboration. I also extend my appreciation to colleagues from the IEA EBC Annex 89 programme for the engaging discussions, shared ideas, and opportunities to participate in expert meetings.

I would like to acknowledge the editors and reviewers of the peer-reviewed publications I have contributed to, as well as the journal teams, for their time and effort in improving the quality of this work.

My thanks also go to the administrative staff at Massey University, including CoS Travel and CoS Finance, for facilitating travel arrangements, and to the School of Agriculture and Environment administration, Massey Library, and the Graduate Research School for their continuous support and guidance.

To my colleagues and friends, thank you for the companionship, the discussions, and the support along the way. Knowing that I was not alone in this journey made a significant difference.

I would like to express my deepest gratitude to my family. To my loving mother, thank you for your endless love, blessings, and belief in me. To my late father, this achievement is something I know you always wished for me, and I carried your memory with me throughout this journey. To my cheerful sisters, thank you for your constant support and for bringing joy and laughter into my life. I am also grateful to my dearest in-laws for their support, encouragement and best wishes. Last but not least, to my loving husband, Gayan, thank you for your unwavering support, trust, and encouragement, especially during the most challenging moments. I would not have been able to complete this journey without you.

Table of Contents

Abstract i
Acknowledgements iii
Table of Contents v
List of Figures xi
List of Tables xiii
Abbreviations xiv
Chapter 1 1
Introduction 1
1.1 Research Background 1
1.2 Summary of Research Gaps 4
1.3 Research Aim, Objectives and Questions 5
1.4 Scope of the Thesis 7
1.5 Novelty and Original Contribution of the Thesis 11
1.6 Structure of the Thesis 12
1.7 Publications/Manuscripts Arising from the Research, and Related Initiatives 15
References 17
Chapter 2 19
Literature Review 19
Preface 19
2.1 Introduction 20
2.2 Accounting for Greenhouse Gas Emissions in the Building Sector 20
2.2.1 Different Life Cycle Assessment Modelling Approaches 20
Top-Down Approaches 21
Bottom-Up Approaches 22
- Dynamic LCA (dLCA) 23
- Prospective LCA (pLCA) 24
2.3 Building Sector Greenhouse Gas Emissions 25
2.4 Temporal Dynamics of Building-Related Emissions 26
2.5 Climate Change, Climate Targets and Associated Budgets 29
2.5.1 Climate Targets and Budgets 29
International Political Agreements on Climate Targets 30
Scientific Analysis Supporting the Setting of Climate Targets 31

2.5.2 Downscaling Global Budgets to National and Sectoral Levels 32
2.5.3 Aotearoa New Zealand Climate Targets 34
2.6 Construction 4.0 and Sustainability 36
2.7 Conclusion 38
References 39
Chapter 3 45
Design for Disassembly Strategies in Steel Eccentric Braced Frames: Climate Change Assessment Using Static and Dynamic Life Cycle Assessment Methods 45
Preface 45
Abstract 46
3.1 Introduction 47
3.2 Methods 51
3.2.1 Overview of the Case Study 51
3.2.2 Accounting for Time in LCA when Assessing Climate Change Impacts 54
3.2.3 Life Cycle Assessment 56
3.2.3.1 Goal and Scope 56
3.2.3.2 Life Cycle Inventory 58
3.2.3.3 Prospective Technology Analysis 62
3.2.3.4 Sensitivity Analyses 63
3.3 Results 64
3.3.1 sLCA Results 64
3.3.2 dLCA Results 66
3.3.3 Prospective Dynamic LCA results 68
3.3.4 Sensitivity Analyses 70
3.4 Discussion 74
3.4.1 Climate Change Impacts of EBF Structures 74
3.4.2 Implications for sLCA Methodology when Addressing DfD Strategies 76
3.4.3 Relevance of Dynamic LCA for Assessment of Climate Change Impacts 78
3.4.4 Climate Change Impacts of EBF Structures with Prospective Technologies 80
3.5 Conclusion 82
References 83
Chapter 4 89
Enabling Circular Office Fit-Outs for a Sustainable Future 89

Preface 89
Abstract 90
4.1 Introduction 90
4.2 Methodological Approach 93
4.3 Climate Change Impacts of Office Fit-Outs 93
4.4 Circular Economy as a Pathway for Sustainable Office Fit-Outs 94
4.5 Enabling the Transition to Circular Fit-Outs in the Built Environment 101
4.5.1 Barriers to Circular Fit-Outs 101
4.5.2 Technology-Based Strategies to Overcome Barriers 103
4.6 Achieving Progress Towards the Sustainable Development Goals Through Circular Fit-Outs 107
4.7 Conclusion 110
References 112
Chapter 5 117
Climate Change Impacts of Recurring Office Fit-Outs: A Prospective Life Cycle Assessment of Circular Economy-Based Improvements 117
Preface 117
Abstract 118
5.1 Introduction 119
5.2 Methods 121
5.2.1 Overview of the Case Study 121
5.2.1.1 Modelling Circular Economy Strategies 122
5.2.1.2 Accounting for the Temporal Dynamics of Recurring Fit-Outs 123
5.2.2 Life Cycle Assessment 125
5.2.2.1 Goal and Scope 125
5.2.2.2 System Boundary 125
5.2.2.3 Life Cycle Inventory 126
5.2.2.4 Life Cycle Impact Assessment 128
5.3 Results 130
5.3.1 Identification of Climate Change Impact Hotspots in a Single Office Fit-Out Cycle 130
5.3.2 Potential Climate Change Impact Reductions from CE Strategies 133
5.3.2.1 Modelling of Circular Fit-Outs 133

5.3.2.2 Climate Change Impact (GWP-fossil) Associated with CE Strategies 136
5.3.2.3 Sensitivity Analysis 138
5.3.3 Prospective Climate Change Impacts of Office Fit-Outs 141
5.3.3.1 Prospective LCA Results of Recurring Office Fit-Outs 141
5.3.3.2 Climate Policy Pathway Analysis 144
5.3.4 Comparison of Future Circular and Conventional Office Fit-Outs 145
5.4 Discussion 146
5.4.1 Climate Change Impacts of Recurring Office Fit-Outs 146
5.4.2 Circular Office Fit-Outs as a Mitigation Strategy in the Building Sector 149
5.4.3 Prospective LCA for Modelling Future Background Systems 152
5.4.4 Temporal Assessment of Mitigation Pathways 153
5.5 Conclusions 154
References 156
Chapter 6 163
Towards Dynamic Carbon Budgets for Aotearoa New Zealand Building Sector 163
Preface 163
6.1 Introduction 164
6.2 Methods 164
6.3 Results and Discussion 166
References 168
Chapter 7 169
Dynamic Carbon Budgets and Carbon Debts for Aotearoa New Zealand and Its Building Sector 169
Preface 169
Abstract 169
7.1 Introduction 170
7.2 Background 171
7.2.1 Global Carbon Budgets Concepts and Definitions 171
7.2.2 Allocating Shares 174
7.2.3 Temporal Dynamics 175
7.2.4 Carbon Budget Exhaustion and the Concept of Negative Budgets 176
7.3 Methodology 178

7.3.1 Downscale Global Remaining Carbon Budgets for Aotearoa New Zealand 178
7.3.2 National Carbon Debts and Building Sector Decarbonisation 182
7.3.3 Sensitivity Analysis 184
7.4 Results 185
7.4.1 National and Sectoral RCBs 185
7.4.2 National and Sectoral Carbon Debts 189
7.4.3 Sensitivity Analysis Results 192
7.5 Discussion 194
7.5.1 Communication of the Urgency to Undertake Near-Term Mitigation Actions 194
7.5.2 Use of a Dynamic Approach for Setting Budgets 196
7.5.3 Provision of a Range of RCBs 197
7.6 Conclusion 198
References 200
Chapter 8 207
Conclusion 207
8.1 Introduction 207
8.2 Summary of the Key Findings 207
8.2.1 Differences Between Static and Time-Differentiated Emission Accounting Approaches (RQ1) 207
8.2.2 Influence of Temporal Dynamics on Whole-of-Life Building Emissions (RQ2) 209
8.2.3 Role of Construction 4.0 in Shaping the Magnitude and Timing of Building Emissions (RQ3) 211
8.2.4 Development of Time-Differentiated Carbon Budgets for the Building Sector (RQ4) 213
8.2.5 Alignment of Building Sector Emissions with Climate Targets and the Concept of Dynamic Carbon Debt (RQ5) 214
8.3 Integrated Conclusion from Main Themes 215
8.4 Contribution to Knowledge 216
8.4.1 Methodological and Conceptual Contributions 216
8.4.2 Industry and Practitioner Contributions 217
8.5 Key Policy Recommendations 219

8.6 International Transferability 220
8.7 Limitations 221
8.8 Future Work 222
References 224
Appendix A 245
Appendix B 250
Appendix C 251
Appendix D: Statement of Contribution 253

List of Figures

Figure 1.1 Overview of the key areas underpin the thesis and their interconnectivity 3
Figure 1.2 Connectivity of RQs, objectives and chapters 7
Figure 1.3 Structure of the Thesis 12
Figure 2.1 Distribution by sector of global net greenhouse gas emissions in 2019 (IPCC, 2023, p. 44) 26
Figure 3.1 Cross section of the steel EBF (a) and 8-storey steel EBF (b) [adapted from (Andisheh et al., 2024)] 52
Figure 3.2 (a) Base models used for the flow diagrams of Structures 1, 2 and 3, and (b) Structures 4 and 5 in both scenarios 58
Figure 3.3 Schematic overview of the methodological framework adopted in this study 64
Figure 3.4 Climate change impacts of each structure in scenario 1 and scenario 2 without Module D 65
Figure 3.5 Climate change impacts of each structure in scenario 1 and scenario 2 including module D 65
Figure 3.6 Dynamic LCA results of EBF structure in scenario 1: Figure (a) and (c) show separate results with disaggregated module D. Figure (b) and (d) show the net results including module D 67
Figure 3.7 Cumulative radiative forcing of all structures in scenario 1 with current technology and prospective technology scenarios (TA1 and TA2 respectively). Figure (a), (b), (c), (d) and (e) show the cumulative radiative forcing of Structures 1, 2, 3, 4 and 5 70
Figure 3.8 Climate change impacts of each structure in scenario 2 assuming a moderate to severe earthquake and a catastrophic earthquake (SA1) 71
Figure 3.9 Climate change impacts of each structure in scenario 1 with 100% reuse rate vs SA2 (80% reuse rate) and SA3 (60% reuse rate). Variations are observed only for Structures 2 and 3, which incorporate reuse at EOL, while Structures 1 and 4 (no reuse) and Structure 5 (reuse benefits allocated to the subsequent life cycle) show no change 72
Figure 3.10 Climate change impacts of each structure using EN 15804 cut-off approach and 50/50 approach (SA4) 73
Figure 4.1 Summary of circular economy strategies as a solution for high office fit-out emissions and their multidimensional benefits 101
Figure 5.1 Summary of the tools and databases used in the life cycle assessment of the office fit-out 129
Figure 5.2 Contribution to the refurbishment material production emissions in each element of the office fit-out 132
Figure 5.3 Climate change impact (GWP-fossil) of a single office fit-out cycle (a) absolute results of each circular economy strategy (b) percentage relative change of each circular economy strategy compared to baseline (for modules B5.1, B5.2 and B5.3, positive values indicate a reduction in climate change impact relative to the baseline; for module D, positive values indicate a net increase in climate change impact relative to the baseline). The acronyms used to denote the circular economy strategies are defined in Table 5.4 136

Figure 5.4 Sensitivity analysis results of each circular economy strategy: (a) and (b) maximising reuse strategies CE1.1 and CE1.2; (c) and (d) design for optimisation strategies CE2.1 and CE2.2; (e) and (f) low-impact material selection strategies CE3.1 and CE3.2 140
Figure 5.5 Prospective climate change (GWP-fossil) results of each fit-out cycle over the reference service life of the office building 142
Figure 5.6 Climate change impacts of each office fit-out cycle under different climate policy pathways 145
Figure 5.7 Climate change impact of conventional and combined CE strategy-implemented office fit-out cycles under SSP2-NDC scenario using prospective life cycle assessment 146
Figure 6.1 Dynamic remaining carbon budgets for Aotearoa New Zealand from 2024-2050 based on equal per capita (EPC) and grandfathering (GF) approaches 166
Figure 6.2 Dynamic remaining carbon budgets for Aotearoa New Zealand building sector from 2024-2050 based on four different approaches and actual emissions in year 2022 167
Figure 7.1 Remaining carbon budgets of Aotearoa New Zealand from 2020-2050 and from 2024-2050 using equal per capita and grandfathering sharing approaches 186
Figure 7.2 Possible exhaustion years of remaining carbon budgets and their shifts due to the emissions from 2020-2023 in Aotearoa New Zealand 187
Figure 7.3 National dynamic remaining carbon budgets from 2024-2050 using equal per capita and grandfathering sharing principles (Same as Figure 6.1) 188
Figure 7.4 Sectoral annual remaining carbon budgets from 2024-2050 using different approaches and actual emissions in year 2022 189
Figure 7.5 (a) National dynamic remaining carbon budgets and dynamic carbon debts from 2024-2050 to stay below 1.5 ºC warming and forecasted national emissions (b) National dynamic carbon debts and forecasted carbon removal from land use, land use change and forest 190
Figure 7.6 Building sector annual carbon debts during 2024-2050 and forecasted sectoral emission pathway with existing measures 191

List of Tables

Table 1.1 Overview of the methodological approaches, key assumptions and limitations across the research....9
Table 2.1 Temporal dynamics modelled in the literature at different life cycle stages in LCA studies of buildings....28
Table 2.2 Required GHG and CO_2 emission percentage reductions based on 2019 emissions, for median and 5-95 percentiles based on modelled global emission pathways (IPCC, 2023, Table SPM.1)....32
Table 3.1 Data and sources used to model the life cycle stages....60
Table 3.2 Conceptual explanation of module D under static and dynamic LCA approaches....66
Table 4.1 Comparative summary of office fit-out case studies demonstrating circular economy strategies, associated emissions reductions and other benefits....96
Table 4.2 Summary of technology-based strategies, barriers for circular fit-outs and their alignment with circular strategies....106
Table 4.3 Contribution of circular fit-outs to specific targets of SDGs 11, 12 and 13 .108
Table 5.1 Summary of the office fit-out categories, sub-categories and elements assessed in the case study....122
Table 5.2 Climate change impact (GWP-fossil) of one office fit-out refurbishment cycle....131
Table 5.3 Percentage contributions of the key contributors to the climate change impact (GWP-fossil) of B5.1....132
Table 5.4 Summary of the modelled circular economy strategies....134
Table 5.5 Cumulative climate change impact of the office fit-out over the reference service life of office building using static and prospective life cycle assessments....143
Table 7.1 Summary of the parameters used in sensitivity analysis....184
Table 7.2 Impact of parameter variation on the national remaining carbon budgets for 2024-2050 under the EPC and GF sharing principles....192
Table 7.3 Impact of parameter variation on national cumulative carbon debts until 2050 under EPC and GF sharing principles....193

Abbreviations

3D	Three-Dimensional
AGWP	Absolute Global Warming Potentials
AI	Artificial Intelligence
AP	Ability to Pay
AR	Assessment Report
AR	Augmented Reality
BECCS	Bioenergy with Carbon Capture and Storage
BF	Blast Furnace
BIM	Building Information Modelling
BRANZ	Building Research Association of New Zealand
BREEAM	Building Research Establishment Environmental Assessment Method
Cat A	Category A
Cat B	Category B
CB	Consumption-based
CBDR	Common But Differentiated Responsibilities
CDR	Carbon Dioxide Removal
CE	Circular Economy
CH_4	Methane
CLF	Carbon Leadership Forum
CO_2	Carbon Dioxide
CRF	Cumulative Radiative Forcing
DACS	Direct Air Capture and Storage
DCFs	Dynamic Characterisation Factors
DfD	Design for Disassembly
DfX	Design for X
dLCA	Dynamic Life Cycle Assessment
DPPs	Digital Product Passports
EAF	Electric Arc Furnace
EBF	Eccentric Braced Frame
EE-MRIO	Environmentally Extended Multi-Regional Input Output
EOL	End-of-life
EPC	Equal Per Capita
EPD	Environmental Product Declaration
EU	European Union
EVA	Economic Value Added
GDP	Gross Domestic Product
GF	Grandfathering
GHG	Greenhouse Gas
GIA	Gross Internal Floor Area

GIS	Geographical Information Systems
GMST	Global Mean Surface Temperature
GWP	Global Warming Potential
GWP100	Global Warming Potential Over a 100-Year Time Horizon
HVAC	Heating, Ventilation and Air Conditioning
IAMs	Integrated Assessment Models
IEA	International Energy Agency
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IRF	Instantaneous Radiative Forcing
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
LULUCF	Land Use, Land Use Change and Forestry
MDF	Medium Density Fibreboard
N_2O	Nitrous Oxide
NABERS	National Australian Built Environment Rating System
NDCs	Nationally Determined Contributions
$NECO_2$	New Zealand National Embodied Carbon Repository
NLA	Net Lettable Area
NZETS	New Zealand Emission Trading Scheme
OECD	Organisation for Economic Co-operation and Development
PB	Production-Based
pLCA	Prospective Life Cycle Assessment
RCB	Remaining Carbon Budget
REMIND	Regional Model of Investment and Development
RF	Radiative Forcing
RQs	Research Questions
RSL	Reference Service Life
SDGs	Sustainable Development Goals
sLCA	Static Life Cycle Assessment
SSPs	Shared Socio-economic Pathways
TCRE	Transient Climate Response to cumulative CO_2 Emissions
TI	Tenant Improvements
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VOCs	Volatile Organic Compounds
WELL	WELL Building Standard
WMO	World Meteorological Organization

Chapter 1

Introduction

1.1 Research Background

The building sector is widely recognised as a significant source of the global greenhouse gas (GHG) emissions, accounting for 37% of total anthropogenic emissions due to its materials and energy use across the building life cycle (United Nations Environment Programme, 2024). With respect to carbon dioxide (CO_2) specifically, in 2023, the building sector accounted for 34% of global CO_2 emissions, with operational emissions reaching 9.8 $GtCO_2$ and embodied carbon emissions around 2.9 $GtCO_2$ (United Nations Environment Programme, 2025). Consequently, the issue of sustainable development within the building sector is extensively discussed in the academic literature and is also addressed in government policymaking worldwide, placing it at the centre of global sustainability and climate mitigation efforts.

The increasing urgency of climate change has shifted this focus towards alignment with stringent, time-bound **climate targets**. International frameworks such as the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) have established global commitments to limit temperature rise to well below 2 ºC and pursue efforts to limit it to 1.5 ºC (UNFCCC, 2015). These commitments are reinforced in the last five scientific assessments by the Intergovernmental Panel on Climate Change (IPCC), which have increasingly highlighted the urgency of rapid and sustained GHG emission reductions across all sectors, including the building sector (IPCC, 2001, 2007, 2013, 2018, 2023). Therefore, international and national policy frameworks for the building sector have been developed with the goal of aligning sector level mitigation efforts with internationally agreed climate targets, to reduce the widening gap between current emissions and climate targets. Translating these targets into quantified emission limits requires the calculation of **carbon budgets** and downscaling methods; however, existing methods often rely on static or aggregated assumptions, with limited consideration of how emissions evolve over time. This constrains their ability to

inform time-sensitive decision-making, indicating a need for temporally differentiated carbon budgeting approaches (pink boxes on Figure 1.1).

Achieving these targets presents a fundamental challenge for the building sector given the **long service life of buildings** and the associated temporal distribution of emissions. Buildings typically operate over several decades, during which time emissions arise at multiple stages and are influenced by evolving technologies, socio-economic conditions, and policy environments. In contrast, climate targets are defined over discrete and often near-term time horizons. This creates a fundamental temporal mismatch between emissions which may occur many years into the future and time-bound mitigation requirements, highlighting the importance of considering not only the magnitude but also the timing of emissions (orange box on Figure 1.1).

In response to these challenges this research explores the three interrelated domains of building sector emissions, climate target setting, and temporal dynamics, to address the opportunity to integrate temporal dynamics into the assessment of building-related emissions. Figure 1.1 maps these interrelated research areas in the broader research context and illustrates their conceptual integration. In the context of emission accounting methods, conventional **life cycle assessment (LCA) methods** provide limited insight into when emissions occur and how they relate to time-differentiated climate targets as they aggregate emissions over time into cumulative indicators. Emerging approaches, such as dynamic and prospective LCA, offer the potential to incorporate temporal resolution; however, their application within the building sector remains limited and requires further development (blue boxes on Figure 1.1).

Collectively, these challenges highlight the need for integrated approaches that link emission accounting, long-term emission pathways, and time-bound climate targets and associated budgets. In parallel, the ongoing technological transformation of the construction sector - commonly referred to as **Construction 4.0** - can influence construction technologies, processes and material flows, thereby creating opportunities to improve resource efficiency and support building decarbonisation. Technologies such as building information modelling (BIM), digital twins, automation and data-enabled life cycle platforms can facilitate the implementation and assessment of decarbonisation strategies under evolving technological and socio-economic conditions. In this thesis,

Construction 4.0 is therefore positioned as a conceptual framework and enabling mechanism, rather than as a standalone analytical method. Its relevance to the research lies in its potential to influence both the magnitude and timing of building-related GHG emissions, thereby shaping future building emission trajectories and their alignment with time-differentiated climate targets and carbon budgets. The thesis focuses specifically on Construction 4.0 developments that are relevant to building decarbonisation, including prospective technological change and circular economy strategies (green dashed box on Figure 1.1).

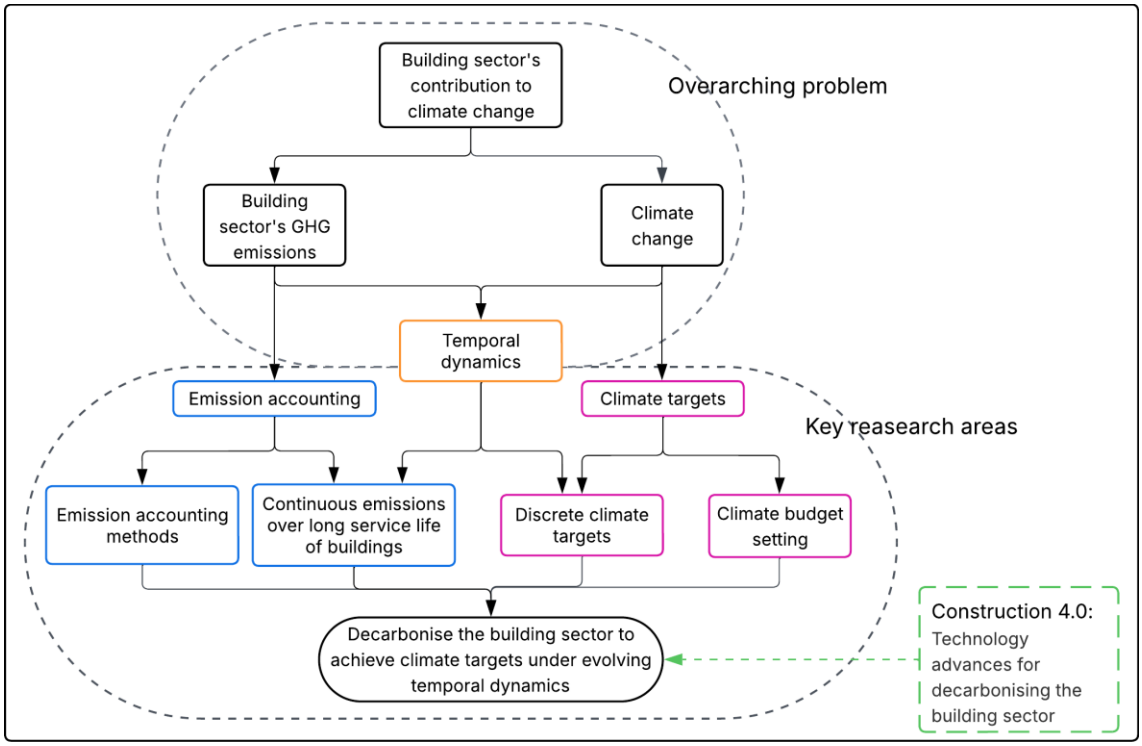


Figure 1.1 Overview of the key areas underpin the thesis and their interconnectivity

Therefore, this thesis explores development of building sector-specific approaches that integrate time-differentiated emission assessment with climate target-aligned decision-making, thereby addressing a critical gap in current understanding and practice of building sector decarbonisation. Even though the empirical analyses are grounded in the context of Aotearoa New Zealand, the methodological approaches and conceptual insights developed in this PhD project extend beyond this case, providing a transferable foundation for application in other nations facing similar challenges in aligning building sector emissions with time-bound climate targets.

1.2 Summary of Research Gaps

Current approaches to building-related emission assessment and carbon budget setting remain predominantly grounded in static frameworks (Chapter 2). The limitations of conventional LCA approach reduce the effectiveness of LCA as a decision-support tool, and are particularly pronounced in the building sector where long service lives and multiple life cycle stages generate complex, time-dependent emission profiles that are not represented in static LCA results.

At the same time, global carbon budgets are guided by time-bound limits that define specific milestones for emission reductions in order to limit global warming. Global carbon budgets emphasise the urgency of implementing mitigation actions within defined time horizons. However, when translating these budgets into actionable strategies at national and sectoral levels, existing downscaling approaches limit the ability to explicitly incorporate such temporal constraints. These downscaling approaches are based on static assumptions about sectoral activities and their associated emissions, and rarely account for the dynamic evolution of sectors in response to technological, socio-economic, and policy changes. Consequently, these approaches provide limited guidance on how emission pathways should adapt over time, constraining their effectiveness in supporting climate target-aligned decarbonisation strategies for the building and other sectors.

Another gap is evident in the application of Construction 4.0. Although this paradigm is concerned with advanced technological innovation in the construction sector, existing Construction 4.0 research and practice predominantly focuses on improving efficiencies at the building design and construction stages. As a result, whole-of-building considerations are insufficiently addressed within the Construction 4.0 literature. Therefore, there is a need for integrated model that link technological advancements in Construction 4.0 with time-differentiated emission accounting and dynamic carbon budgeting approaches, to support effective and climate target-aligned decarbonisation pathways for the building sector.

In the Aotearoa New Zealand context, diverse policy frameworks and initiatives have been established to support the decarbonisation of the building sector. These include the government's commitments under the Paris Agreement (UNFCCC, 2015), its legislative

framework to achieve net-zero emissions by 2050 under the Climate Change Response (Zero Carbon) Amendment Act 2019 (New Zealand Legislation, 2019), and sector-specific programmes aimed at transforming the building sector to reduce emissions and improve climate resilience e.g. the Building for Climate Change programme (Ministry of Business Innovation and Employment, 2020). However, again these initiatives give limited attention to the temporal distribution of emissions across building life cycles.

There is therefore a need for the development of methodologies that integrate time-differentiated emission accounting with dynamic and forward-looking carbon budget frameworks, capable of reflecting evolving technological, policy, and socio-economic conditions in the building sector. Such approaches are essential to support the design and evaluation of decarbonisation pathways that are aligned with the timing and urgency of carbon budgets.

1.3 Research Aim, Objectives and Questions

The aim of this research is to develop time-differentiated emission accounting approaches and associated carbon budgets for the building sector, and to investigate how such approaches can support building sector decarbonisation under evolving temporal dynamics. In response to the research gaps identified in Section 1.2 and based on the research aim, a set of research objectives was established to guide the study. There are two primary objectives, each supported by sub-objectives that define the scope and direction of the research.

Objective 1: To develop time-differentiated emission accounting methods that represent the dynamic nature of building-related emissions over the service life of buildings and building elements.

Sub-objectives:

1.1. To evaluate the appropriateness of static versus dynamic GHG emission accounting methods in building LCA studies

1.2. To assess the potential influence of future technology and socio-economic changes on whole-of-life building GHG emissions

1.3. To understand how to account the GHG mitigation opportunities of prospective decarbonisation initiatives for buildings under alternative future scenarios.

Objective 2: To develop time-differentiated carbon budgets for the building sector to align with Aotearoa New Zealand commitments to international climate targets

Sub-objectives:

2.1. To incorporate temporal dynamics into carbon budget downscaling methods

2.2. To develop dynamic carbon budgets at national and sectoral levels

2.3. To develop the concept of dynamic carbon debts alongside dynamic carbon budgets, to assess the alignment (or not) of Aotearoa New Zealand building sector emissions with downscaled time-differentiated international carbon budgets.

Building on these objectives, a set of research questions (RQs) were formulated to operationalise the research. Overall, these research questions provide the analytical backbone of the thesis and inform the ordering of the subsequent chapters:

- RQ1: What are the differences in building-related GHG emissions when using conventional static and time-differentiated accounting approaches?
- RQ2: What is the influence of temporal dynamics (such as future technological and socio-economic changes) on the whole-of-life GHG emissions of buildings?
- RQ3: How can evolving Construction 4.0 techniques contribute to building decarbonisation by influencing the magnitude and timing of emissions?
- RQ4: Can time-differentiated carbon budgets be developed for the building sector to align with international climate targets?
- RQ5: How do current and forecasted emissions from Aotearoa New Zealand's building sector compare with emission pathways aligned with international climate targets?

Figure 1.2 illustrates how each RQ is linked to the objectives and corresponding chapters.

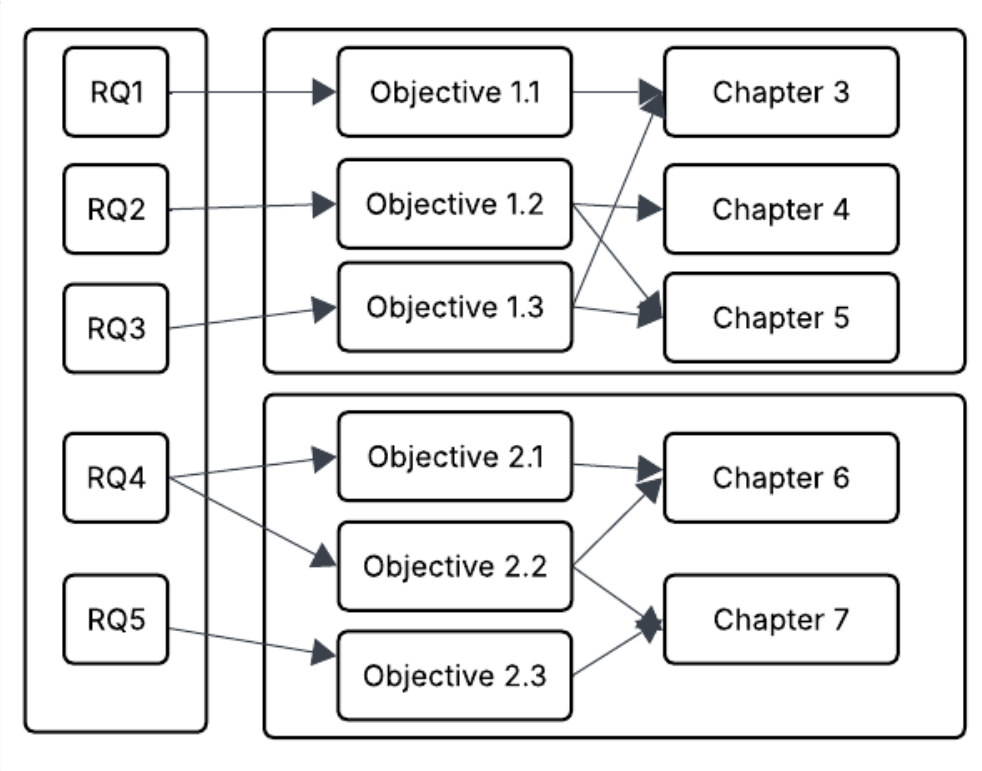


Figure 1.2 Connectivity of RQs, objectives and chapters

1.4 Scope of the Thesis

Methodologically, this thesis adopts a quantitative research approach comprising two narrative literature reviews, two building-level case studies, and time-differentiated carbon budget accounting. The first literature review establishes the conceptual and methodological foundation of the research and identifies gaps in current approaches to building emission accounting and carbon budget setting, while the second examines recurring building emissions and circular economy (CE) strategies to inform the second case study. The two case studies provide quantitative evidence for investigating temporal building-related GHG emissions through static, dynamic and prospective LCA approaches. They investigate time-differentiated emission accounting methods using: (i) an Eccentric Braced Frame (EBF) steel structure of a multi-storey building to represent a long-lived building element assessment, and (ii) a recurring office fit-out over a service life of a multi-tenant office building to represent recurring future emissions with interior refurbishments. These building-level assessments are then complemented by time-differentiated carbon budget accounting, which extends the analysis from emission trajectories to their alignment with time-bound climate targets at national and sectoral

levels. The methodologies are progressively connected from identifying research gaps and understanding emission timing, to assessing future emission trajectories and mitigation opportunities, and ultimately to evaluating their alignment with carbon budget allocation in the building sector. The methodological approaches, key assumptions and principal limitations associated with each research strand are summarised in Table 1.1, with detailed methodological descriptions provided in the respective chapters.

Due to the potentially wide-ranging scope of the research, the PhD thesis was constrained to focus on aspects considered most significant in accounting for the temporal dynamics of GHG emissions associated with the building sector and associated mitigation activities. In particular:

- At the national and sectoral scale, the research involves calculation of Aotearoa New Zealand-specific emission projections, and their comparison with downscaled carbon budgets calculated based on pre-existing internationally and scientifically established climate targets. It does not develop new climate models or global carbon budgets, but rather adopts existing global carbon targets and budgets as a basis for assessing the performance of Aotearoa New Zealand.
- While Construction 4.0 is employed as a conceptual lens, the analysis is selective, focusing on aspects most relevant to emission trajectories and decarbonisation pathways rather than providing a comprehensive evaluation of future technological pathways.

Through these case studies, the research evaluates emission accounting methodologies and their relevance for climate change mitigation decision-making, explicitly incorporating technological, socio-economic, and policy influences at a conceptual and scenario-based level. The scope of the analysis is therefore focused on methodological development and system-level emission dynamics, rather than detailed predictive modelling. Accordingly, the case studies do not include high-resolution building performance simulations, occupant behaviour modelling, or operational energy optimisation. This is because the primary objective of the research is to assess the influence of temporal dynamics on building emissions, for which the added complexity of detailed performance modelling would be unlikely to materially influence the methodological insights, but would significantly increase model uncertainty and reduce transparency.

Table 1.1 Overview of the methodological approaches, key assumptions and limitations across the research

Research focus	Methodological approach	Key assumptions	Principal limitations
Time-differentiated emissions assessment	Static vs. dynamic LCA of a steel EBF case study, CE strategies assessment, Temporal dynamics assessment	Primary steel is sourced from Australia, emissions are assigned to their respective periods of occurrence to enable temporal assessment	Results depend on data inventory quality, temporal assumptions and characterisation; dLCA can be more computationally and data intensive; limited direct compatibility between radiative forcing-based outputs and mass-based carbon budgets
Future building emissions	Prospective LCA with scenario-based modelling of future background systems of an office fit-out case study	Future technological, socio-economic and policy changes can be represented through plausible scenarios; future scenario assumptions provide reasonable representations of alternative pathways	Results are scenario-dependent and should not be interpreted as precise predictions; uncertainty increases with the temporal horizon; future technology adoption and policy implementation cannot be known with certainty
Construction 4.0 and decarbonisation	Prospective assessment of decarbonisation initiatives, including CE and evolving technological systems using both case studies	Selected Construction 4.0 developments can enable changes in construction processes, material flows and mitigation strategies	Construction 4.0 is broader than the technologies/strategies assessed; not all technological, socio-economic and policy pathways are quantified; mitigation outcomes

	and a narrative literature review		depend on future adoption and implementation
Dynamic carbon budgeting	Downscaling global climate targets to national and building sector carbon budgets using alternative sharing approaches	Remaining carbon budgets provide an appropriate limit, allocation principles can translate global budgets to national/sectoral scales	Carbon budgets are sensitive to allocation principles, starting points, target pathways and uncertainty in global budgets; different allocation approaches produce different budget ranges
NZ building sector alignment	Comparison of current, forecast building sector emissions with time-differentiated budgets, quantification of delayed mitigation actions	Building sector emissions can be estimated over the assessment period; allocated budgets provide a meaningful benchmark, accumulated overshoot can be represented through dynamic carbon debt	Results depend on emissions projections, sector boundaries and budget allocation assumptions, dynamic carbon debt is an accounting indicator rather than a direct measure of physical climate damage

1.5 Novelty and Original Contribution of the Thesis

This thesis is the first study to integrate time-differentiated emission accounting and carbon budget setting for the Aotearoa New Zealand building sector. The research advances current knowledge by integrating time-differentiated emission assessment with carbon budget setting to support the development of climate target-aligned decarbonisation pathways in the building sector. Thus, it provides methodological and conceptual contributions that extend beyond the specific context of Aotearoa New Zealand.

Methodologically, the research contributes a novel integration of dynamic carbon budgeting and carbon debt quantification, providing a means to align sectoral emissions with near-term international climate targets. This addresses a key limitation in existing approaches, which typically rely on static assumptions and cumulative emissions that overlook the implications of differences in timing of both emissions and mitigation efforts. By integrating temporal dynamics into both emission accounting and carbon budget allocation, the research provides an approach that enables investigation of alignment with climate targets under evolving technological and socio-economic conditions.

Conceptually, the thesis advances the understanding of building sector decarbonisation by reframing emissions as the output of temporally distributed activities that interact dynamically with time bound carbon budgets. In particular, it extends the discourse on Construction 4.0 by emphasising the need to incorporate time-differentiated GHG accounting alongside technological innovations. Therefore, the research positions Construction 4.0 as an integrative lens that connects technological advancements, circular economy (CE) strategies, and temporal emission dynamics within an integrated framework for climate change mitigation.

From a policy and industry perspective, the thesis provides actionable insights to support decision-making across multiple stakeholders. The developed approaches enable LCA practitioners to incorporate temporal dynamics into climate change assessments, support policymakers in identifying and implementing timely mitigation actions aligned with

national and international climate commitments, and assist industry stakeholders in evaluating decarbonisation strategies with evidence-based modelling. Furthermore, the dynamic carbon budgeting framework facilitates the development of sector-specific policies and provides a basis for continuous monitoring of emission pathways in relation to climate targets.

1.6 Structure of the Thesis

The thesis is presented in the format of a thesis by publication and consists of eight chapters. Chapter 1 and Chapter 8 provide the introduction to the thesis and overall conclusions respectively. Chapters 2 to 7 comprise peer reviewed publications and a manuscript currently under peer review. Figure 1.3 illustrates the flow and the structure of the thesis.

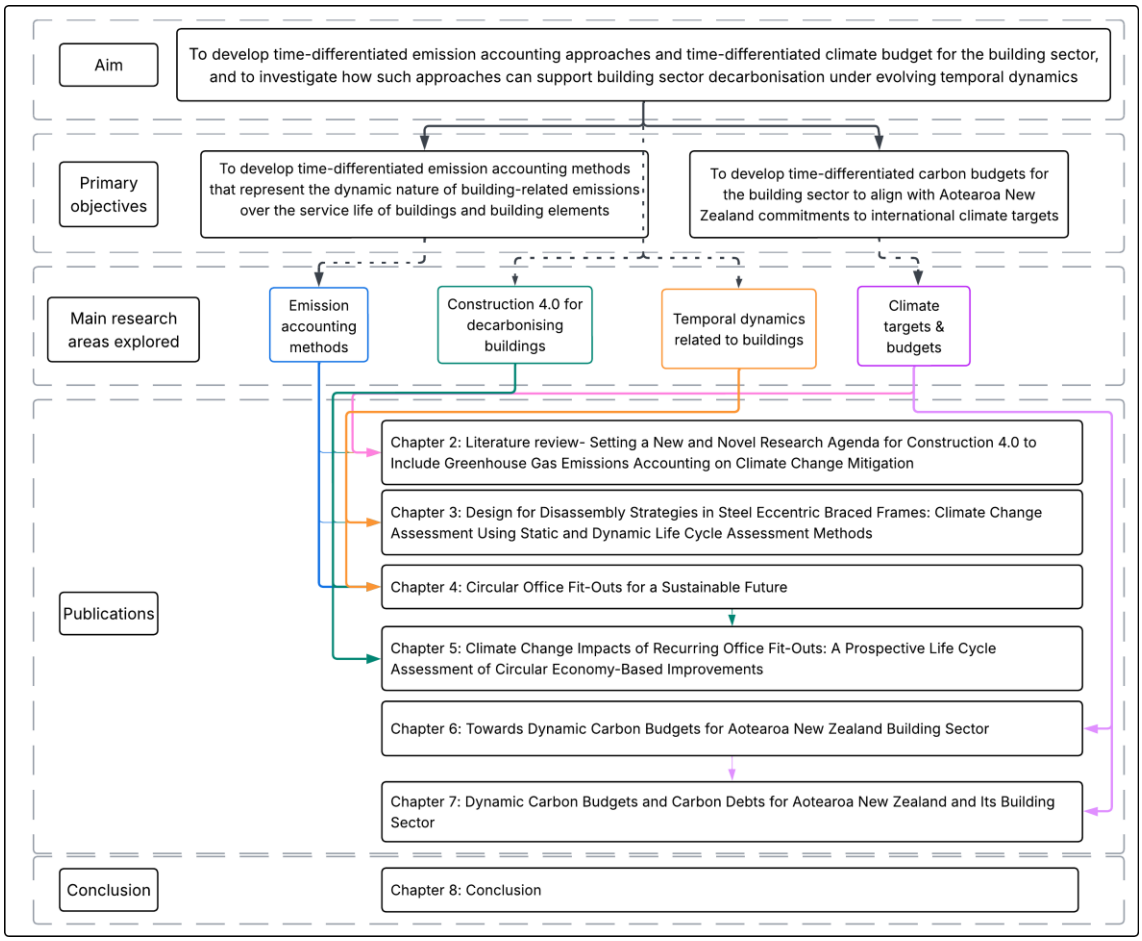


Figure 1.3 Structure of the Thesis

Chapter 2 establishes the conceptual foundation of the thesis by synthesising the key research areas identified. It functions as both a comprehensive review and an integrative analysis that develops a forward-looking research agenda for including emissions accounting for climate change mitigation in the building sector in Aotearoa New Zealand with a particular attention to temporal dynamics.

Chapter 3 addresses the limitations of conventional emission accounting approaches in capturing the temporal distribution of GHG emissions in buildings. To examine this, the chapter presents a comparative assessment of building related climate change impacts using a time-differentiated emission accounting approach - dynamic LCA approach - with a conventional static LCA method. A case study is employed to examine differences in climate change impact outcomes and their representation over time. The chapter further evaluates CE strategies as a key element of Construction 4.0 and assesses how these are captured under both accounting approaches. Prospective changes, including anticipated technological developments related to the case study, are also incorporated to reflect evolving future conditions. The findings demonstrate that static approaches limit the representation of timing of emissions, whereas dynamic LCA method provide enhanced insights into emission profiles over time, highlighting the importance of accounting for emission timing in supporting climate target-aligned decision-making.

Progressing from the findings of Chapter 3, which highlight the importance of accounting for the timing of emissions in buildings, Chapter 4 addresses a relatively underexplored aspect of building-related emissions in the life cycle of buildings: recurring emissions associated with frequent refurbishment activities during buildings use phase. Although refurbishment activities such as deep energy refurbishment and refurbishment at the end of service life have been examined in the literature, limited attention has been given to the recurring emissions over the service life of buildings, particularly in sectors such as multi-tenant office buildings where fit-outs occur regularly. To address this gap, Chapter 4 provides a thematic review of recurring emissions in office fit-outs, and decarbonisation opportunities arising from frequent fit-outs, with particular emphasis on decarbonisation opportunities aligned with the CE. Using office building fit-outs as a focal example, the chapter synthesises current knowledge and industry practice on how frequently recurring interventions can be mitigated through developments associated with Construction 4.0. The findings highlight that recurring emissions represent a significant component of

whole-of-life impacts and that their mitigation requires the integration of CE strategies and technology-enabled approaches.

Progressing from Chapter 4, which identifies the significance of recurring emissions and their mitigation potential through CE and technology-enabled strategies, Chapter 5 quantitatively assesses climate change impacts associated with recurring emissions in buildings using an office fit-out case study. The study applies time-differentiated emission accounting through a prospective LCA framework to evaluate how emissions evolve over time. Using the strategies identified in Chapter 4, CE interventions are assessed alongside projected socio-economic, technological, and policy developments to model future emission pathways. The findings demonstrate that implementing CE strategies in office fit-outs significantly reduces the climate change impacts associated with recurring emissions over the building service life. Furthermore, the incorporation of alternative prospective scenarios reveals that future technological, socio-economic and policy developments can further accelerate emission reductions, highlighting the role of forward-looking assessments in identifying long-term decarbonisation pathways. In comparison to Chapter 3, which establishes the importance of emission timing, and Chapter 4 which identifies key mitigation strategies, this chapter advances the analysis by providing a quantitative and prospective evaluation of how such strategies influence emissions over time.

While Chapters 3 to 5 focus on advancing time-differentiated emission accounting at the building level, Chapters 6 and 7 address the complementary challenge of aligning these emissions with time-bound climate targets through carbon budgeting. To address the limitation of existing static carbon budget setting methods, Chapter 6 develops a novel methodological approach for setting time-differentiated carbon budgets by identifying temporal dynamics at national and sectoral levels. The approach combines multiple downscaling principles and incorporates temporally varying parameters in setting carbon budgets to reflect changes in emissions over time. The findings demonstrate that incorporating temporal dynamics into setting carbon budgets enables an improved understanding of the consequences of delayed mitigation activities. This chapter therefore establishes the critical link between time-differentiated emissions and setting carbon budgets.

Chapter 7 applies dynamic carbon budget modelling to the Aotearoa New Zealand building sector, comparing projected emission trajectories against the time-dependent carbon budgets derived in Chapter 6. The chapter introduces the concept of dynamic carbon debt, which quantifies the extent to which delayed mitigation leads to the accumulation of excess emissions and increases the burden of future mitigation. The results show that dynamic carbon budgets and projected emission pathways are not aligned, leading to the accumulation of carbon debt over time relative to the target of staying below the Paris Agreement warming limit of 1.5 ºC. This highlights the significant consequences of delayed mitigation and underscores the importance of early and sustained emission reductions. The results further show that time-differentiated carbon budgeting provides a robust basis for evaluating alignment with climate commitments and offers actionable insights for policy development. The chapter establishes a direct link between international climate targets and national and sectoral mitigation pathways, supporting more informed and forward-looking climate governance.

1.7 Publications/Manuscripts Arising from the Research, and Related Initiatives

The research presented in this thesis has contributed to several peer-reviewed journal articles, conference publications, book chapters and ongoing manuscripts. The research has also benefited from the author's involvement in the Ministry of Business, Innovation and Employment's Endeavour funded project "Developing a Construction 4.0 transformation of Aotearoa New Zealand's construction sector", and the International Energy Agency Annex 89: Energy in Buildings and Communities programme. These two initiatives provided valuable industry engagement, international collaboration, and broader research perspectives that informed the development of this thesis.

The following list summarises the publications arising from this thesis, indicating their status and corresponding thesis chapters.

- Chapter 2: Weerasinghe, S. N., McLaren, S. J., & Dowdell, D. (2025). Setting a new and novel research agenda for Construction 4.0 to include greenhouse gas emissions accounting and Indigenous perspectives on climate change mitigation. In K. Husted, T. Coyle, & R. Amor (Eds.), *Building the future: Advancing*

Construction 4.0 in Aotearoa (pp. 115-134). NZ Heavy Engineering Research Association (HERA).

- Chapter 3: Weerasinghe, S. N., McLaren, S. J., Dowdell, D., Boulic, M., & Chandrakumar, C. (2026). Design for disassembly strategies in steel eccentric braced frames: climate change assessment using static and dynamic life cycle assessment methods. *The International Journal of Life Cycle Assessment*, *31*(6), 99. https://doi.org/10.1007/s11367-026-02677-2
- Chapter 4: Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2026). Enabling Circular Office Fit-Outs for a Sustainable Future. In S. M. E. Sepasgozar & R.J. Tumpa (Eds.), Accepted for publication in *Circular Economy enabling the SDGs through assessment governance and multi-scale built environment strategies from waste to neighbourhood design*
- Chapter 5: Weerasinghe, S. N., McLaren, S. J., Sacchi, R., Boulic, M., Dowdell, D., & Chandrakumar, C. (forthcoming). Climate Change Impacts of Recurring Office Fit-Outs: A Prospective Life Cycle Assessment of Circular Economy-Based Improvements. Under review in International Journal of Life Cycle Assessment
- Chapter 6: Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2025, 25.06.2025-27.06.2025). Towards Dynamic Carbon Budgets for Aotearoa New Zealand Building Sector. SBE Conference Series, Zurich, Switzerland.
- Chapter 7: Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2026). Dynamic carbon budgets and carbon debts for Aotearoa New Zealand and its building sector. *Building and Environment*, *287*, 113805. https://doi.org/10.1016/j.buildenv.2025.113805

References

IPCC. (2001). *Climate change 2001: the scientific basis. Intergovernmental Panel on Climate Change*. UK: Cambridge University Press.

IPCC. (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4_syr_full_report.pdf

IPCC. (2013). *Climate Change 2013: The Physical Science Basis*. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf

IPCC. (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. https://www.ipcc.ch/sr15/

IPCC. (2023). *Climate Change 2023: Synthesis Report*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

Ministry of Business Innovation and Employment. (2020). *Building for Climate Change: Transforming the Building and Construction Sector to reduce emissions and improve climate resilience*. https://www.mbie.govt.nz/dmsdocument/11522-building-for-climate-change

New Zealand Legislation. (2019). *Climate Change Response (Zero Carbon) Amendment Act 2019*. Retrieved 15 08 from https://www.legislation.govt.nz/act/public/2019/0061/latest/whole.html#LMS183736

UNFCCC. (2015). The Paris Agreement. In.

United Nations Environment Programme. (2024). *Global Status Report for Buildings and Construction*. https://www.unep.org/resources/report/global-status-report-buildings-and-construction

United Nations Environment Programme. (2025). *Global Status Report for Buildings and Construction 2024/2025: Not just another brick in the wall - The solutions exist. Scaling them will build on progress and cut emissions fast.* https://wedocs.unep.org/20.500.11822/47214

van der Heijden, J. (2023). Construction 4.0 in a narrow and broad sense: A systematic and comprehensive literature review. *Building and Environment*, *244*, 110788. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110788

This page is intentionally left blank

Chapter 2

Literature Review

Preface

This chapter is based on a peer-reviewed book chapter titled “Setting a New and Novel Research Agenda for Construction 4.0 to Include Greenhouse Gas Emissions Accounting on Climate Change Mitigation” published as a part of the ongoing research project “Developing a Construction 4.0 transformation of Aotearoa New Zealand’s construction sector”, led by Heavy Engineering Research Association (HERA) and supported by the Endeavour Fund administered by Te Hīkina Whakatutuki - The Ministry of Business, Innovation and Employment (MBIE). The original chapter was intentionally written for a broader, non-technical audience, with an emphasis on accessibility and interdisciplinary relevance. For the purposes of this thesis, the content has been revised, extended, and reframed to align with the requirements of a doctoral thesis literature review. In particular, the chapter has been expanded to include an in-depth review of existing and currently practiced emission accounting approaches for building-related emission assessment, the role of temporal dynamics in building emissions, and the development of climate targets and associated carbon budgets.

Chapter 2 establishes the conceptual and methodological foundation for the research by identifying the limitations and gaps in current approaches to time-differentiated emission assessment and carbon budgeting. The findings from this review provide the basis for the building-level investigations undertaken in Chapters 3,4 and 5, and carbon budgeting in Chapters 6 and 7.

2.1 Introduction

This chapter builds on the research framing established in Chapter 1 by critically reviewing the key areas of literature relevant to the assessment and mitigation of greenhouse gas (GHG) emissions in the building sector in the context of climate change. The chapter is presented as a set of interrelated research areas that collectively inform the research presented in this thesis. Section 2.2 reviews approaches used to account for GHG emissions in the building sector, including different modelling approaches. Section 2.3 examines the current status of building sector emissions. Section 2.4 discusses the temporal dynamics associated with building-related emissions. Section 2.5 reviews climate change targets, carbon budgets, and associated carbon budgets relevant to the building sector. Section 2.6 explores the role of Construction 4.0 and related technological advancements in supporting sustainability and building sector decarbonisation. Finally, Section 2.7 summarises the key findings from the literature review and identifies the research gaps addressed in this thesis.

2.2 Accounting for Greenhouse Gas Emissions in the Building Sector

2.2.1 Different Life Cycle Assessment Modelling Approaches

Life Cycle Assessment (LCA) modelling approaches applied to GHG emission accounting can be broadly categorised according to their modelling logic and treatment of system dynamics. These include top-down and bottom-up approaches, which differ in the direction and level of aggregation used to quantify emissions. This section first examines the top-down method for economy-wide emission accounting. It then focuses on bottom-up approaches, including conventional static LCA (sLCA), followed by time-differentiated and forward-looking modelling approaches such as dynamic LCA (dLCA) and prospective LCA (pLCA).

Top-Down Approaches

There are two distinct approaches used to account for GHG emissions in any economic sector: top-down and bottom-up approaches. The top-down approach provides a comprehensive overview of total GHG emissions by considering them at higher, aggregated levels, e.g., GHG emissions arising from all economic activities in a country. This approach is often used to inform the setting of national and international climate change mitigation strategies. In contrast, the bottom-up approaches account for GHG emissions from individual activities, and assessment involves calculating the sum of GHG emissions from all relevant activities involved in producing and using products (e.g., windows, insulation, floor coverings) or delivering services (e.g., electricity supply, transportation, waste management). The bottom-up approach is useful for informing product-related climate change mitigation strategies. There are also hybrid approaches that combine elements of both top-down and bottom-up approaches. For example, You et al. (2023) used process-based datasets (bottom-up approach) in their study of large-span steel structures but augmented them with input-output analysis (top-down approach) for processes such as labour and machinery production, where process-specific GHG emission data were not readily available.

When assessing GHG emissions using the top-down approach at national level, two dominant accounting methods are used: production-based (PB) and consumption-based (CB) accounting. CB accounting allocates the emissions related to products and services to the end consumer and excludes the GHG emissions of exported products and services. Conversely, PB accounting allocates the GHG emissions related to delivered products and services to the producer without considering the GHG emissions from imported products and services (Davis & Caldeira, 2010). For both approaches, GHG emission calculations often utilise an Environmentally Extended Multi-Regional Input Output (EE-MRIO) framework (Tukker *et al*., 2020). The EE-MRIO framework uses a top-down approach to calculate environmental impacts due to economic activities within a specific geographical region (Lenzen *et al*., 2014; Leontief, 1970). For example, Chandrakumar *et al*. (2019) used the EE-MRIO analysis to quantify the PB and CB emissions of Aotearoa New Zealand for the year 2012. These national CB and PB results can be disaggregated to calculate the environmental impacts of different economic sectors - such as the building sector - in various countries and regions

(Wiedmann, 2009). However, EE-MRIO has a number of limitations, including limited availability of time series data, requiring resource-intensive labour, and limited sector disaggregation (Lenzen *et al*., 2012; Wiedmann, 2009; Wiedmann *et al*., 2011).

Bottom-Up Approaches

The bottom-up approach to GHG emission assessment relies on product-level accounting methods, with LCA serving as the predominant method for evaluating environmental impacts across the full life cycle of product systems. The life cycle extends from raw material extraction, through manufacturing, transportation, utilisation, and concludes with end-of-life (EOL) activities. LCA methodology typically involves four phases: 1) Goal and Scope Definition, 2) Life Cycle Inventory (LCI), 3) Life Cycle Impact Assessment (LCIA), and 4) Interpretation (ISO, 2006a, 2006b). These sequential phases collectively facilitate a holistic assessment of the environmental impacts of a product system.

In applying LCA to building-related GHG emission accounting, Goldstein and Rasmussen (2018) specifically highlight a key challenge associated with assessing environmental impacts over the building long-life cycle: the potentially significant societal and technological changes that could take place over the typically long building lifetime. However, conventional sLCA typically offers a snapshot of environmental impacts at a specific point in the life cycle. To address this time challenge, Goldstein and Rasmussen (2018) recommended integrating the sLCA within a system dynamics framework. dLCA has emerged as a response to the need to comprehensively account for the evolving environmental impacts of product systems over time (Collinge et al., 2013; Levasseur et al., 2010; Su et al., 2017; Su et al., 2020). As Construction 4.0 emerges in the building sector (Section 2.6), disruptive technologies are expected to introduce dynamic changes in the environmental performance of this sector over time. Therefore, this aspect requires further consideration in the context of assessing climate change mitigation.

In recent years, pLCA has emerged as a forward-looking approach that incorporates anticipated changes in technologies, socio-economic conditions, and policy developments into LCA (Abu-Ghaida et al., 2025; Arvidsson et al., 2018; Bruhn et al., 2023; Eberhardt et

al., 2019a; Horup et al., 2025; Sacchi et al., 2022). Both dLCA and pLCA go beyond sLCA by addressing the dynamic nature of environmental impacts and are thus particularly useful for product systems characterised by extended life cycles, such as buildings.

- ***Dynamic LCA (dLCA)***

dLCA represents an advancement beyond conventional sLCA methodology, as it incorporates the dynamic nature of GHG emissions, particularly for product systems characterised by extended life cycles. Several methodological frameworks have been developed to quantitatively assess climate change impacts using dLCA. Among these, the approach proposed by Levasseur et al. (2010) is one of the most widely applied for climate change impact assessment. It has been applied in various LCA studies, including on the building and construction sector (Fouquet et al., 2015; Su et al., 2017), bioethanol (Levasseur et al., 2010), energy technologies (Lan & Yao, 2022) and landfill emissions (Wang et al., 2020).

Levasseur et al. (2010)'s dLCA approach incorporates the temporal dimension of GHG emissions in climate change impact characterisation. Rather than aggregating emissions into a static, time-independent global warming potential (GWP) score, dLCA maps the actual timing of emissions across a product life cycle and applies time-dependent characterisation factors derived from atmospheric impulse response functions. These functions model the radiative forcing (RF) exerted by each pulse of GHG (such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)) as they decay in the atmosphere according to their unique atmospheric lifetimes and warming potentials. The result is a dynamic characterisation of climate impact expressed as a function of time, enabling analysts to assess the distribution of RF over a defined time horizon.

The dynamic inventory for each GHG is derived by segmenting the lifetime of each GHG into one-year time steps and by aggregating the different emissions of each GHG occurring at discrete intervals. Subsequently, these data are used in a dynamic LCIA characterisation model. For LCA, the characterisation factors for the impact assessment are developed based

on the RF, and are referred to as dynamic characterisation factors (DCFs). A DCF is formulated by integrating absolute global warming potentials (AGWP) throughout the time considered for the study. Consequently, the annual GHG emissions are multiplied by annual DCFs to give the time-dependent instantaneous and/or cumulative radiative forcing results. Thus, dLCA enables a time-differentiated assessment of climate change impacts. However, at the same time dLCA studies may assume fixed system conditions in the background processes, and such studies do not capture the influence of future technological and socio-economic transformations, necessitating the use of pLCA.

- ***Prospective LCA (pLCA)***

In recent years, pLCA has emerged as a forward-looking extension of sLCA, designed to account for anticipated changes in technologies, energy systems, and socio-economic conditions over time (Arvidsson et al., 2018; Cucurachi et al., 2022; Thonemann et al., 2020). pLCA integrates projections of future system developments, often informed by integrated assessment models (IAMs) and scenario-based approaches (Bruhn et al., 2023; Sacchi et al., 2022). This enables the assessment of environmental impacts under alternative future pathways, making pLCA particularly relevant for long-lived systems.

Methodologically, pLCA modifies life cycle inventories to reflect expected changes in key parameters, including energy mixes, material production processes, and technological efficiencies. Approaches such as integrating IAM-derived scenarios into LCA databases have enabled systematic incorporation of future dynamics into environmental assessments (Sacchi et al., 2022). Therefore, pLCA supports the evaluation of multiple plausible futures, allowing for comparative analysis of future scenarios under varying technology, socio-economic and policy conditions. This represents a significant advancement over static approaches, which assume fixed emission intensities and therefore risk misrepresenting long-term impacts.

However, within the building sector, there are few studies using pLCA (or dLCA), and these studies mostly apply these modelling techniques in isolation to specific components

(Abu-Ghaida et al., 2025; Horup et al., 2025; Rodrigues et al., 2023; Rodrigues et al., 2024). For example, Rodrigues et al. (2024) developed a pLCA framework integrating future climate projections and decarbonisation scenarios to evaluate building retrofit strategies under evolving energy and climatic conditions, demonstrating how future grid decarbonisation and climate change alter the relative significance of operational and embodied emissions over time. However, the application of time-differentiated emission accounting within building decarbonisation studies remains fragmented and insufficiently integrated into broader mitigation decision-making frameworks.

2.3 Building Sector Greenhouse Gas Emissions

The building sector is a major contributor to global GHG emissions due to activities occurring throughout the life cycle of buildings. The two main categories of sources for these emissions are (i) operation of buildings, including energy for heating, cooling and lighting (operational emissions), and (ii) raw material extraction, transportation, manufacturing processes, construction site activities, material losses/ repair/ maintenance/ replacement, and end-of-life (EOL) processing (collectively known as embodied emissions) (MBIE, 2020). The carbon footprint of buildings is influenced by all these activities as well as additional factors that include choice of technologies, building design and occupant behaviour.

In the 2010-2019 decade, average human-caused GHG emissions were higher than in any previous decade (IPCC, 2023, p. 44). In 2019, global net anthropogenic GHG emissions were estimated to be 59±6.6 $GtCO_2eq$, which is 54% higher than those emissions in 1990 (IPCC, 2023, p. 44). Figure 2.1 shows the contribution of different economic sectors to global net GHG emissions in 2019, with the building sector accounting for 5.6% of total GHG emissions (approximately 3.3 $GtCO_2eq$) (IPCC, 2023, p. 44). However, in 2019, the operation of buildings[1] and the manufacture of construction products contributed approximately 28% and 10% of global GHG emissions, respectively (United Nations Environment Programme, 2020). These trends emphasise the significant direct and indirect

[1] Operation of buildings refers to residential and non-residential direct and indirect emissions at the operation stage. Indirect emissions are emissions from power generation for electricity and commercial heat.

contributions of the building sector to global GHG emissions. In Aotearoa New Zealand, emissions in the construction sector constituted 8.5% of the nation's consumption-based emissions in 2011 (Chandrakumar, Malik, et al., 2020). In 2015, the contribution of the whole built environment including the construction sector was approximately 20% on a consumption basis, and 13% when excluding emissions embodied in international trade (thinkstep Ltd, 2018). It should be noted that the construction sector and the built environment differ in scope, with the latter encompassing a broader range of activities, including building operation and use.

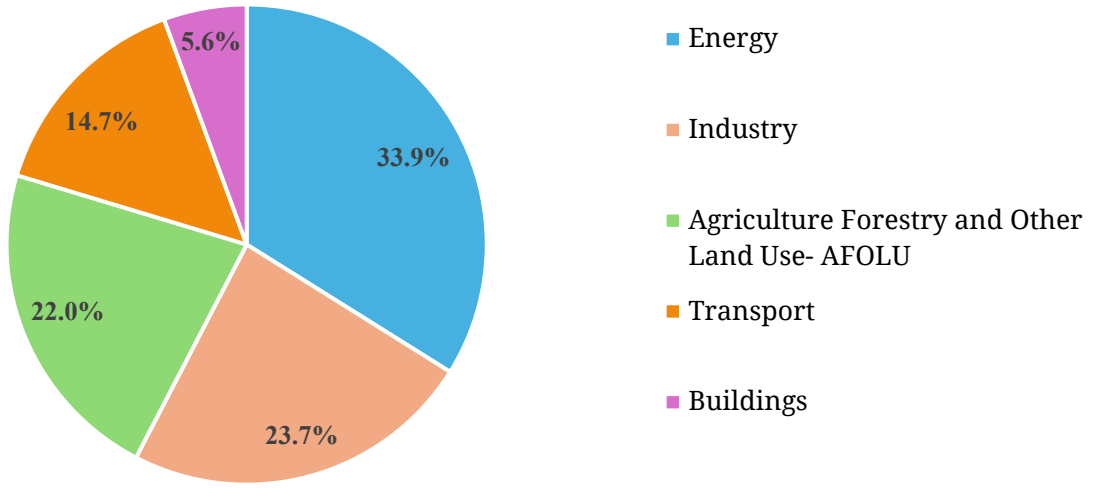


Figure 2.1 Distribution by sector of global net greenhouse gas emissions in 2019 (IPCC, 2023, p. 44)

2.4 Temporal Dynamics of Building-Related Emissions

As noted earlier, buildings are characterised by their exceptionally lengthy life cycles, which often extend for time scales ranging from 50 to 90 years (Alcorn, 2021; Ouellet-Plamondon et al., 2022) or even longer. Over this extended time scale, buildings undergo a variety of changes in response to diverse influencing factors including shifts in social, technological, economic, political and environmental dynamics occurring over time (Goldstein & Rasmussen, 2018). A number of studies have shown the significant impact of temporal variations on the environmental impacts associated with buildings over their extended life

cycles (Collinge et al., 2013; Fouquet et al., 2015; Negishi et al., 2018). Table 2.1 summarises findings from several studies investigating temporal dynamics at different life cycle stages of buildings. These studies have mostly focused on changes in energy generation and use, and waste management techniques.

Modelling temporal dynamics throughout a building's life cycle has potential to enhance the relevance of building LCAs, particularly LCA studies related to building performance and to support policymaking related to the building sector. This is because the timing of emissions influences their contribution to near-term climate impacts and the risk of exceeding time-bound carbon budgets, and accounting for temporal dynamics enables a more accurate representation of emission trajectories. This supports decision-making that prioritises the timing and sequencing of mitigation actions, aligning building-level strategies with broader climate targets.

Table 2.1 Temporal dynamics modelled in the literature at different life cycle stages in LCA studies of buildings

Reference	Description	A1-A3 Product Stage	A4-A5 Construction Process Stage	B1-B7 Use stage	C1-C4 End-of-life stage	D Reuse/ Recovery/ Recycling	Other Variables
Negishi et al. (2018)	Systematic exploration of temporal variations within the context of dLCA for buildings	-	-	Energy consumption related to occupancy Degradation of technical performance of building components and materials Improvements of materials Electricity grid mix	Techniques used	-	Biogenic carbon
Fouquet et al. (2015)	Construction of low-energy buildings and techniques utilised	-	-	Electricity grid mix Potential innovations of refurbished materials	Techniques used	-	Biogenic carbon
Collinge et al. (2011)	Temporal variations in internal and external conditions during the operational stage of a building	-	-	Electricity /steam /chilled water usage Energy consumption related to occupancy	-	-	-
Collinge et al. (2013)	Evaluating the LCA of buildings incorporating dynamic behaviour of buildings	Efficiency changes in industrial processes	Supply chain dynamics	Electricity grid mix	Regional waste treatment practices	-	-
Collinge et al. (2018)	Temporal variations in energy consumption and the energy mix utilised during the use of two buildings	-	-	Energy grid mix Energy consumption	-	-	-
Su et al. (2017)	Temporal variations integrated in dLCA within the context of buildings	-	-	Energy mix Energy consumption related to occupancy	Techniques used	-	-

2.5 Climate Change, Climate Targets and Associated Budgets

Climate change is a result of global warming, a phenomenon mainly caused by the emission of GHGs into the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) uses two main metrics to assess the contribution of GHGs to climate change (IPCC, 2001, 2007): RF and GWP. RF is defined as the change in energy flux at the top of the Earth's atmosphere caused by, amongst other things, changes in atmospheric GHG gas concentrations. GWP quantifies the RF following an emission of a unit mass of a given GHG, relative to a specific reference gas emission, accumulated over a chosen time period (most commonly 100 years). Generally, CO_2 is designated as the reference gas according to the IPCC (2001) guidelines.

2.5.1 Climate Targets and Budgets

The setting of climate targets is addressed using two different but interrelated approaches in the recent literature: international political agreements and scientific analyses. Political initiatives on climate change have focused on defining a "safe zone" for GHG concentrations in the atmosphere that can support economic development, human well-being and social harmony in the world. For example, the United Nations Framework Convention on Climate Change (UNFCCC) has political agreements to limit global warming and set climate targets (UNFCCC, 2015). Scientific analyses may involve calculating specific GHG emission budgets on the basis of climate targets set in political agreements. For example, the IPCC has calculated and published global carbon budgets based on temperature-limiting targets such as restricting global warming to 1.5 ºC and well below 2 ºC above pre-industrial levels, consistent with the objectives of the Paris Agreement. Carbon budgets are the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a specified level with a specified likelihood according to the IPCC (2023).

International Political Agreements on Climate Targets

International agreements on climate change mitigation policies are essential because anthropogenic GHG emissions contribute to climate change irrespective of their original geographical sources. These agreements are typically reached through international negotiations and serve as the foundation for national and regional climate policies.

The UNFCCC is a global initiative aiming at stabilising GHG concentrations in the atmosphere and is the parent treaty of the Kyoto Protocol and the subsequent Paris Agreement. It was adopted at the United Nations Conference on Environment and Development (UNCED) in 1992 and entered into force in 1994, with the aim of "stabilising GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992, p. 3). Initially, the UNFCCC placed more responsibility on developed nations, categorised as Annex I countries and belonging to the Organisation for Economic Co-operation and Development (OECD), to take the lead in reducing GHG emissions.

The Kyoto Protocol, adopted in 1997 and in force from 2005, operationalised the UNFCCC targets by setting individual targets for industrialised Annex I countries. Over the first and second commitment periods of the Kyoto Protocol, these targets added up to an average of 5% (from 2008 to 2012) and 18% (from 2013 to 2020) reduction in emissions, respectively, compared to 1990 levels (UNFCCC, 2021).

The Paris Agreement was adopted in 2015 and came into force in 2016. The overarching goal of the Paris Agreement is to limit the global average temperature rise to well below 2 ºC above the pre-industrial level and to pursue efforts to limit global warming to 1.5 ºC above pre-industrial levels (UNFCCC, 2015). For the first time, this agreement obligated all countries to address climate change and adopt a multi-gas abatement strategy, and to do so in accordance with the most up-to-date scientific knowledge. The agreement provides a framework for financial and technical support and capacity building for climate mitigation and adaptation at the country level. The Paris Agreement remains the central international climate framework currently in force, operating through successive Nationally Determined

Contributions (NDCs) and periodic global stocktakes intended to strengthen mitigation ambition over time toward achieving long-term temperature goals of limiting warming.

Scientific Analysis Supporting the Setting of Climate Targets

The IPCC was established by the United Nations Environment Programme (UNEP) and World Meteorological Organization (WMO) to assess and synthesise the latest climate change scientific research. Regular assessments of climate change, its impacts and future risks, and options for adaptation and mitigation are provided by the IPCC to policymakers, governments and the public. The first Assessment Report (AR) was published in 1990, and IPCC published its sixth AR in March 2023 (IPCC, 2023). IPCC defines climate targets as limiting the change in global average surface temperature to a specified level, commonly 1.5 ºC or 2.0 ºC above the pre-industrial level, as per political agreements. The total carbon budgets are then defined as the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a specified level with a specified likelihood, according to the IPCC (2023, p. 121). The remaining carbon budget (RCB)[2] is the carbon budget, calculated using a specified baseline year, that can be emitted as GHGs before the target is exceeded. The most recently calculated global RCBs - from the beginning of 2020 - were estimated as 500 $GtCO_2$ for a 50% chance of limiting global warming to 1.5 ºC and 1150 $GtCO_2$ for a 67% chance of limiting it to 2 ºC (IPCC, 2023). However, the IPCC highlights the fact that future CO_2 emissions from existing fossil fuel policies and practices alone, without additional abatement, have the potential to exceed the RCB for limiting warming to 1.5 ºC.

In addition to calculating carbon budgets, the IPCC has provided the percentage reduction of emissions (in terms of both all GHGs and CO_2 specifically) to achieve the targets given by the Paris Agreement. The required emission reduction percentages from 2019 emission levels for both all GHGs and CO_2 separately to remain within the 1.5 ºC and 2 ºC targets are

[2] The quantification of the remaining carbon budget (RCB) is based on the Shared Socioeconomic Pathways (SSPs) and estimated value of Transient Response to Cumulative CO_2 Emissions (TRCE) and its uncertainty, estimates of historical warming, feedback from the climate system, and variations in projected warming from non-CO_2 emissions as a result of mitigation action.

presented in Table 2.2. The calculated emission reductions are based on modelled global scenarios and pathways that are used to explore future emissions, climate change impacts and risks, and mitigation and adaptation strategies. These scenarios, known as Shared Socio-economic Pathways (SSPs), represent a range of possible future changes in societies (IPCC, 2023, p. 84).

Table 2.2 Required GHG and CO_2 emission percentage reductions based on 2019 emissions, for median and 5-95 percentiles based on modelled global emission pathways (IPCC, 2023, Table SPM.1)

Climate target	Reductions from 2019 emission levels (%)				
	Gases	2030	2035	2040	2050
Limit warming to 1.5 °C (>50% likelihood) with no or limited overshoot	GHG	43 [34-60]	60 [49-77]	69 [58-90]	84 [73-98]
	CO_2	48 [36-69]	65 [50-96]	80 [61-109]	99 [79-119]
Limit warming to 2 °C (>67% likelihood)	GHG	21 [1-42]	35 [22-55]	46 [34-63]	64 [53-77]
	CO_2	22 [1-44]	3 [21-59]	51 [36-70]	73 [55-90]

The IPCC's reports make clear that sector-based contributions are crucial for achieving climate targets. Specifically, the agricultural and forestry sectors (particularly as they impact land use change, land use change and forestry (LULUCF) activities) and the energy supply sector show potential for reaching net-zero CO_2 emissions earlier than the transport, buildings and industry sectors (IPCC, 2023, p. 93). This highlights the necessity of prioritising policy implementation and mitigation efforts in these three latter sectors to align with global climate targets.

2.5.2 Downscaling Global Budgets to National and Sectoral Levels

To operationalise the IPCC's RCB, it needs to be apportioned to different entities (e.g. region, country, industry, company) so that they can contribute to meeting climate targets. The process of allocating global budgets to national and sectoral scale is referred to as downscaling within an absolute sustainability context (Bjørn et al., 2020; Ryberg et al., 2020). Downscaling is performed based on different sharing principles which are chosen

according to underpinning ethical principles (Bjørn et al., 2020; Ryberg et al., 2020; Sandin et al., 2015).

Bjørn et al. (2020) summarised the sharing principles from the literature to mainly 10 distinct principles which can apply to anthropogenic systems, and are underpinned by ethical norms. The most frequently used and applied in studies are equal per capita (EPC), grandfathering (GF) and economic value added (EVA) principle (Bjørn et al., 2020). The **EPC principle** is a type of egalitarianism ethical principle; budgets are distributed among individuals regardless of geographical scope and focus on equal welfare, capabilities and resources amongst individuals (Ryberg et al., 2020). EPC sharing can be applied as a stand-alone principle for a country-level assessment i.e. the budget is distributed amongst countries according to their populations. However, it needs to be combined with another principle when it is applied to individual products or economic sectors that do not directly align with a specified number of people. As an example, Ryberg et al. (2020) recommend when downscaling the global budgets to industrial sectors, first, the global budget should be assigned to all people in a region (EPC), and then assigned to the industrial sector based on the utility provided by that industry (which mostly depends on the number of users and utility provided to users).

The **GF principle** falls under the inegalitarian ethical norm; shares of the budget are assigned in proportion to the environmental impacts that occurred in a reference year; this is also known as acquired rights (Bjørn et al., 2020; Horup et al., 2023). The **EVA principle** falls under the utilitarian ethical norm which underpins the concept of maximising the well-being for all of society (Bjørn et al., 2020; Ryberg et al., 2020). For this sharing approach, the application of a geographical scale is not particularly relevant because most cradle-to-grave product systems include activities that span across multiple regions; therefore treating the global carbon budget as a global common is recommended by Ryberg et al. (2020). However, temporal variations are still relevant when considering the EVA principle, as the carbon budget needs to be distributed among people who would likely live during the time frame of the study - because populations, technological and economic development are likely to increase the anthropogenic activities over time (Bjørn et al., 2020; Ryberg et al., 2018).

The selection of principles must be considered judiciously. The choice can have a high impact on the results, and there is a lack of agreement on the most appropriate one (Chandrakumar et al., 2018; Ryberg et al., 2016). A previous study which focused on selecting distributional approaches in large economies concluded that the EPC principle might be favourable for one country but, on the other hand, the EVA principle would be favourable for some other countries (Lucas et al., 2020). Ryberg et al. (2020) recommend using the EPC principle for downscaling the RCB from a global scale to a regional or individual scale because it is complex to use other methods in allocating the shares, and the EPC approach needs only population data for the calculations. These limitations highlight the need for downscaling approaches that incorporate temporal dynamics, multiple allocation principles, and uncertainty ranges to support more robust and policy-relevant carbon budgeting.

2.5.3 Aotearoa New Zealand Climate Targets

The Paris Agreement mandates that individual countries formulate Nationally Determined Contributions (NDCs) outlining their climate actions post-2020, aimed at aligning with the overarching global objective of limiting temperature rise to 1.5 ºC by 2050. Aotearoa New Zealand's NDC for the period of 2021-2023 was updated in the last quarter of 2021 and aims to reduce net GHG emissions to 50% below gross 2005 emission levels by 2030. Aotearoa New Zealand's methodological approach to calculate anthropogenic GHG emissions and removals uses the global warming potential over 100 years (GWP100) metric recommended by the IPCC (2013) and pre-existing methodologies from the IPCC 2006 GHG inventory guidelines and the 2013 IPCC Kyoto Protocol Supplement (IPCC, 2014).

To further efforts to meet its Paris Agreement commitment, the Aotearoa New Zealand government passed the Climate Change Response Amendment Act (Zero Carbon Act) 2019 to develop and implement climate change policies. Aotearoa New Zealand's GHG emission budget has been calculated as 571 $MtCO_2eq$ for 2021-2030 for the first NDC (Ministry for the Environment, 2022b). Aotearoa New Zealand plans to achieve its NDC commitment in this period by prioritising reduction of selected sectoral GHG emissions in the country and by increasing CO_2 removals through sustainable forest management practices.

The Zero Carbon Act is an amendment act to the Climate Change Response Act 2002. This has established a broader framework to develop and implement climate change policies over time in Aotearoa New Zealand with 2050 NDC targets. The main purpose of this Act is to contribute to the global targets under the Paris Agreement on limiting the global average temperature rise to 1.5 ºC and allow Aotearoa New Zealand to prepare for - and adapt to - the effects of climate change (New Zealand Legislation, 2019). The targets for emission reductions by 2050 are to bring net GHG emissions to zero except for biogenic methane; for biogenic methane, the targets are to reduce biogenic methane to 10% less than 2017 emissions by 2030 followed by 24-47% less than 2017 emissions by 2050 (New Zealand Legislation, 2019).

Aotearoa New Zealand's emission reduction plans are intended to provide strategies, policies and advice on climate action with the objective of achieving the two main climate targets for long-lived gases and for biogenic methane under the Zero Carbon Act. Six emission reduction plans are proposed up to 2050, each covering a five-year period (except for the first plan which is for four years), along with emission budgets.

The building and construction sector is one of the sectors included in the first emission reduction plan as it is a significant contributor to Aotearoa New Zealand's GHG emissions; for example, it was responsible for nearly 9.4% (7.4 $MtCO_2eq$) of domestic emissions in 2018 (Ministry for the Environment, 2022c). In addition to these domestic emissions, the Ministry for the Environment (2022c) estimated that a further 2.9 $MtCO_2eq$ of emissions occurred outside of Aotearoa New Zealand due to the production of imported construction materials and products in the building and construction sector.

During the first emission budget period, the building and construction sector is expected to reduce its emissions by 0.9 to 1.7 $MtCO_2eq$ mainly through non-regulatory initiatives such as behaviour change and providing technical infrastructure such as data and tools (Ministry for the Environment, 2022c). But from the second emission budget period onwards (i.e. 2026 onwards), it is expected that reductions will be achieved through regulatory settings. During the second (from 2026-2030) and third (from 2031-2035) emission budgets, emission

reductions for the building sector are expected of 1.5 to 3.4 $MtCO_2eq$, and 3.9 to 7.5 $MtCO_2eq$ respectively relative to the projected emissions based on 2020 building and construction emissions (Ministry for the Environment, 2022c, Figure 12.2).

2.6 Construction 4.0 and Sustainability

Construction 4.0 builds upon the principles of Industry 4.0, which is characterised by the integration of advanced technologies and digitalisation in manufacturing. In the context of construction, this integration involves the use of technologies such as Building Information Modelling (BIM), Internet of Things (IoT), robotics, artificial intelligence (AI), and augmented reality (AR) to improve efficiency and productivity throughout the construction life cycle. However, recent literature emphasises that Construction 4.0 goes beyond just technological integration. It also considers the broader context in which construction activities take place, to include social, economic, governance and environmental aspects (van der Heijden, 2023, 2024; Wang & Guo, 2022).

This comprehensive approach implies that Construction 4.0 is not only concerned with advanced technologies but also addresses the development of sustainable and resilient built environments that align with socio-cultural needs while mitigating environmental impacts. For example, BIM is software that is utilised to design, construct and operate buildings, and delivers a digital model that contains information about the physical and functional aspects of a building structure. BIM has the potential to support more accurate LCA of buildings by managing the complex data associated with design, construction and operation of buildings. For example, BIM may be extended to include data on construction waste, energy consumption and GHG emissions in the life cycle of buildings, and this could be included in materials passports (also known as digital product passports), which are digital repositories containing information on material composition, environmental impacts, reuse potential, and recovery pathways to support circular economy (CE) strategies for buildings.

Four common topics in Construction 4.0 that have the potential to leverage advanced technologies to achieve environmental sustainability outcomes are briefly discussed here: the

CE, smart construction materials, IoT, and renewable energy technologies. The **CE** is focused on keeping materials in use for as long as possible. There is ongoing work on the integration of CE principles with advanced digital construction tools (Jemal *et al*., 2023) in the Construction 4.0 context. By embracing innovative strategies focused on reusing, recycling, and designing for disassembly and reassembly (McDonough & Braungart, 2003), the construction industry can potentially mitigate resource depletion and minimise waste generation, thus contributing to a more sustainable approach to construction.

Two examples of the use of **smart construction materials** (Balasubramanian *et al*., 2024; Hildebrandt *et al*., 2017) are i) shape memory materials such as alloys and polymers that can recover their original shape after being subjected to large deformations (Tabrizikahou *et al*., 2021), and ii) self-healing, high-performance concrete (Nilimaa, 2023). These materials have both lower embodied GHG emissions and the potential to reduce associated operational emissions compared to traditional construction materials.

The integration of more sophisticated **IoT** could enable better monitoring, control and optimisation of real time energy and water consumption in buildings using IoT devices. For example, IoT-enabled heating, ventilation and air conditioning (HVAC) systems can adjust heating and cooling based on occupancy and weather conditions, leading to energy savings and reduced GHG emissions (de Almeida Barbosa Franco *et al*., 2022; Martínez *et al*., 2021). Integration of **renewable energy technologies** is another topic catalysing the shift towards an environmentally sustainable construction industry. These technologies, such as solar panels and wind turbines, are being increasingly incorporated into buildings and reduce dependence on fossil fuels as energy sources (Bagheri *et al*., 2018).

There is an opportunity for Construction 4.0 data management systems to collect and integrate this additional information into decision-support systems. For all these transformational initiatives, however, it is imperative that they do, in fact, deliver environmental sustainability benefits. This requires future-oriented environmental assessment of building design, alternative technologies and materials, and implementation of new practices that are being developed as part of the Construction 4.0 agenda.

2.7 Conclusion

Across emission accounting methods, temporal dynamics, climate target setting and carbon budgeting, and the emerging role of Construction 4.0, the review highlights a common limitation: the predominance of static and aggregated approaches that inadequately represent the temporal nature of emissions and their alignment with time-bound climate change objectives. While recent methodological advancements, including dynamic and prospective LCA, and developments in carbon budget downscaling, are beginning to address these challenges, their application within the building sector remains fragmented and insufficiently integrated.

The review further demonstrates that building-related emissions are inherently dynamic, shaped by long service lives, and evolving technological, socio-economic, and policy conditions. However, existing approaches inadequately capture how these temporal dynamics influence emission trajectories and the effectiveness of mitigation strategies. Similarly, current downscaling methods for carbon budgets provide limited insight into the timing and sequencing of emission reductions required to remain within climate targets. Although Construction 4.0 offers significant potential to enable more data-driven and life cycle-oriented decision-making, its role in supporting temporally informed whole-of-life decarbonisation remains underexplored. These gaps underscore the need for integrated approaches that explicitly account for temporal dynamics in both emission assessment and climate target alignment. Addressing this need forms the central focus of this thesis, which advances time-differentiated emission accounting and dynamic carbon budgeting frameworks to support climate-aligned decision-making in the building sector.

References

Abu-Ghaida, H., Hollberg, A., Ritzen, M., Wöhler, A., & Lizin, S. (2025). Assessing the environmental benefits of design for disassembly in buildings with a time-resolved prospective LCA approach. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-025-02526-8

Alcorn, J. A. (2021). *Global Sustainability and the New Zealand House* Open Access Te Herenga Waka-Victoria University of Wellington]. https://openaccess.wgtn.ac.nz/articles/thesis/Global_Sustainability_and_the_New_Zealand_House/16992619

Arvidsson, R., Tillman, A. M., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D., & Molander, S. (2018). Environmental assessment of emerging technologies: recommendations for prospective LCA. *Journal of Industrial Ecology*, *22*(6), 1286-1294.

Bagheri, M., Shirzadi, N., Bazdar, E., & Kennedy, C. A. (2018). Optimal planning of hybrid renewable energy infrastructure for urban sustainability: Green Vancouver. *Renewable and Sustainable Energy Reviews*, *95*, 254-264. https://doi.org/https://doi.org/10.1016/j.rser.2018.07.037

Balasubramanian, S., Shukla, V., Islam, N., & Manghat, S. (2024). Construction Industry 4.0 and Sustainability: An Enabling Framework. *IEEE Transactions on Engineering Management*, *71*, 1-19. https://doi.org/10.1109/TEM.2021.3110427

Bjørn, A., Chandrakumar, C., Boulay, A.-M., Doka, G., Fang, K., Gondran, N., Hauschild, M. Z., Kerkhof, A., King, H., Margni, M., McLaren, S., Mueller, C., Owsianiak, M., Peters, G., Roos, S., Sala, S., Sandin, G., Sim, S., Vargas-Gonzalez, M., & Ryberg, M. (2020). Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. *Environmental Research Letters*, *15*(8), 1-23. https://doi.org/10.1088/1748-9326/ab89d7

Bruhn, S., Sacchi, R., Cimpan, C., & Birkved, M. (2023). Ten questions concerning prospective LCA for decision support for the built environment. *Building and Environment*, *242*, 110535. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110535

Chandrakumar, C., Malik, A., McLaren, S. J., Owsianiak, M., Ramilan, T., Jayamaha, N. P., & Lenzen, M. (2020). Setting Better-Informed Climate Targets for New Zealand: The Influence of Value and Modeling Choices. *Environ Sci Technol*, *54*(7), 4515-4527. https://doi.org/10.1021/acs.est.9b06991

Chandrakumar, C., McLaren, S. J., Jayamaha, N. P., & Ramilan, T. (2018). Absolute Sustainability-Based Life Cycle Assessment (ASLCA): A Benchmarking Approach to Operate Agri-food Systems within the 2°C Global Carbon Budget. *Journal of Industrial Ecology*, *23*(4), 906-917. https://doi.org/10.1111/jiec.12830

Chandrakumar, C., McLaren, S. J., Malik, A., Ramilan, T., & Lenzen, M. (2019). Understanding New Zealand's consumption-based greenhouse gas emissions: an application of multi-regional input-output analysis. *The International Journal of Life Cycle Assessment*, *25*(7), 1323-1332. https://doi.org/10.1007/s11367-019-01673-z

Collinge, W. O., Landis, A. E., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2013). Dynamic life cycle assessment: framework and application to an institutional building. *The*

International Journal of Life Cycle Assessment, *18*(3), 538-552. https://doi.org/10.1007/s11367-012-0528-2

Collinge, W. O., Liao, L., Xu, H., Saunders, C. L., Bilec, M. M., Landis, A. E., Jones, A. K., & Schaefer, L. A. (2011, 16-18 May 2011). Enabling dynamic life cycle assessment of buildings with wireless sensor networks. Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology,

Collinge, W. O., Rickenbacker, H. J., Landis, A. E., Thiel, C. L., & Bilec, M. M. (2018). Dynamic Life Cycle Assessments of a Conventional Green Building and a Net Zero Energy Building: Exploration of Static, Dynamic, Attributional, and Consequential Electricity Grid Models. *Environmental Science & Technology*, *52*(19), 11429-11438. https://doi.org/10.1021/acs.est.7b06535

Cucurachi, S., Steubing, B., Siebler, F., Navarre, N., Caldeira, C., & Sala, S. (2022). Prospective LCA methodology for Novel and Emerging Technologies for BIO-based products. *Publications Office of the European Union, Luxembourg*.

Davis, S. J., & Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences*, *107*(12), 5687-5692. https://doi.org/10.1073/pnas.0906974107

de Almeida Barbosa Franco, J., Domingues, A. M., de Almeida Africano, N., Deus, R. M., & Battistelle, R. A. (2022). Sustainability in the Civil Construction Sector Supported by Industry 4.0 Technologies: Challenges and Opportunities. *Infrastructures*, *7*(3).

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019). Dynamic Benchmarking of Building Strategies for a Circular Economy. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012027. https://doi.org/10.1088/1755-1315/323/1/012027

Fouquet, M., Levasseur, A., Margni, M., Lebert, A., Lasvaux, S., Souyri, B., Buhé, C., & Woloszyn, M. (2015). Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. *Building and Environment*, *90*, 51-59. https://doi.org/10.1016/j.buildenv.2015.03.022

Goldstein, B., & Rasmussen, F. N. (2018). LCA of Buildings and the Built Environment. *Life cycle assessment: theory and practice*, 695-722.

Hildebrandt, J., Hagemann, N., & Thrän, D. (2017). The contribution of wood-based construction materials for leveraging a low carbon building sector in europe. *Sustainable Cities and Society*, *34*, 405-418. https://doi.org/https://doi.org/10.1016/j.scs.2017.06.013

Horup, L., Bruhn, S., Hoxha, E., Birgisdottir, H., Secher, A. Q., Ohms, P., & Hauschild, M. (2025). Absolute sustainability assessment of the Danish building sector through prospective LCA. *Science of The Total Environment*, *966*, 178780. https://doi.org/https://doi.org/10.1016/j.scitotenv.2025.178780

Horup, L. H., Birgisdóttir, H., & Ryberg, M. W. (2023). Defining dynamic science-based climate change budgets for countries and absolute sustainable building targets. *Building and Environment*, *230*. https://doi.org/10.1016/j.buildenv.2022.109936

IPCC. (2001). *Climate change 2001: the scientific basis. Intergovernmental Panel on Climate Change*. UK: Cambridge University Press.

IPCC. (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4_syr_full_report.pdf

IPCC. (2013). *Climate Change 2013: The Physical Science Basis*. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf

IPCC. (2014). *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol*. https://www.ipcc-nggip.iges.or.jp/public/kpsg/pdf/KP_Supplement_Entire_Report.pdf

IPCC. (2023). *Climate Change 2023: Synthesis Report*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

ISO. (2006a). *ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework*. ISO.

ISO. (2006b). ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines. In.

Jemal, K. M., Kabzhassarova, M., Shaimkhanov, R., Dikhanbayeva, D., Turkyilmaz, A., Durdyev, S., & Karaca, F. (2023). Facilitating Circular Economy Strategies Using Digital Construction Tools: Framework Development. *Sustainability*, *15*(1).

Lan, K., & Yao, Y. (2022). Dynamic Life Cycle Assessment of Energy Technologies under Different Greenhouse Gas Concentration Pathways. *Environmental Science & Technology*, *56*(2), 1395-1404. https://doi.org/10.1021/acs.est.1c05923

Lenzen, M., Geschke, A., Wiedmann, T., Lane, J., Anderson, N., Baynes, T., Boland, J., Daniels, P., Dey, C., Fry, J., Hadjikakou, M., Kenway, S., Malik, A., Moran, D., Murray, J., Nettleton, S., Poruschi, L., Reynolds, C., Rowley, H., . . . West, J. (2014). Compiling and using input-output frameworks through collaborative virtual laboratories. *Sci Total Environ*, *485-486*, 241-251. https://doi.org/10.1016/j.scitotenv.2014.03.062

Lenzen, M., Kanemoto, K., Moran, D., & Geschke, A. (2012). Mapping the structure of the world economy. *Environ Sci Technol*, *46*(15), 8374-8381. https://doi.org/10.1021/es300171x

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics*, *52*(3), 262-271. https://doi.org/10.2307/1926294

Levasseur, A., Lesage, P., Margni, M., Deschênes, L., & Samson, R. (2010). Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environmental Science & Technology*, *44*(8), 3169-3174. https://doi.org/10.1021/es9030003

Lucas, P. L., Wilting, H. C., Hof, A. F., & van Vuuren, D. P. (2020). Allocating planetary boundaries to large economies: Distributional consequences of alternative perspectives on distributive fairness. *Global Environmental Change*, *60*, 102017. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2019.102017

Martínez, I., Zalba, B., Trillo-Lado, R., Blanco, T., Cambra, D., & Casas, R. (2021). Internet of Things (IoT) as Sustainable Development Goals (SDG) Enabling Technology towards Smart Readiness Indicators (SRI) for University Buildings. *Sustainability*, *13*(14).

MBIE. (2020). *Whole-of-Life Embodied Carbon Emissions Reduction Framework*. https://www.mbie.govt.nz/dmsdocument/11794-whole-of-life-embodied-carbon-emissions-reduction-framework

McDonough, W., & Braungart, M. (2003). Towards a sustaining architecture for the 21st century: the promise of cradle-to-cradle design. *Industry and environment*, *26*(2), 13-16.

Ministry for the Environment. (2022a). *New Zealand's Greenhouse Gas Inventory 1990–2020*. https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-1990-2020/

Ministry for the Environment. (2022b). *Towards a productive, sustainable and inclusive economy: Aotearoa New Zealand's first emissions reduction plan*. Retrieved 15 08 from https://environment.govt.nz/publications/aotearoa-new-zealands-first-emissions-reduction-plan/

Negishi, K., Tiruta-Barna, L., Schiopu, N., Lebert, A., & Chevalier, J. (2018). An operational methodology for applying dynamic Life Cycle Assessment to buildings. *Building and Environment*, *144*, 611-621. https://doi.org/10.1016/j.buildenv.2018.09.005

New Zealand Legislation. (2019). *Climate Change Response (Zero Carbon) Amendment Act 2019*. Retrieved 15 08 from https://www.legislation.govt.nz/act/public/2019/0061/latest/whole.html#LMS183736

Nilimaa, J. (2023). Smart materials and technologies for sustainable concrete construction. *Developments in the Built Environment*, *15*, 100177. https://doi.org/https://doi.org/10.1016/j.dibe.2023.100177

Ouellet-Plamondon, C., Ramseier, L., Balouktsi, M., Delem, L., Foliente, G., Francart, N., Garcia, A., Hoxha, E., Lützkendorf, T., Nygaard Rasmussen, F., Peuportier, B., Butler, J., Birgisdottir, H., Dowdell, D., Dixit, M., Silva, V., Silva, M., de Cózar, J., Kjendseth Wiik, M., & Frischknecht, R. (2022). *Carbon footprint assessment of a wood multi-residential building considering biogenic carbon*. https://doi.org/10.21203/rs.3.rs-2273783/v1

Rodrigues, C., König, J., & Freire, F. (2023). Prospective life cycle assessment of a novel building system with improved foam glass incorporating high recycled content. *Sustainable Production and Consumption*, *36*, 161-170. https://doi.org/https://doi.org/10.1016/j.spc.2023.01.002

Rodrigues, C., Rodrigues, E., S. Fernandes, M., & Tadeu, S. (2024). Prospective life cycle approach to buildings' adaptation for future climate and decarbonization scenarios. *Applied Energy*, *372*, 123867.

Ryberg, M. W., Andersen, M. M., Owsianiak, M., & Hauschild, M. Z. (2020). Downscaling the planetary boundaries in absolute environmental sustainability assessments – A review. *Journal of Cleaner Production*, *276*. https://doi.org/10.1016/j.jclepro.2020.123287

Ryberg, M. W., Owsianiak, M., Clavreul, J., Mueller, C., Sim, S., King, H., & Hauschild, M. Z. (2018). How to bring absolute sustainability into decision-making: An industry case study using a Planetary Boundary-based methodology. *Sci Total Environ*, *634*, 1406-1416. https://doi.org/10.1016/j.scitotenv.2018.04.075

Ryberg, M. W., Owsianiak, M., Richardson, K., & Hauschild, M. Z. (2016). Challenges in implementing a Planetary Boundaries based Life-Cycle Impact Assessment methodology. *Journal of Cleaner Production*, *139*, 450-459. https://doi.org/10.1016/j.jclepro.2016.08.074

Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., & Luderer, G. (2022). PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renewable and Sustainable Energy Reviews*, *160*, 112311. https://doi.org/https://doi.org/10.1016/j.rser.2022.112311

Sandin, G., Peters, G. M., & Svanström, M. (2015). Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts. *The International Journal of Life Cycle Assessment*, *20*(12), 1684-1700. https://doi.org/10.1007/s11367-015-0984-6

Su, S., Li, X., Zhu, Y., & Lin, B. (2017). Dynamic LCA framework for environmental impact assessment of buildings. *Energy and Buildings*, *149*, 310-320. https://doi.org/10.1016/j.enbuild.2017.05.042

Su, S., Wang, Q., Han, L., Hong, J., & Liu, Z. (2020). BIM-DLCA: An integrated dynamic environmental impact assessment model for buildings. *Building and Environment*, *183*, 107218. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.107218

Tabrizikahou, A., Kuczma, M., Nowotarski, P., Kwiatek, M., & Javanmardi, A. (2021). Sustainability of Civil Structures through the Application of Smart Materials: A Review. *Materials*, *14*(17).

thinkstep Ltd. (2018). *The carbon footprint of New Zealand's built environment: Hotspot or not?* https://www.thinkstep-anz.com/resrc/reports/the-carbon-footprint-of-new-zealands-built-environment/

Thonemann, N., Schulte, A., & Maga, D. (2020). How to conduct prospective life cycle assessment for emerging technologies? A systematic review and methodological guidance. *Sustainability*, *12*(3), 1192.

Tukker, A., Pollitt, H., & Henkemans, M. (2020). Consumption-based carbon accounting: sense and sensibility. *Climate Policy*, *20*(sup1), S1-S13. https://doi.org/10.1080/14693062.2020.1728208

United Nations Framework Convention on Climate Change, (1992). https://unfccc.int/sites/default/files/convention_text_with_annexes_english_for_posting.pdf

UNFCCC. (2015). The Paris Agreement. In.

UNFCCC. (2021). *What is the Kyoto Protocol?* unfccc.int/kyoto_protocol

United Nations Environment Programme. (2020). 2020 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector - Executive Summary.

van der Heijden, J. (2023). Construction 4.0 in a narrow and broad sense: A systematic and comprehensive literature review. *Building and Environment*, *244*, 110788. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110788

van der Heijden, J. (2024). Public governance in the context of Construction 4.0: a systematic and comprehensive literature review. *Smart and Sustainable Built Environment*, *ahead-of-print*(ahead-of-print). https://doi.org/10.1108/SASBE-06-2023-0150

Wang, K., & Guo, F. (2022). Towards Sustainable Development through the Perspective of Construction 4.0: Systematic Literature Review and Bibliometric Analysis. *Buildings*, *12*(10).

Wang, Y., Levis, J. W., & Barlaz, M. A. (2020). An Assessment of the Dynamic Global Warming Impact Associated with Long-Term Emissions from Landfills.

Environmental Science & Technology, *54*(3), 1304-1313. https://doi.org/10.1021/acs.est.9b04066

Wiedmann, T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics*, *69*(2), 211-222. https://doi.org/https://doi.org/10.1016/j.ecolecon.2009.08.026

Wiedmann, T., Wilting, H. C., Lenzen, M., Lutter, S., & Palm, V. (2011). Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. *Ecological Economics*, *70*(11), 1937-1945. https://doi.org/10.1016/j.ecolecon.2011.06.014

You, J., Xu, X., Wang, Y., Xiang, X., & Luo, Y. (2023). Life cycle carbon emission assessment of large-span steel structures: A case study. *Structures*, *52*, 842-853. https://doi.org/https://doi.org/10.1016/j.istruc.2023.04.001

Chapter 3

Design for Disassembly Strategies in Steel Eccentric Braced Frames: Climate Change Assessment Using Static and Dynamic Life Cycle Assessment Methods

Preface

Chapter 3 is based on a journal article developed as part of this doctoral research. This article is accepted for publication in the International Journal of Life Cycle Assessment. The version presented here is the published version. No substantive changes have been made to the content; however, minor adjustments have been undertaken to ensure consistency with the overall thesis.

Building on the gaps identified in Chapter 2 regarding the representation of temporal dynamics in building-related emissions, Chapter 3 provides a building-level assessment of the differences between conventional static and time-differentiated emission accounting. It addresses Objectives 1.1 and 1.3 and establishes the methodological basis for considering when emissions occur, rather than only their cumulative magnitude. The findings provide a foundation for the subsequent chapters by demonstrating the importance of temporal emission profiles and motivating the consideration of future changes in building systems, and decarbonisation pathways explored through the circular economy and prospective assessment in Chapters 4 and 5.

Article citation:
Weerasinghe, S. N., McLaren, S. J., Dowdell, D., Boulic, M., & Chandrakumar, C. (2026). Design for disassembly strategies in steel eccentric braced frames: climate change

assessment using static and dynamic life cycle assessment methods. *The International Journal of Life Cycle Assessment*, *31*(6), 99. https://doi.org/10.1007/s11367-026-02677-2

Abstract

Purpose: The "*avoid-shift-improve*" strategy framework was developed by the United Nations Environment Programme (UNEP) to foster material decarbonisation in the building and construction sector. This study applies the framework to use of Eccentric Braced Frames (EBF) in buildings structures, assessing how structural design and material choices affect whole-of-life climate change impacts. We identify the relevance of specific Life Cycle Assessment (LCA) methodological choices on the results, and the implications for supporting informed decision-making during the building design stage.

Methods: Five steel EBF structures were modelled which differ according to their source of raw materials (primary steel or reconditioned/reused steel), design for disassembly (DfD) features (bolted or welded), and end-of-life (EOL) management (recycling, reusing and/or landfilling). The climate change impacts were assessed based on two main scenarios: no seismic activity and one anticipated seismic activity during the 50 years reference service life (RSL). Additionally, sensitivity analyses were conducted to account for modelling assumptions and prospective technologies. The study was performed using both static and dynamic LCA methods to address the temporal dynamics associated with these EBF structures, focusing on the climate change impacts over 150 years from the construction year.

Results and discussion: Using static LCA, the results show that using reconditioned/reused steel for constructing EBF structures significantly reduces the climate change impacts compared with use of primary steel. The climate change impacts are higher in the seismic scenario compared to the no seismic activity scenario for all the structures, mainly due to the additional demolition and reconstruction activities. As expected, the reuse strategies have lower climate change impacts than recycling and landfilling at the EOL stage (although the ranking may change depending upon the chosen allocation method). The dynamic LCA (dLCA) results additionally show the contribution to radiative forcing over time associated

with greenhouse gas (GHG) emissions (measured in Wm^{-2}), and how prospective technological advances in steel manufacturing and recycling can influence the climate change impacts over time.

Conclusions: The study highlights the importance of: (i) reusing now rather than in the future to "*avoid"* the climate change impacts associated with primary steel manufacture, and to "*improve"* CE practices in the building and construction sector to align with the "*avoid-shift-improve*" framework; and (ii) use of static LCA complemented by dynamic LCA for robust climate change assessment in order to provide deeper insights into the longer-term influence of design-stage decisions when assessing products with extended lifespans (such as buildings).

3.1 Introduction

Greenhouse gas (GHG) emissions in the building sector are related to two main sources: operational GHG emissions (including energy and water use) and embodied GHG emissions (including manufacture of materials and products, their transport, installation/construction, use and end-of-life in a building). Numerous initiatives have been implemented to mitigate these emissions, and historically there has been a greater focus on strategies to reduce operational GHG emissions as opposed to embodied carbon emissions. However, as operational carbon emissions are projected to decline from 75% to 50% of the sector's total emissions in the upcoming decades (United Nations Environment Programme, 2023), attention has now shifted towards embodied carbon emissions. A recent report by United Nations Environment Programme (2023) outlined three core principles for fostering material decarbonisation in the building and construction industry. These principles are defined based on an avoid-shift-improve approach:

1. **Avoid**: avoidance of raw material extraction by promoting a circular economy (CE).
2. **Shift**: uptake of regenerative material practices that incorporate choice of responsibly-produced low carbon building materials.

3. **Improve**: improvement of conventional building materials and processes to significantly reduce their carbon footprints.

For example, the use of steel in the building sector has tripled over the past 65 years (United Nations Environment Programme, 2023). Currently, steel is the second most abundant material employed in buildings (after concrete), and the iron and steel industry's embodied emissions represent 7.2% of global GHG emissions (United Nations Environment Programme, 2023). It is also a material with potential for "closing the loop" on material recycling (Durmisevic & Noort, 2003; European Commission, 2002). Steel has always been inherently recyclable due to its high scrap value and the ease of recovery due to its magnetic properties. As the most recycled material globally, approximately 680 million tonnes of steel were recycled in 2021, preventing over one billion tonnes of CO_2 emissions from primary steel production (World Steel Association, 2024). Therefore, implementation of the three UNEP principles for steel used in the building sector is an important topic.

Regarding the first UNEP principle, Geissdoerfer et al. (2017, p. 759) define the CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling". The CE approach represents a modification of the linear economy model in which materials flow through in one direction from resource extraction to final waste management. Instead, in the CE end-of-life (EOL), material processing is focused on retaining materials in use for as long as possible (MacArthur, 2013; McLaren, 2021). The concept of the CE and its application in the building sector has been explored by many researchers over the past two decades, focusing on different areas, e.g. energy (Gallagher et al., 2017; Ishaq et al., 2022; Tomić & Schneider, 2018), building and construction (Eberhardt et al., 2022; Norouzi et al., 2021; Pomponi & Moncaster, 2017), and waste management (Diemer et al., 2022; Oluleye et al., 2022; Schützenhofer et al., 2022; Spišáková et al., 2022).

For steel structures, the climate change mitigation benefits of employing the CE approach have been investigated using steel recyclability scenarios for building materials (e.g.,Akanbi et al., 2018; Antwi-Afari et al., 2023), different CE practices for construction products

(e.g.,Lima et al., 2024), and in steel structures of prefabricated buildings (e.g.,Minunno et al., 2018). Many studies have emphasised the benefits associated with utilising steel in building materials and structures - particularly due to its compatibility with CE strategies and its comparatively lower climate impact when contrasted with materials like concrete and brick (Akanbi et al., 2019; Akanbi et al., 2018; Antwi-Afari et al., 2023; Broadbent, 2016). These findings emphasise the positive role of steel in advancing building construction practices and reducing the overall climate change impact of the building sector.

Two primary strategies in CE-based product design are “design to slow the loops” and “design to close the loops” (Bocken et al., 2016). Design to slow the loops is a strategy to create long-life products and extend the product utilisation stage. Design to close the loops aim at cradle-to-cradle design, thereby avoiding waste generation (McDonough & Braungart, 2010). As the concept of the CE has evolved, a variety of more detailed Design for X (DfX) strategies have emerged in academia and industry (Sassanelli et al., 2020) which support both slow- and closed-loop design strategies (Bocken et al., 2016). One of these strategies is Design for Disassembly (DfD) which focuses on EOL options such as recycling and reuse (Vanegas et al., 2018).

DfD is a proactive approach implemented during the design and planning phases (Boothroyd & Alting, 1992; Guy et al., 2006) to facilitate the eventual deconstruction of a product and its reuse in a subsequent product system, typically involving the use of demountable connections in buildings (Selvaraj & Chan, 2024). It has gained significant attention in the building sector (Crowther, 2005; Lausselet et al., 2023; Norouzi et al., 2021; Rios et al., 2015), not least because it offers potential economic as well as environmental benefits (Broughton, 2023; Crowther, 2005; Eberhardt et al., 2019b; Mestre & Cooper, 2017). Its relevance has been recognised through award of credits for DfD structural systems in green building rating programmes (New Zealand Green Building Council, 2023; UK Green Building Council, 2024; Webster & Costello, 2006). However, the quantification of the climate change benefits of using DfD in the building sector is case-specific and often complicated (Eberhardt et al., 2019c; Lausselet et al., 2023) because buildings are characterised by their lengthy life cycles, which often extend for time scales ranging from 50

to 90 years (Ouellet-Plamondon et al., 2022) or even longer. Such long-lived structures undergo a variety of changes over time in response to diverse influencing factors including shifts in social, technological, economic, political (Goldstein & Rasmussen, 2018). Addressing these temporal dynamics is arguably critical to the assessment, and may involve consideration of external risks, technological advances in materials and technologies used in repair/replacement/refurbishment, and changes in EOL technology (Collinge et al., 2011; Negishi et al., 2018; Su et al., 2017). Furthermore, for buildings located in areas subject to natural disasters such as earthquakes, the consequences of such disasters are an important consideration in DfD because of the ease of disassembly of structures and replaceability of connections for necessary repairs and reconstructions (Pongiglione et al., 2017; Xiao et al., 2021).

In the context of CE design concepts such as DfD, omitting consideration of temporal dynamics during the design stage of buildings may lead to provision of misinformation on future climate change impacts related to design strategies. Consequently, addressing temporal dynamics of products with long lifespans, such as buildings, is essential for providing more relevant information on future climate change impacts. Particularly, the long-term climate impact of a building is significantly affected by its service life due to temporal dynamics and potential alternative EOL scenarios based on CE (Hawkins et al., 2021). For example, Eberhardt et al. (2019a) found that the ranking of two alternative building designs based on their climate change impacts could change depending on whether technological advances that are likely to occur during the building's service life are considered or not. They demonstrated that the uncertainty associated with technological advancements may have a more significant impact on climate change than changes in the future energy grid mix. Use of a time-differentiated approach enables designers to better understand and anticipate the long-term consequences of material choices, energy strategies, and construction practices (Hawkins et al., 2021).

Given the importance of adopting CE practices for building structures, and of addressing temporal dynamics when considering climate change mitigation, this research assesses the climate change impacts associated with a steel EBF structure in an 8-storey building located

in Auckland, Aotearoa New Zealand (ANZ). Climate change impacts are assessed considering different connection mechanisms (welding and bolting) for DfD strategies, using different steel resources (primary and reconditioned steel), and using different EOL mechanisms (recycling, landfilling and reconditioning). We use both static and dynamic Life Cycle Assessment (LCA) methods to develop a better understanding of the role of temporal dynamics in the case study. Furthermore, as ANZ is prone to seismic activity due to its geographical location along the boundary of the Pacific and Australian tectonic plates (Davenport, 2003), the study assesses the relevance of seismic activity on the climate change impacts of EBF structures as part of the analysis. The core novelty of this study is the comparative assessment of the appropriateness of both static and dynamic LCA approaches to evaluate how temporal dynamics influence building-related GHG emissions and associated climate change impacts, including the effects of seismic events, prospective technological developments, and CE strategies.

3.2 Methods

3.2.1 Overview of the Case Study

Five types of steel EBF structures for use in an 8-storey building were selected based on Andisheh et al. (2024) and Hasanali et al. (2024); these types are all designed to enhance their resilience to earthquakes. The EBF structure for all types comprises three main components: the frame (including columns, collector beams, and braces), connection plates, and shear link. The shear link functions as an energy absorber during seismic events, dissipating energy and safeguarding the structural integrity of the remainder of the structure. Connector plates are a standard way to join columns, beams, braces and shear link, and ensure proper alignment of the structure. Figure 3.1 shows the 8-storey EBF structure (right); one storey is expanded at left to show a cross section of the EBF structure with its main components.

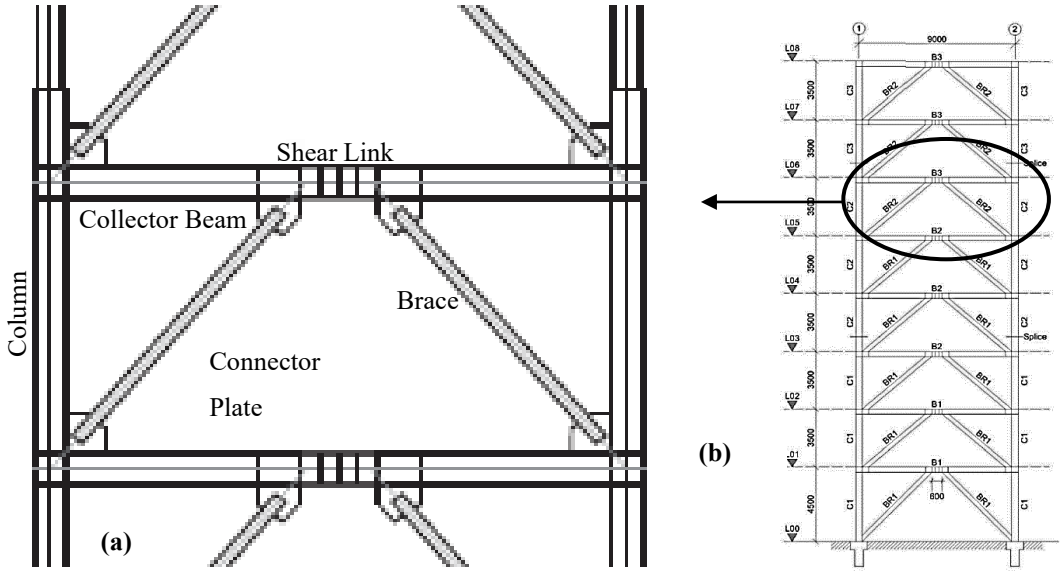


Figure 3.1 Cross section of the steel EBF (a) and 8-storey steel EBF (b) [adapted from (Andisheh et al., 2024)]

The selected five structures have a 50-year reference service life (RSL) but have different characteristics based on the (i) type of the steel used to construct the EBF structure, (ii) connections between the main components, and (iii) the EOL mechanism. Two types of steel sources are assumed in the study: primary steel with 17.4% recycled content (referred to hereafter as primary steel) and reconditioned steel or reused steel components (referred to hereafter as reconditioned steel) from demolished structures. The connections of the whole structure are welded, bolted or just the shear link is bolted while the rest of the connections are welded, reflecting different DfD features. The EOL of the structures may vary depending on the DfD features. Each component of the structure is either recycled or reconditioned at EOL; if it is recycled, it is assumed that 85% of the component is sent to recycling and 15% is landfilled (HERA, 2021). It is important to note that the assumed 85% recycling rate for structural steel may be conservative, as potentially approaching full recovery is possible with appropriate systems in place. At EOL, if it is reconditioned, it is assumed that 100% of the steel sections are reconditioned.

The study uses two scenarios to account the climate change impacts of the selected EBF structures: scenario 1 represents no seismic activity during the RSL, and scenario 2 represents

seismic activity which is assumed to occur at the midpoint of the RSL (year 25). It is assumed that only the shear link of the structure is damaged following a seismic activity.

Structure 1 is constructed using primary steel and features an entirely welded EBF design through its connection/connector plates, and is unsuitable for disassembly of the main components due to the welded connections. The whole frame is recycled at EOL in scenario 1. However, in scenario 2, the shear link including its connection plates are replaced with a new shear link containing bolted connections after the seismic activity. The new shear link and its connection plates are reused at EOL. The old shear link and connectors are recycled after the seismic activity, and the rest of the structure is recycled at EOL.

Structure 2 is also constructed using primary steel but features welded beams, columns and braces while the shear link is bolted to the structure, hence it can be replaced at EOL. The rest of the frame must be recycled at EOL in scenario 1 while the shear link is sent to reconditioning at EOL. In scenario 2, the shear link is replaced with a new shear link after the seismic activity. The new shear link is reconditioned at EOL. The old shear link is recycled after the earthquake, and the rest of the structure is recycled at EOL.

Structure 3 is constructed using primary steel and features an entirely bolted EBF design through its connector plates. The whole frame is reconditioned at EOL in scenario 1. In scenario 2, the shear link is replaced with a new shear link after the seismic activity, and the old shear link is recycled after the seismic activity. The new shear link and the rest of the structure is reconditioned at EOL.

Structures 4 and 5 have the same design features in terms of connection strategy of the main components and EOL mechanism as Structures 1 and 3 respectively. But the type of the steel used to construct Structures 4 and 5 is reconditioned steel. Therefore, Structure 4 has the same functions and goes through the same changes after the construction stage as Structure 1 in both scenario 1 and 2, while Structure 5 has the same functions and goes through the same changes after the construction stage as Structure 3 in both scenarios. The flow diagrams for each structure in the two scenarios can be found in the Appendix A.

3.2.2 Accounting for Time in LCA when Assessing Climate Change Impacts

The conventional LCA approach, termed static LCA (sLCA), provides a snapshot of environmental impacts but does not represent the fact that both human activities and their related environmental impacts may occur at different times (Rosenbaum et al., 2018). This is particularly an issue for long-lived products such as buildings where the service(s) provided by buildings, the building repair/refurbishment/replacement activities, and associated secondary supply chain activities may occur over several decades (Goldstein & Rasmussen, 2018; Ouellet-Plamondon et al., 2022).

The **service(s) provided** by a building may change due to a change in occupancy and/or change in the building function, such as transition from residential to commercial use. These changes may affect energy and water consumption because an increase in occupants typically leads to higher demand for energy and water for daily activities. Also, a change in the function of the building may lead to changes in operational demands and occupancy levels associated with the new use of the building (Collinge et al., 2013; Negishi et al., 2018; Su et al., 2017).

Building repair/refurbishment/replacement activities may change over time due to changes in material and component manufacturing technologies. For example, future refurbishment and replacement activities are more likely to use thermal resistant insulated materials (Negishi et al., 2018) and low carbon cement (Fouquet et al., 2015).

The secondary supply chain activities that may change over time include changes in the electricity grid mix due to implementation of new technologies or shifts towards renewable energy sources (Collinge et al., 2011; Collinge et al., 2018; Negishi et al., 2018; Su et al., 2017). Also, waste management techniques are likely to change with the introduction of improved low carbon recycling methods, waste to energy plants (Eboh et al., 2019), and changes in regional waste management practices (Collinge et al., 2013). These changes

should all be considered when assessing the environmental impacts of buildings using a whole-of-life modelling approach.

In addition, temporally differentiated environmental assessment is arguably relevant. In particular, for climate change the timing of emissions is significant because the contribution of GHGs to climate change depends on the time they are released and how long these GHGs stay in the atmosphere. The dynamic LCA (dLCA) method can be used to account for the temporal dynamics of environmental impacts throughout the life cycle of a product system. dLCA extends conventional static LCA by explicitly accounting for the timing of GHG emissions over the life cycle. This allows the climate change impacts of emissions occurring at different points in time to be evaluated, which is particularly relevant for long-lived product systems such as buildings where emissions and material replacements occur across several decades. Compared to sLCA, dLCA does not assume static conditions over the assessment period and accounts for changes in environmental impacts over time. Different approaches to employ dLCA in assessing environmental impacts have developed over time (Collinge et al., 2013; Levasseur et al., 2010; Tiruta-Barna et al., 2016). For this study, we use the approach developed by Levasseur et al. (2010) and present the climate change impact using the radiative forcing (RF) concept. The results are presented in two metrics: instantaneous RF (IRF), which represents the RF over a one-year period, and cumulative RF (CRF), which is the total of the annual IRFs for the entire duration considered. The climate change impact is calculated using time dependent dynamic characterisation factors (DCFs) for emissions of CO_2, CH_4 and N_2O at 1-year time intervals. These DCFs represent the RF per unit mass of a GHG released into the atmosphere from the year of the initial emission. Then the time dependent climate change impact is derived by combining a dynamic inventory with annual DCFs.

Both the sLCA and dLCA use the same inventory data (see Section 3.2.3.2). For this study, the climate change impact is assessed over 150 years i.e. the 50-year RSL of the structure and an additional 100 years after the last economic activity associated with the building under study (i.e. the EOL stage) to align with the 100-year time-horizon commonly used for the Global Warming Potential (GWP) metric.

3.2.3 Life Cycle Assessment

The climate change impacts of the structures were assessed using LCA methodology and guided by the building-specific LCA standards. In particular, EN 15978 (CEN, 2012) informed the calculations and EN 15804: 2012+A2 (CEN, 2019) informed the categorisation into building life cycle stages. The assessment focuses exclusively on the climate change impact category, in order to evaluate the temporal implications of GHG emissions using static and dynamic LCA approaches. Other environmental impact categories are outside the scope of this study.

3.2.3.1 Goal and Scope

The functional unit for the study is an EBF structure with the provision of equivalent lateral load-resisting capacity for a 75 m^2 floor area of an 8-storey steel building over a 50-year RSL, designed in accordance with NZS 3404 and HERA P4001 seismic performance requirements. All EBF structures are designed to satisfy identical loading conditions, seismic hazard assumptions, and performance criteria in accordance with NZS 3404 and HERA P4001 (Andisheh et al., 2024; Hasanali et al., 2024). The differences in cyclic force displacement analyses of the structures are not statistically significant, and all systems meet required seismic performance levels for moderate to severe earthquakes. Although minor variations in cyclic performance can be expected but, these do not alter the intended structural function or compliance with seismic design requirements (Hasanali et al., 2024). Also, the energy dissipation capacity confirmed compliance across all alternatives. Therefore, differences among EBF structures arise from connection detailing and material sourcing rather than variations in structural capacity or seismic resilience.

The start date of the building's use stage is considered year 1, with all construction activities considered as occurring in year 0. The reference flow is 24.71+(6-18%) tonnes of EBF, with the variable additional amount due to the different connection types used in the five structures (see Appendix A).

The life cycle of the EBF structure comprises cradle-to-grave activities including product stage (module A1-A3), construction stage (module A4-A5), and EOL activities (module C1-C4) (CEN, 2019). The use stage (modules B1 to B7) is omitted as it is outside the scope of the study. The module D potential benefits or loads associated with EOL strategies are separately accounted in the background system (ISO, 2017). For Structures 1, 2 and 3, a module D benefit is allocated to the first life cycle of the steel sections as they are manufactured using primary steel. For Structures 4 and 5, reconditioned steel represents the subsequent life cycle of steel sections that were previously used in another steel structure. This new life cycle begins when the steel is reconditioned or recycled, and ready to use in construction. It includes the steel section reconditioning (module A3). Deconstruction of the previous structure and transport activities to the reconditioning facility are allocated to the previous life cycle to avoid double counting of emissions. Therefore, module D of Structures 4 and 5 is modelled considering only the transport activities associated with reconditioning or recycling facility to the new construction site.

Figure 3.2 shows the base models used for the flow diagrams of the structures in both scenarios 1 and 2. The foreground system (FS) includes activities from the cradle-to-grave, and the background system (BS) includes all the activities beyond the system boundary. The box in the middle of the FS represents the common flow of each structure. The outward flow from that box represents the scrap steel flow that is going to either recycling or reconditioning facilities. In Figure 3.2a (Structures 1, 2 and 3), the middle box (pink colour) includes the cradle-to-grave activities from the extraction of raw materials through to disposal and/or steel scrap which is ready for reconditioning or recycling. In Figure 3.2b (Structures 4 and 5), the middle box (green colour) extends from reconditioning of steel sections at the reconditioning facility through to disposal and/or steel scrap which is ready for reconditioning or recycling.

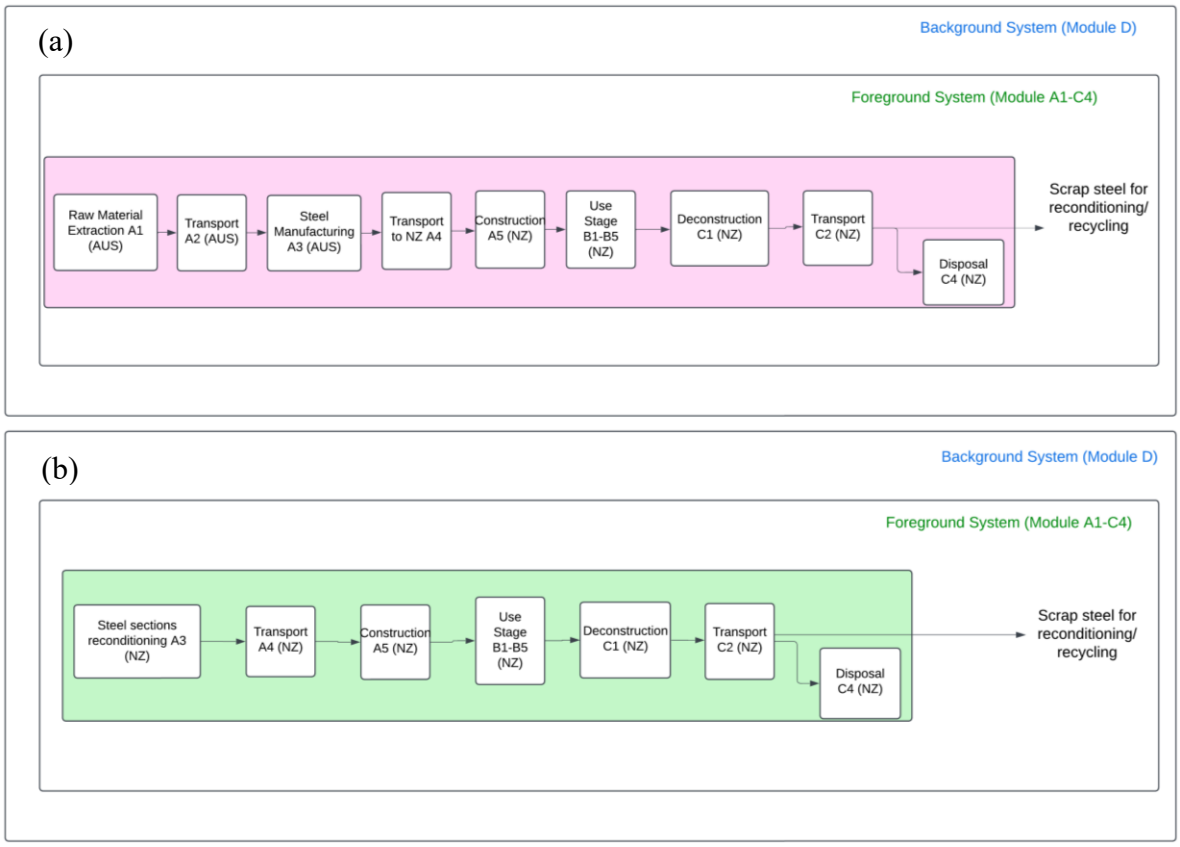


Figure 3.2 (a) Base models used for the flow diagrams of Structures 1, 2 and 3, and (b) Structures 4 and 5 in both scenarios

3.2.3.2 Life Cycle Inventory

The study was conducted using ecoinvent 3.2 data (ecoinvent, 2023), ANZ government data (Ministry for the Environment, 2022a), and Environmental Product Declaration (EPD) data from steel manufacturers in Australia for the components of the EBF structures (see Table 3.1). Due to the unavailability of up-to-date EPDs for steel in ANZ at the time of the study, steel was modelled as being sourced from Australian manufacturers (from New South Wales (NSW), Australia) and then transported to ANZ for Structures 1,2 and 3. Generally, ANZ's steel production is relatively small compared with the local market requirements, and the remaining demand is met through imports (Robertson & Hurren, 2021); Australia is one of the primary sources of ANZ's steel imports (Stats NZ, 2024b).

EPD values from BlueScope Steel Limited (2020a) were used for beams, columns, braces and shear link, and EPD values from BlueScope Steel Limited (2020b) were used for connections in the FS of Structures 1, 2 and 3 in both scenarios. For Structures 4 and 5, EPD values from EMR Group (2022) were used for all components in the FS since the construction of the frame involves reconditioned steel. For the BS, the EPD data sources included InfraBuild Australia Pty Ltd (2024) for manufacturing reinforcing steel rod using electric arc furnace (EAF) from steel scrap; EMR Group (2022) for manufacturing reconditioned steel sections from steel sections, to account for blast furnace (BF); BlueScope Steel Limited (2020a) for manufacturing welded beams and columns; and InfraBuild Australia Pty Ltd (2024) for manufacturing reinforcing steel rods.

Table 3.1 Data and sources used to model the life cycle stages

Life cycle stage	Modelling data	Sources for emission factors	Relevant structures
Product stage (A1-A3)	Emission factors for A1, A2 and A3 from EPDs	For welded beams and columns: BlueScope Steel Limited (2020a)	1, 2, 3
		For steel connector plate:	
	Emission factor for A3 from EPD	EMR Group (2022)	4, 5
Transport to construction site (A4)	2,192 nautical miles from Whyalla, NSW to Auckland harbour via a bulk carrier ship and road freight (to the construction site 50 km from harbour via truck)	Ministry for the Environment (2022a)	1, 2, 3
	Reconditioned steel: Road freight of 50 km from reconditioned steel manufacturing facility to construction site	Ministry for the Environment (2022a)	4, 5
Construction (A5)	(A4-A5) is taken as 4.3% of (A1-A3) modules and then deduct A4 to get A5	Wu et al. (2022)	All
Use (B1, B6,	Omitted as it is outside the scope of the study	-	All
Use: maintenance/repair/ replacement/refurbishment (B2-B5)	EBF structure is designed to serve without any failures during its 50 years of service life	-	All
Deconstruction (C1)	Emission factors from EPDs	BlueScope Steel Limited (2020a)	1, 2, 3
		EMR Group (2022)	4, 5

Transport (C2)	Road transportation of 50 km from construction site to scrap steel collection point/disposal site	Ministry for the Environment (2022a)	All
Waste processing (C3)	Omitted as waste processing is minimal and waste is sent either to disposal or to scrap steel collection directly from the deconstruction site	-	All
Disposal (C4)	EPD values	BlueScope Steel Limited (2020a)	1, 2 and 3
		EMR Group (2022)	4 and 5
Benefits and loads (D)	EPD values for EAF steel reinforcing bar production	InfraBuild Australia Pty Ltd	For recycling
	EPD values for BF steel reinforcing bar production	InfraBuild Australia Pty Ltd	For recycling
	EPD values for BF steel welded beams and columns	BlueScope Steel Limited	For
	EPD Values for reconditioned steel section production	EMR Group (2022)	For
	2,192 nautical miles from Auckland harbour to Whyalla, NSW via a bulk carrier ship	Ministry for the Environment (2022a)	For recycling

For module A5, several activities take place during construction, including site preparation, transportation of equipment and materials, scaffolding works, onsite welding, prestressing, steel installation work, onsite energy consumption and construction waste processing. Also, there are embodied emissions in construction equipment and transportation. However, these activities are required for other components as well as the steel structure (e.g. walls, roof and floors). Data for module A5 were therefore calculated as a percentage of the values for the A1-A3 modules, based on two studies. Wu et al. (2022) derived climate change impact results for the steel framing of a building in ANZ. The climate change impact of modules A4-A5 was found to be 4.3% of A1-A3 and 2.8% of whole life cycle for a steel structure of a building (Wu et al., 2022). These figures are relatively close to the findings of a study by Huang et al. (2024) which synthesised literature from 100 studies. We modelled modules A4-A5 based on climate change impacts from Wu et al. (2022) because that study was undertaken on a building in ANZ and also those results fall within the range identified in Huang et al. (2024)'s results from the literature synthesis. Therefore, the A4-A5 module results are assumed to constitute 4.3% of A1-A3 module results in this study.

For module D benefits, the cut-off method according to EN 15804 was followed and the benefits associated with the recycled steel are quantified as avoided burdens at the end-of-waste state and reported separately. For recycling of recovered steel sections, we assumed that the steel scrap is sent to Australia to recycle using EAF to produce steel reinforcing bars (InfraBuild Australia Pty Ltd, 2024). The BS for recycling includes the transport of steel scrap to Australia, EAF steel reinforcing bar production and avoided BF steel reinforcing bar production to account for the module D benefits. For reusing steel sections, we assumed that the steel sections are sent to a steel reconditioning facility in ANZ. For Structure 4, the background system includes additional BF steel production to account for the steel landfilled during the current life cycle.

3.2.3.3 Prospective Technology Analysis

To assess the significance of incorporating prospective dynamics in life cycle modelling, this study modelled potential future changes in the EBF structure's life cycle using a prospective LCA approach. A prospective LCA approach can be used to evaluate the potential climate change impacts of emerging technologies (Arvidsson et al., 2018) that

are anticipated to be adopted during the service life of the EBF frame. A prospective technology assessment was conducted to evaluate the impact of two technology improvements (TA1 and TA2) on GHG emissions during the RSL. These were selected to illustrate how specific advancements can alter emission trajectories over time. Other potential future changes, such as improvements in the electricity mix, EAF improvements and manufacturing efficiency were excluded to maintain analytical focus and reduce model complexity, as the objective was to demonstrate indicative rather than extensive technological changes. Technology analysis 1 (TA1) examined the effect of anticipated technological improvements and modifications in current BF based steel making, assuming a 50% emission reduction by 2050 based on Holappa (2020). To model this scenario, a 50% decrease in steel manufacturing emissions in Australia was applied to data for modules A3 and D for the processes that occur from 2050 onwards. Technology analysis 2 (TA2) assessed the impact of future steel recovery technologies on improving the steel recycling rate, assuming a 95% recycling rate with the remaining 5% sent to landfill in 2050; this was applied to data for modules C3, C4, and D.

3.2.3.4 Sensitivity Analyses

To assess the robustness of the climate change impact results with respect to key modelling assumptions related to the scale of the seismic event, reuse rates at the EOL and allocation approach, sensitivity analyses were conducted. In scenario 2, the seismic event was modelled as a moderate to severe earthquake where only the shear link elements require replacement, based on the designed seismic performance of EBF. To assess the influence of more extreme resilience events, a sensitivity analysis (SA1) was considered in which a catastrophic seismic event results in structural damage that prevents component reuse at the EOL, with the whole structure therefore assumed to be recycled right after the seismic activity and a new structure reconstructed. In addition, the assumption of 100% reconditioning of structural steel components was tested by applying further sensitivity analyses with reduced reuse rates of 80% (SA2) and 60% (SA3), to represent potential material degradation, market constraints, or quality limitations that affect reuse feasibility. In SA2 and SA3, the remaining steel was assumed to be conventionally recycled. To assess the sensitivity of the results to allocation assumptions, an additional allocation scenario was considered (SA4). In addition to the EN 15804 cut-off approach adopted in the main analysis, a 50/50 allocation approach (Allacker et

al., 2017) was applied. For 50/50 allocation, the structures were modelled by assuming two service lives, reflecting the practical limitation of reuse cycles in structural applications, where safety and design considerations may restrict repeated reuse.

A schematic overview of the study design is provided in Figure 3.3, showing the scenarios, LCA methodologies, prospective technology assessments and the sensitivity analyses undertaken in the study.

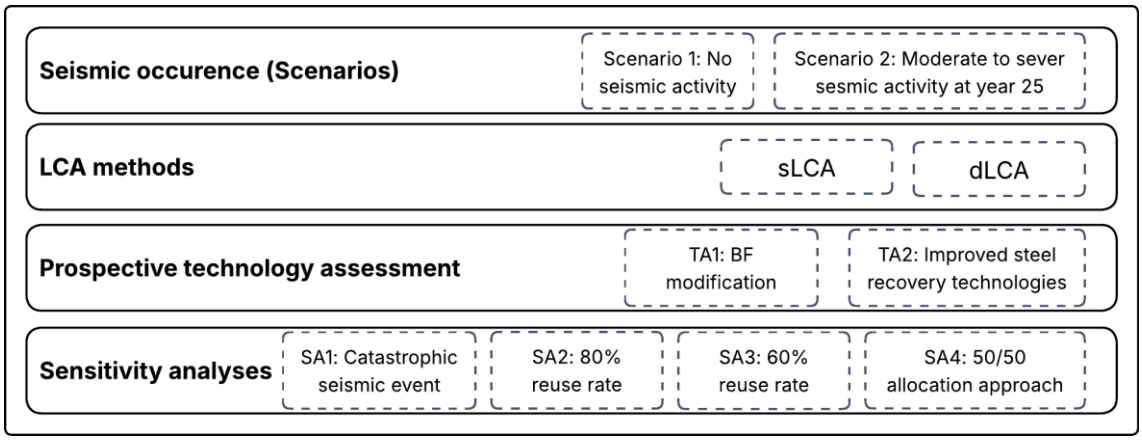


Figure 3.3 Schematic overview of the methodological framework adopted in this study

3.3 Results

3.3.1 sLCA Results

Figures 3.4 and 3.5 show the climate change impacts of the five structures and two scenarios excluding and including module D, using the sLCA approach. Excluding module D, Structures 1, 2 and 3 have higher climate change impacts compared to Structures 4 and 5 for both scenarios (Figure 3.4). This is because Structures 4 and 5 are constructed using reconditioned steel, and the reconditioning process has a much lower impact than primary steel manufacturing. In Figure 3.4, for scenario 1, Structure 2 has the highest net climate change impacts but for scenario 2, Structure 1 has the highest net climate change impacts. In both scenarios, Structure 5 has the lowest climate change impacts compared to the other structures due to the use of reused steel components in its construction and its reusability at the EOL.

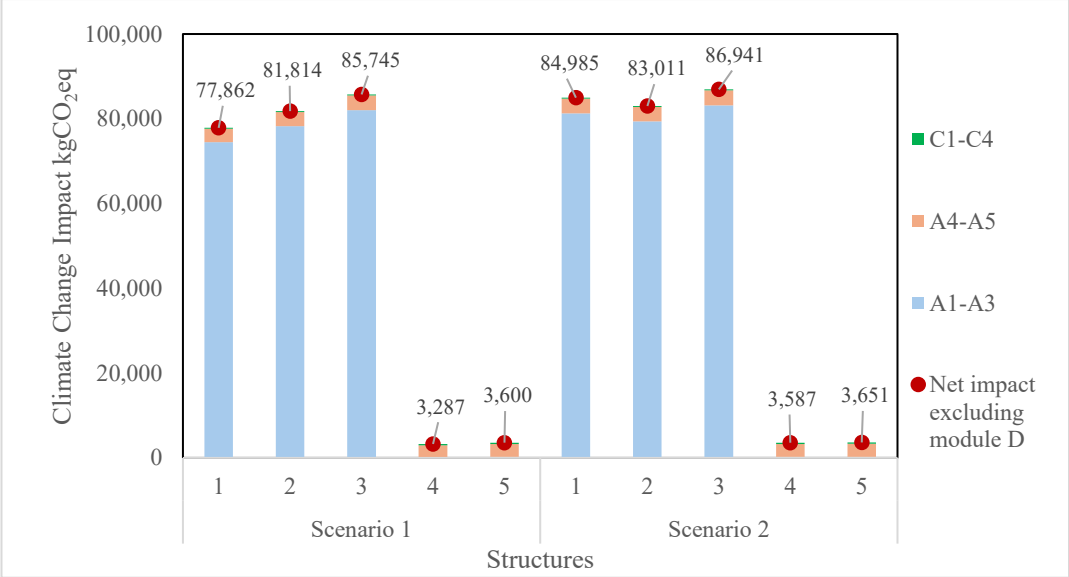


Figure 3.4 Climate change impacts of each structure in scenario 1 and scenario 2 without Module D

Including module D, Structures 1 and 2 have higher climate change impacts compared to Structures 3, 4 and 5 for both scenarios (Figure 3.5). Structure 3 has a lower climate change impact due to reconditioning of steel at EOL which is associated with a credit from displacing primary steel manufacturing; for Structures 4 and 5, the lower impacts are due to initial use of reconditioned steel. The impacts for scenario 2 are higher than scenario 1 for each of the five structures due the additional deconstruction and reconstruction after the earthquake.

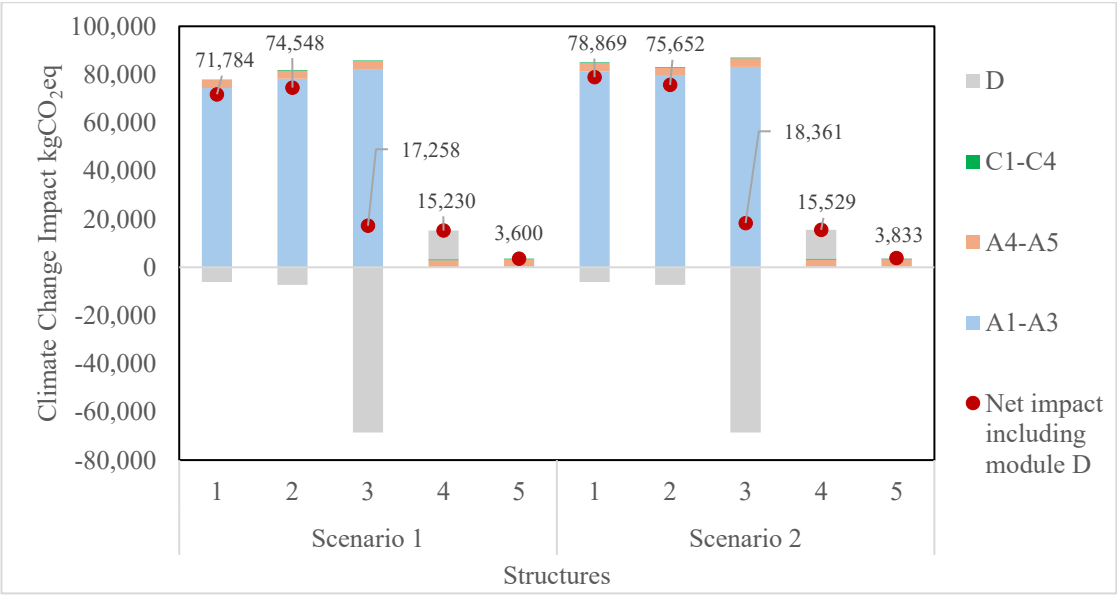


Figure 3.5 Climate change impacts of each structure in scenario 1 and scenario 2 including module D

3.3.2 dLCA Results

The climate change impact results utilising dLCA for scenario 1 are shown in Figure 3.6. It shows the results using IRF (Figure 3.6(a) and 3.6(b)) and CRF (Figure 3.6(c) and 3.6(d)), and also presents the results including module D (Figure (b) and (d)) and with separate module D results (Figure (a) and (c)). To improve the clarity, Table 3.2 presents the conceptual differences between sLCA and dLCA module D representation. In Figure 3.6(a), the immediate increase in IRF during year 0 is due to the manufacture, transport and construction of the structures. From year 0 to 50, the gradual decline in the IRF is due to the declining RF contribution of GHGs over this time. The slight increase in IRF at year 50 is due to the EOL activities, and the gradual decrease happens afterwards due to the declining RF of the GHGs. Structures 4 and 5 have the lowest results throughout the 150 years for both the instantaneous and cumulative RF results compared to Structures 1, 2 and 3. All the RF curves reach a near-steady state after year 100 reflecting the long atmospheric lifetime of the remaining CO_2.

Table 3.2 Conceptual explanation of module D under static and dynamic LCA approaches

Criteria	sLCA	dLCA
Representation	Avoided impact at the end of waste stage as static credit	Avoided impacts at the end of waste stage modelled according to the timing of emissions
Interpretation	Benefits are fixed values	Benefits vary depending on when avoided impacts are realised
Effect of delayed recycle/reuse benefit	The timing of delays does not influence the result	Delayed benefits contribute less to near-term RF reduction
Influence on ranking	Ranking of alternatives is not affected by changes in timing of module D activities	Ranking of alternatives at any point in time may change depending on the timing and related annual RF magnitude of the emissions

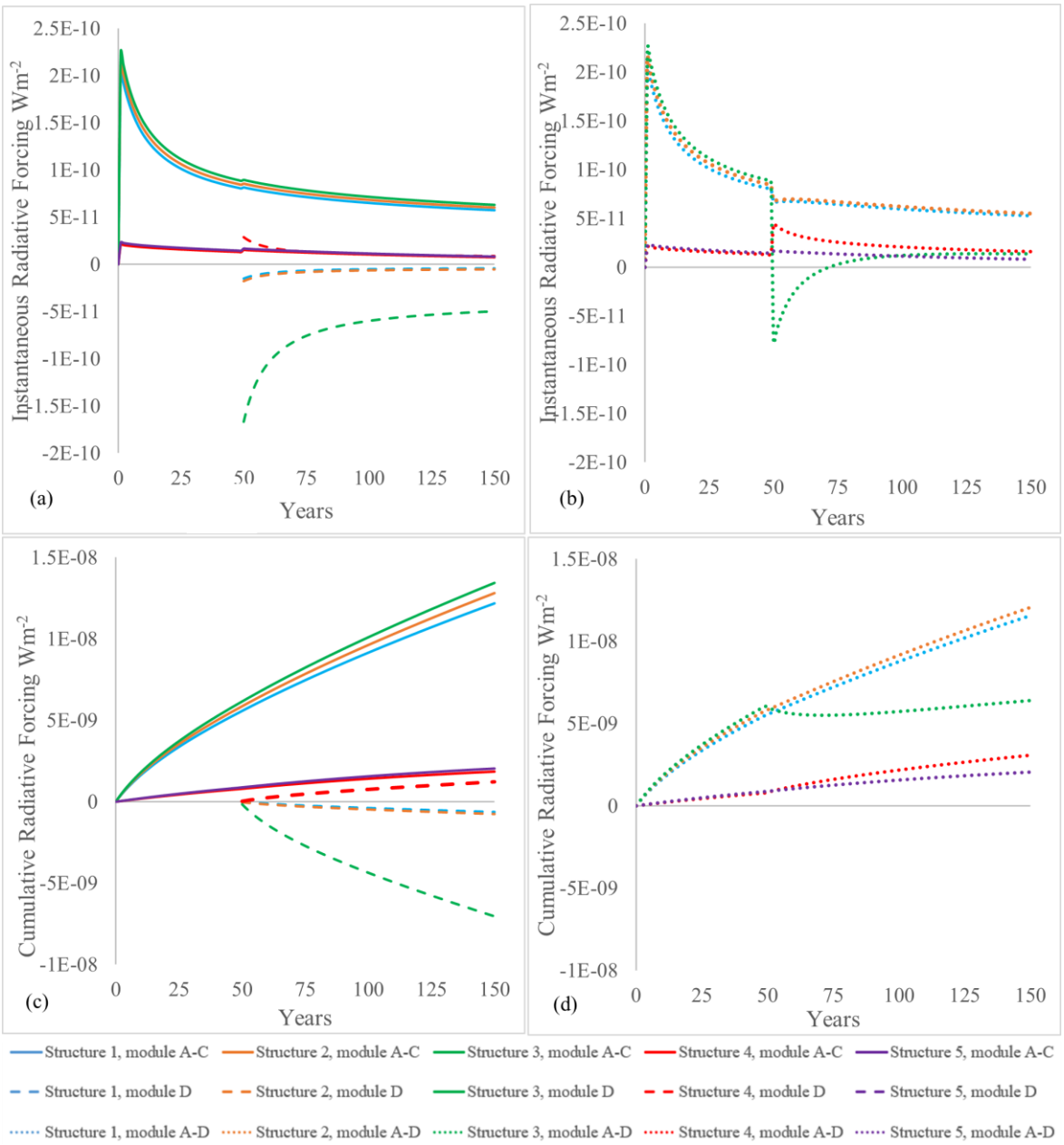


Figure 3.6 Dynamic LCA results of EBF structure in scenario 1: Figure (a) and (c) show separate results with disaggregated module D. Figure (b) and (d) show the net results including module D

Structure 3 has the highest module D credits compared to other structures due to its reusability. Module D credits for Structures 1 and 2 are similar as they both involve recycling at EOL. Structure 4 shows a module D burden due to the additional BF production to account for the landfilled steel. Structure 5 does not show a module D burden or a credit as it is reused at the EOL and reconditioning for its second life cycle is outside the system boundary (see Section 3.4.2). For the CRF results, the rankings of the

structures are similar to the rankings of the structures based on the IRF results although there are differences in the relative magnitudes of the structures at different times (Figure 3.6(c) and (d)).

In scenario 1, comparing the dLCA IRF and CRF results with the sLCA results, excluding module D, Structure 3 has slightly higher impacts for both the sLCA and dLCA results. Including module D, the sLCA results show that Structure 3 has a lower net climate change impact compared to Structures 1 and 2 due to its large module D credit. However, the dLCA results including module D show that Structure 3 is marginally worse than Structures 1 and 2 up to year 50, and then with the module D credit it ranks better than Structures 1 and 2 after year 50. In reality, the module D credit for Structure 3 only begins at year 50 but this can only be seen in the dLCA results. Structures 4 and 5 are the best options using both sLCA and dLCA (based on the CRF results).

In scenario 2, the dLCA results (Figure A1. 13, Appendix A1) increase at year 25 due to post-earthquake reconstruction. Structure 1 exhibits the highest radiative forcing increase due to replacement of the shear link and connectors, whereas Structure 4 shows significantly lower impacts due to use of reconditioned steel. Structures 2 and 3 have smaller increases, reflecting shear link replacement. Overall, both the static and dynamic assessments confirm that Structures 4 and 5 have the lowest climate impacts.

3.3.3 Prospective Dynamic LCA results

Figure 3.7 shows the sensitivity of the dLCA CRF results to implementation of prospective technologies (TA1 and TA2) versus the current technology for scenario 1. The results for each of the structures are fairly similar for each prospective technology implementation (i.e. overlapped CRF lines) up to year 50 because modules A-C remain unchanged due to the technology improvements occurring after the EOL of the structures. **For TA1 (technology improvement for BF reduces emissions by 50%) after year 50**, module D of Structures 1 and 2 show positive CRF impacts whilst Structure 3 shows negative CRF impacts. These differences arise because the original module D credit associated with BF steel is reduced by half, while the EAF credit remains unchanged, as no technological or emission changes related to EAF operations were considered in the technology analysis. Structure 4 has a 50% decrease in module D in TA1 (green dashed line) compared to the baseline (blue dashed line). This is mainly due to the BF reduces

emissions by 50% in TA1. Structure 5 is not sensitive to TA1 because its module D includes only the transport activities associated with reconditioning/recycling, and benefits associated with reconditioning/recycling are allocated to the subsequent life (see Section 3.4.2). For **TA2 (technology improvement to increase recycling rate up to 95% and reduce landfilling to 5%) after year 50**, all the structures except Structure 4 have only very minor changes for both modules A-C and module D because the change in recycling rate from 85% to 95% does not have a significant influence on the overall results. The exception is Structure 4 which has a 67% reduction in module D in TA2 (red dashed line) compared to the baseline; this is because in Structure 4, module D represents only the BF steel production required to offset the landfilled steel (see the flow diagrams in Appendix A). When the recycling rate increases from 85% to 95% in TA2, the landfilled share decreases from 15% to 5%, corresponding to a 67% reduction. In scenario 2, the dLCA results (Figure A1. 13, Appendix A) show minimal sensitivity across Structures 1-5 under prospective technologies (TA1 and TA2) compared to the current technology. Modules A-C remain largely unaffected, except for Structure 1 which requires additional BF steel for new connections post-earthquake. Since TA1 applies only from year 25 and its effect is minor (similar to scenario 1), changes in module D credits are not distinctly visible.

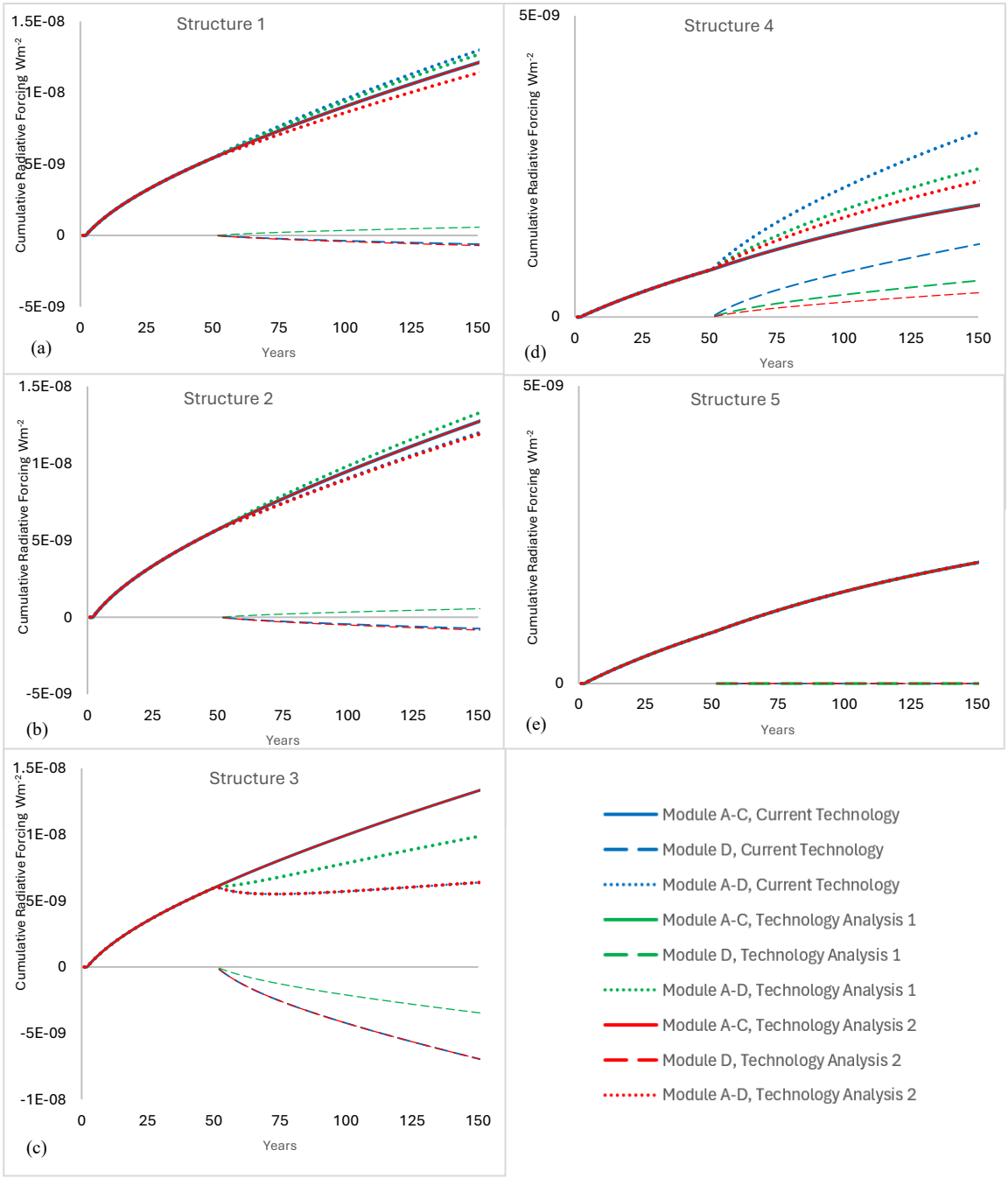


Figure 3.7 Cumulative radiative forcing of all structures in scenario 1 with current technology and prospective technology scenarios (TA1 and TA2 respectively). Figure (a), (b), (c), (d) and (e) show the cumulative radiative forcing of Structures 1, 2, 3, 4 and 5

3.3.4 Sensitivity Analyses

The climate change impact results of the five EBF structures under the catastrophic seismic event modelled in SA1 indicate a strong sensitivity to this type of event. The

sensitivity results of SA1 compared to scenario 2 (moderate to severe earthquake) climate change impacts are presented in Figure 3.8. The catastrophic event nearly doubles the impacts in modules A1-A3 and A4-A5, primarily due to the manufacturing and reinstallation of the EBF structures. At the end-of-waste stage, the benefits beyond the system boundary (module D) are also reduced in each structure (except for Structure 3) - as the avoided impacts from reusing structural components are replaced by the lower benefits associated with recycling. Structure 3 increases its module D benefit by 3% as the newly installed structure can be completely reused at the EOL while the steel in the other newly installed structures still has to be recycled and reused (causing a net increased module D burden). The largest change occurs for Structure 5 which exhibits a module D burden increase of 9474% relative to the moderate-to-severe seismic scenario, as the reconditioned steel is recycled following the catastrophic event. Consequently, the total impacts increase due to both higher embodied emissions from reconstruction and a reduced module D benefit as there is no material reuse.

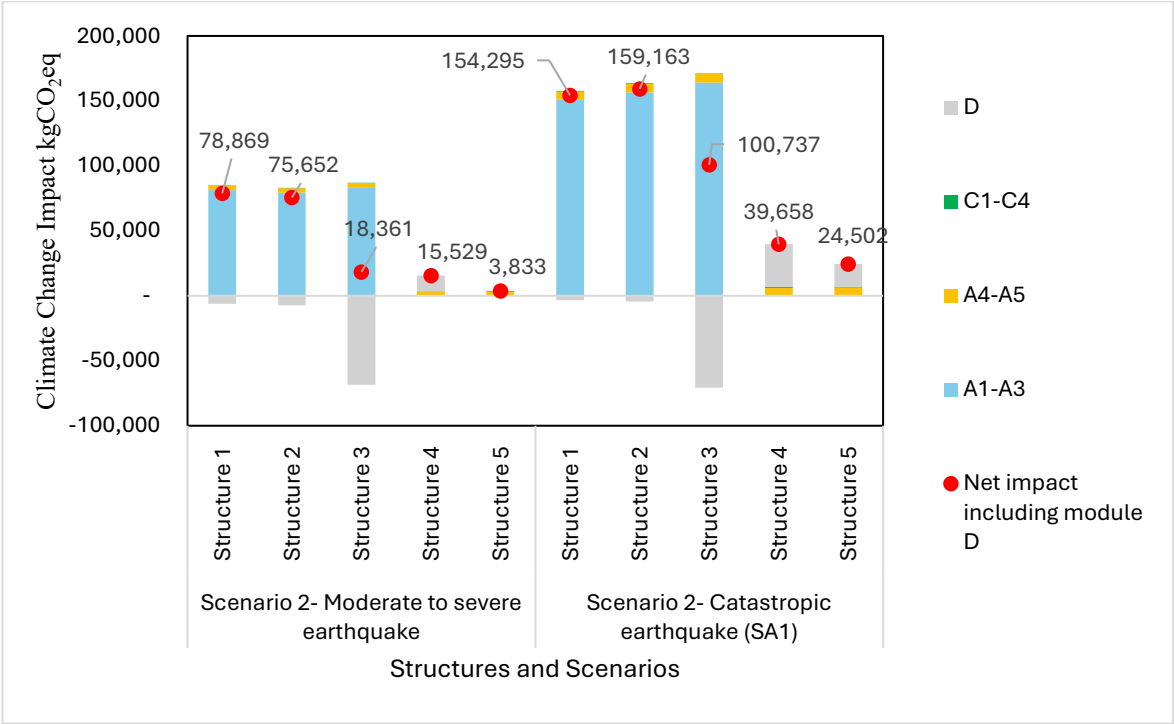


Figure 3.8 Climate change impacts of each structure in scenario 2 assuming a moderate to severe earthquake and a catastrophic earthquake (SA1)

The sensitivity results of SA2 and SA3 compared to the scenario 1 climate change impacts are presented in Figure 3.9. Only Structures 2 and 3 showed a sensitivity to the reuse rates as Structures 1 and 4 are not reused at the EOL, and the Structure 5 reuse benefits are

allocated to the subsequent life cycle. Compared with the scenario 1 assumption of 100% reuse of structural steel components, decreasing the reuse rate to 80% (SA2) and 60% (SA3) results in an increase in net impacts for Structures 2 and 3 due to decreased module D benefits and increased EOL impacts. These changes are primarily attributed to the reduced benefits in module D with reduced reuse rates and increased recycling, and increased EOL impacts due to the additional landfilling. Consequently, decreasing the component reuse rate from 80% to 60% reduces the associated avoided impacts, resulting in higher net climate change impacts for Structure 3. Compared to the baseline scenario (100% reuse), net impacts increase by approximately 3.3 times under SA2 and 4.3 times under SA3.

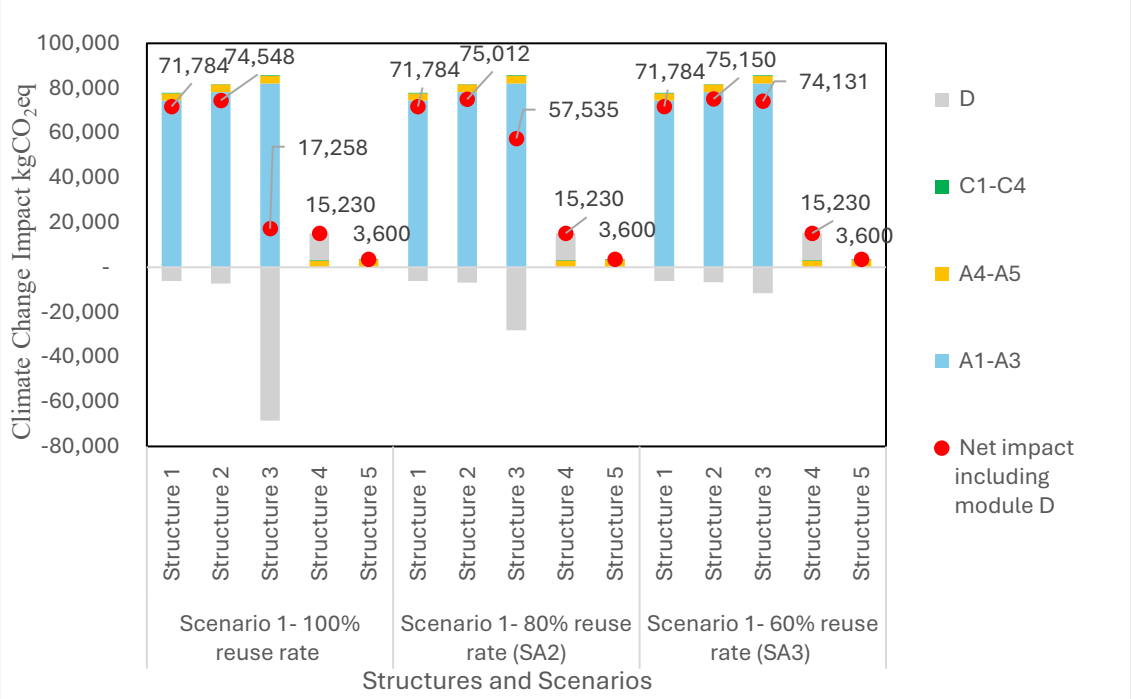


Figure 3.9 Climate change impacts of each structure in scenario 1 with 100% reuse rate vs SA2 (80% reuse rate) and SA3 (60% reuse rate). Variations are observed only for Structures 2 and 3, which incorporate reuse at EOL, while Structures 1 and 4 (no reuse) and Structure 5 (reuse benefits allocated to the subsequent life cycle) show no change

The sensitivity analysis results for use of different allocation methods to represent reuse (SA4) are presented in Figure 3.10. The comparison between the EN 15804 cut-off approach and the 50/50 allocation method indicates that the influence of allocation is most pronounced in structures incorporating higher levels of reuse. Structures 1 and 2 show

negligible variation between the two approaches, as Structure 1 does not involve reuse and Structure 2 includes only a minor proportion of reused components (i.e. shear link only). In contrast, Structures 3, 4, and 5 exhibit significant changes. Under the 50/50 allocation approach, the upstream burdens from primary material production and reconditioned impacts are redistributed across two reuse cycles. This leads to a reduction in impacts for Structure 3 due to shared primary material production between current and subsequent life cycle, while Structures 4 and 5 show increased impacts due to the inclusion of shared primary material production burdens from the previous life cycle. Overall, the results highlight that allocation assumptions substantially influence the magnitude of impacts in reused/reuseable steel structures (but do not show differences in the timing of emissions).

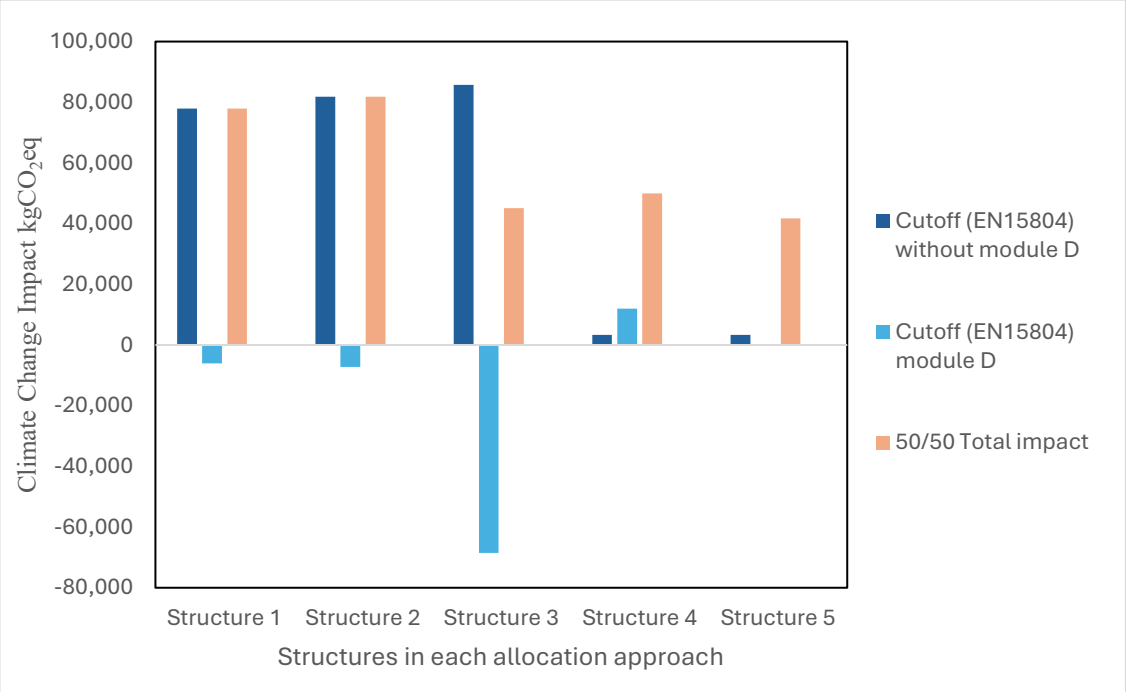


Figure 3.10 Climate change impacts of each structure using EN 15804 cut-off approach and 50/50 approach (SA4)

3.4 Discussion

3.4.1 Climate Change Impacts of EBF Structures

Structures constructed using reconditioned steel (Structures 4 and 5) have significantly lower climate change impacts in both scenarios, using both sLCA and dLCA, compared with structures using primary steel (Structures 1, 2 and 3) (Figures 3.4 and 3.5). These lower results are primarily driven by the avoidance of GHG emissions associated with raw material extraction and steel manufacturing processes. These findings reinforce the importance of the use of reconditioned steel over primary steel for construction as a key strategy for reducing the climate change impacts of the built environment.

Using sLCA and including module D, structures that are bolted rather than welded (Structure 3 versus Structures 1 and 2; Structure 5 versus Structure 4) have lower climate change impacts in both scenarios due to the reuse of components at EOL (Figure 3.5). At the same time, these bolted structures have higher climate change impacts when module D is excluded (Figure 3.4) because the additional mass of steel required for the bolted connections is not offset by the credit for reuse at EOL. Using dLCA and including module D, the ranking of the different structures changes over time in both scenarios: Structure 3 initially has higher emissions compared to Structures 1 and 2 due to its heavier connection weights but this changes after year 50 due to modelling the reuse of the steel sections (enabled by the bolted connections of the main components). Similarly, Structure 5 initially has higher emissions than Structure 4 but this changes after year 50 for the same reason. Thus, structures which are designed for disassembly (i.e. bolted) demonstrate the benefit of reusability only after the EOL and only when including module D.

The climate change impact results also highlight the distinction between reuse and recycling pathways for structural steel components. Although both strategies contribute to reduced impacts, direct reuse of structural elements provides greater climate benefits than recycling, as it avoids both the production of new steel and the energy intensive remelting processes associated with recycling. In this context, DfD strategies play a critical role by enabling the recovery of structural components in a condition suitable for reuse rather than downcycling through conventional recycling pathways. Consequently,

structural designs that prioritise component recoverability can significantly enhance the circularity and climate mitigation potential of steel structures.

For scenario 2 which models the situation where there is an earthquake at year 25, there is relatively little difference in the results compared with scenario 1. This is because only the shear link is replaced after the earthquake - which represents a very small proportion of the total steel content of the EBF. These results highlight the environmental benefits of earthquake-resistant structural designs, particularly EBFs featuring replaceable shear links. In these frames, post-earthquake reconstruction activities are minimal, as only the damaged shear link component requires replacement rather than extensive structural repair or reconstruction. Consequently, the emission profile shows a relatively small difference after the seismic event. From a life cycle perspective, such DfD configurations enhance both environmental and structural performance, providing a strong case for integrating resilience-based design principles into low-carbon building strategies. However, the sensitivity analysis under a catastrophic seismic scenario (SA1) demonstrates that when all five structures require full replacement and involve recycling at EOL after the earthquake, the climate change impacts increase substantially due to both additional embodied emissions and reduced circular benefits in module D. As such extreme events are relatively rare, it can be concluded that it is important to design structural systems for disassembly and reuse so that climate change impacts can be minimised when repairable damage occurs. In this regard, the EBF configurations designed to withstand moderate-to-severe earthquakes are associated with lower impacts as they enable replacement of damaged elements (shear link) while preserving the reuse potential of the primary structural components. From a practical perspective, this highlights the feasibility of DfD-enabled EBF systems for seismic applications, where concentrating damage within replaceable link elements may simplify post-earthquake repair and replacement. In terms of cost implications, although additional detailing and fabrication may be required around the links, these requirements may be partially offset by reductions in structural steel quantities and improved repairability. However, broader implementation may still depend on industry familiarity, detailed seismic design requirements, and the development of practical reuse frameworks for structural steel components (Mughrabi, pers.comm., 8 April, 2026).

Construction stage impacts were modelled as a proportion of product stage impacts for both the welded and bolted structures. Effectively, this reflects the structural steel mass which increases by 6 to 12% for the partially and fully bolted structures respectively compared to the welded structures. Detailed process-level data distinguishing construction activities for welded versus bolted connections were not available, but any differences are likely to be small relative to the energy required for crane lifting and member positioning (Mughrabi, pers.comm., 6 March, 2026). However, future research should confirm this assumption by collecting and assessing detailed process level construction data for welded and bolted steel EBF structures.

The overall results show the climate change mitigation potential of DfD strategies that involve both utilising existing steel for steel structures, and designing structures for reuse at EOL. Incorporating these strategies into building codes, certification schemes, and policy frameworks can support the transition to a circular economy. However, future research should extend the analysis to additional environmental impact categories, such as resource depletion, water use, and toxicity, to provide a more comprehensive assessment of environmental performance.

3.4.2 Implications for sLCA Methodology when Addressing DfD Strategies

Accounting for DfD in building products using LCA to assess associated climate change impacts raises several methodological issues (Larsen et al., 2022; Lausselet et al., 2023; Walzberg et al., 2021).

The first issue is module D, where the EOL techniques related to DfD are a significant determinant of the LCA results, and this modelling is arguably not adequately addressed in current sLCA methods (Abu-Ghaida et al., 2025; Lausselet et al., 2023). According to the ISO 21930:2017 standard (ISO, 2017), the benefits calculated in module D related to DfD techniques must be accounted separately. Using sLCA, Figure 3.5 shows the relevance of the module D results in determining the overall magnitude, and the ranking, of the five structures when using sLCA. Interpretation is facilitated by showing the net results on the diagram alongside the disaggregated results. Likewise, using the dLCA approach, if the module D results are shown separately (Figure 3.6(a) and 3.6(c)) it is

difficult to compare the overall performance of the five structures. However, when the net dLCA results including module D (Figure 3.6(b) and 3.6(d)) are shown alongside the disaggregated results, this facilitates easier interpretation of the net benefits or burdens along the timeline under consideration.

The second issue is selection of the product manufactured from the recycled material at the EOL. In this study, we assumed manufacture of steel reinforcing bars using EAF for modelling steel recycling at EOL; however, if a different type of steel beam or other steel components is assumed as the final product after recycling, this could give different results due to different manufacturing processes. Given the impact of such choices, standards should provide guidance on selecting the most suitable product for modelling in module D.

The third issue concerns modelling of use and reuse of the same material or product over several life cycles. In this case study, for the reconditioned steel in Structures 4 and 5, we modelled it as a "burden-free" input (albeit accounting for the reconditioning activities) into both the current life cycle and the subsequent life cycle (after transport to an EAF steel production or steel reconditioning facility) - assuming it was recycled (Structure 4) or reused (Structure 5) at EOL. Effectively, this approach assumes the module D benefit of reuse is credited to the first life cycle of the steel framing and not to subsequent life cycles. This approach reflects the fact that the total number of expected life cycles is not known, and cannot be estimated based on the available data. EN 15804, ISO 21930, ISO 21931, and EN 15978 do not provide guidance for this modelling aspect. Instead, they defer this modelling aspect to practitioner judgement, requiring transparency and justification of the chosen allocation approach in line with the principles outlined in ISO 14044. However, the results of the sensitivity analysis (SA4) on different allocation approaches show that allocation choices influence the magnitude of climate change impacts. The 50/50 allocation approach redistributes upstream production burdens across life cycles and can be interpreted as a pragmatic representation of reuse under practical constraints (BSI, 2011, p. 22). In structural applications, safety requirements and liability considerations may limit the number of reuse cycles, making the assumption of just two service lives plausible. Furthermore, reuse does not necessarily result in a one-to-one substitution of new steel elements, as reused components may be applied in less optimised configurations, thereby reducing the effective substitution benefits. In this study, a

one-to-one substitution was assumed for modelling purposes; however, in practice, deviations from this assumption may occur and could lead to lower realised benefits.
These findings highlight that current sLCA methodologies are insufficiently detailed with respect to modelling of circular systems. More specific guidance would provide policy- and decision-makers with a more consistent basis for setting carbon targets and developing regulations that support material reuse in the building sector.

3.4.3 Relevance of Dynamic LCA for Assessment of Climate Change Impacts

The case study shows that sLCA climate change results are limited in their ability to support decision-making because GHG emissions are summed even though they occur at different points in time (Figure 3.4); this means that it is not possible to see when, and if, carbon targets are being exceeded. This lack of differentiation between GHG emissions occurring in different years is particularly relevant for products with long life cycles such as buildings. In contrast, the dLCA method enables explicit presentation of the RF due to GHG emissions along a timespan whose length can be chosen by the LCA commissioner or other interested stakeholders (or specified in guidelines). Three examples from the case study illustrate the relevance of time differentiation:

- Using sLCA and including module D, the net climate change impact difference between Structure 3 and 4 is only 13% (Figure 3.5). However, the dLCA results reveal greater differences throughout the timeline. Structure 3 shows approximately 617% and 107% higher CRF than Structure 4 at year 50 and 150 respectively (Figure 3.6(d)). This is because the emission offsets are not apparent until after year 50 in dLCA results. Structure 3 exhibits a substantial module D credit due to reusing the whole structure whereas Structure 4 maintains consistently lower emissions throughout the assessment period.
- Using sLCA and including module D, Structure 4 has a 76 % higher climate change impact than Structure 5 (Figure 3.5). However, the dLCA results show that the CRF of Structure 5 is 10% higher than Structure 4 up to year 50 (because the bolted Structure 5 uses more steel compared with the welded Structure 4); the CRF values for the two structures then begin to diverge due to the avoided GHG

emissions associated with reuse of the bolted frames from year 50 onwards (Figure 3.6(d)).

- The sLCA SA4 results for different allocation methods show that Structures 3, 4 and 5 have relatively similar results when using a 50/50 allocation approach (Figure 3.10). But, in reality, the majority of Structure 3's emissions occur in year 0 whereas the steel reused in Structures 4 and 5 already existed prior to year 0 and therefore the majority of these emissions are "pre-existing" emissions that are unaffected by the current system under analysis.

Thus, accounting for time using the dLCA approach enables policymakers and building sector stakeholders to understand and make more informed decisions on the timeliness of carbon reduction strategies. In particular, dLCA highlights the importance of early mitigation actions, which are also increasingly being emphasised in climate policy frameworks aligned with cumulative carbon budgets. For example, this study illustrated how dLCA communicates the relevance of reuse of steel components in EBF structures now rather than designing for future reuse at the EOL of these EBF structures. Similarly, when accounting for the effect of seismic events on the climate change impacts, sLCA does not differentiate between immediate emissions and delayed benefits associated with reuse or recycling, but dLCA reveals how near-term seismic events and design decisions influence the timing of climate change impacts. Moreover, the dLCA approach communicates clearly that the benefits associated with recycling or reuse at EOL, represented in module D, occur several decades after the initial emissions from steel production; thus, they make a useful contribution to identifying mitigation actions designed to enable the achievement of near-term carbon budgets.

The appropriateness of using dLCA remains debated in the literature. One key limitation concerns its reliance on temporal emission profiles and time-dependent characterisation factors. Unlike sLCA, which aggregates emissions into a single inventory, dLCA requires detailed temporal resolution which increases data requirements and introduces additional uncertainty (Levasseur et al., 2010). Another alleged limitation is the use of fixed temporal endpoints, and the assertion that this effectively discounts GHG emissions occurring further into the future (Jørgensen & Hauschild, 2013; Levasseur et al., 2016; Lueddeckens et al., 2020; Ventura, 2023). However, regarding this last point there is no

requirement to fix temporal endpoints when using dLCA, and GHG emissions can be modelled for any timespan, decision-makers can then use this time-differentiated information to support timely carbon reduction strategies that are aligned with carbon targets.

This study shows that dLCA can provide significant insights as a "message-oriented" LCA application to inform decision-making at the level of individual product systems, where the temporal dynamics of emissions can influence design and material selection. In particular, this approach highlights the relative importance of emission timing in informing targeted mitigation actions and supporting decision-making (Weerasinghe et al., 2026). As Finkbeiner et al. (2025) note, distinguishing between message-oriented and analytical LCA applications is essential to maintain methodological consistency and safeguard the credibility of LCA as both a quantitative and decision-making framework in climate mitigation contexts.

3.4.4 Climate Change Impacts of EBF Structures with Prospective Technologies

The climate change impact of the five structures to the two prospective technology scenarios over a 150-year period varies considerably, depending on their unique functional characteristics and defined system boundaries. These differences influence how future technological changes that could be applied in practice in another 25 years (in year 2050), affect the net climate change impact of existing steel structures in buildings. Technology improvement in BF operation (TA1) shows the most substantial effect on climate change impacts. For Structures 1 and 2, the module D contribution shifts from a negative CRF under the current technology to a positive module D CRF. This transition occurs because the background BF process which represents the displaced activity becomes less carbon-intensive under future technology assumptions. Consequently, the magnitude of the recycling credit decreases. TA1 shows an approximately 50% reduction in Structures 3 and 4 while Structure 5 does not show any difference as it does not use the BF technology. However, as these prospective technologies are only modelled to occur in another 25 years (in 2050), their influence is limited to the EOL stage of the assessed structures; they only become relevant earlier if there is an earthquake which leads to replacement of shear links after the BF technology improvement is implemented (and

even then it makes a negligible difference to the total climate change impact results). In this scenario, an important finding is that technological improvement in the background system can increase the carbon footprint when BF steel production is the displaced activity in module D. As the BF process decarbonises, the avoided emissions associated with recycling diminish, reducing the offset potential in carbon footprint assessments.

In contrast, advancements in steel separation technologies which improve the steel recycling rate (TA2) shows less impacts compared to TA1 results. At year 50, this technology change leads to a lower module D impact relative to the current technology for those structures that are recycled at EOL. For Structures 1 and 2, there is around a 13-15% increase in the module D credit; for Structures 3 and 5 there is no change (because they do not involve recycling at EOL); for Structure 4 there is a 67% reduction in the module D impact as the landfilling rate decreases. This highlights the importance of accounting separately for module D activities, and interpreting them relative to their displaced processes and time, as future emission reductions in the background system can alter the magnitude and direction of module D.

It is important to acknowledge that many other prospective technologies are likely to emerge in the future, potentially influencing climate change impacts. This study focused on only two prospective technology scenarios, selected based on the availability and reliability of existing data. Future research should explore a broader range of technological developments, such as innovations in low carbon steel, and technology advancements in steel manufacturing and construction, to more comprehensively evaluate the sensitivity of climate change impacts to prospective technology in the built environment. In addition, although this study focuses on a specific building structure and regional context, the methodological approach used to assess changes in the climate change impact due to temporal dynamics, future technologies and DfD strategies, can be applied to other building components and geographical contexts. Applying this framework across a broader set of buildings would further support the generalisation of the findings and strengthen the evidence base for circular and low-carbon design strategies in the building sector.

3.5 Conclusion

This study provides a comprehensive assessment of GHG emissions associated with EBF steel structures in a multi-storey building across its life cycle and beyond. By applying a dLCA approach integrated with prospective technology scenarios, this research highlights the benefits of moving beyond traditional sLCA methods when evaluating climate change impacts in the built environment. The overall findings highlight the substantial GHG emission mitigation potential associated with using reconditioned steel rather than primary steel for building steel structures, and the importance of adopting DfD strategies which facilitate material recovery and reuse at EOL as part of a circular economy. This is particularly relevant for buildings located in earthquake-prone regions such as ANZ.

The application of dLCA offers greater insights than sLCA in supporting early-stage design decisions that significantly influence the life cycle emissions of building structures.

Integrating reuse practices into industry standards and policy frameworks will further enhance sustainability efforts in the sector as it aligns design-stage decision-making with CE principles and promotes long-term reductions in GHG emissions in buildings. By considering prospective technologies that may evolve over time, particularly in steel manufacturing and recycling, designers and policymakers can better anticipate the future emission pathways of buildings under changing technological conditions. Finally, this study highlights the need for advancing LCA frameworks that integrate dynamic assessments, enabling policymakers to make more informed and timely decisions on material reuse strategies alongside incentivising DfD practices, and promoting long-term sustainability planning in the building sector.

References

Abu-Ghaida, H., Hollberg, A., Ritzen, M., Wöhler, A., & Lizin, S. (2025). Assessing the environmental benefits of design for disassembly in buildings with a time-resolved prospective LCA approach. *Int. J. Life Cycle Assess.* https://doi.org/10.1007/s11367-025-02526-8

Akanbi, L., Oyedele, L., Davila Delgado, J. M., Bilal, M., Akinade, O., Ajayi, A., & Mohammed-Yakub, N. (2019). Reusability analytics tool for end-of-life assessment of building materials in a circular economy. *World J. Sci. Technol. Sustain. Dev.*, *16*(1), 40-55. https://doi.org/10.1108/WJSTSD-05-2018-0041

Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Davila Delgado, M., Bilal, M., & Bello, S. A. (2018). Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resour. Conserv. Recycl.*, *129*, 175-186. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.10.026

Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *Int. J. Life Cycle Assess.*, *22*(9), 1441-1458. https://doi.org/10.1007/s11367-016-1244-0

Andisheh, K., Hasanali, M., Jármai, K., Taheri, H., Mago, N., ShahMohammadi, A., Karpenko, M., Dong, P., Clifton, G. C., & MacRae, G. A. (2024). *EVALUATING SEISMIC RESPONSE OF INNOVATIVE REUSABLE ECCENTRIC BRACED FRAMES (EBF)* World Conference on Earthquake Engineering Milan.

Antwi-Afari, P., Ng, S. T., Chen, J., Oluleye, B. I., Antwi-Afari, M. F., & Ababio, B. K. (2023). Enhancing life cycle assessment for circular economy measurement of different case scenarios of modular steel slab. *Build. Environ.*, *239*, 110411. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110411

Arvidsson, R., Tillman, A. M., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D., & Molander, S. (2018). Environmental assessment of emerging technologies: recommendations for prospective LCA. *J. Ind. Ecol.*, *22*(6), 1286-1294.

BlueScope Steel Limited. (2020a). *Steel – Welded Beams and Columns Environmental Product Declaration*.

BlueScope Steel Limited. (2020b). *XLERPLATE® steel Environmental Product Declaration*.

Bocken, N. M., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. *J. Ind. Prod. Eng.*, *33*(5), 308-320.

Boothroyd, G., & Alting, L. (1992). Design for Assembly and Disassembly. *CIRP Annals*, *41*(2), 625-636. https://doi.org/https://doi.org/10.1016/S0007-8506(07)63249-1

Broadbent, C. (2016). Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy. *Int. J. Life Cycle Assess.*, *21*(11), 1658-1665. https://doi.org/10.1007/s11367-016-1081-1

Broughton, J. (2023). 20 - Disassembly. In L. Harper & M. Clifford (Eds.), *Design and Manufacture of Structural Composites* (pp. 499-526). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-0-12-819160-6.00017-2

BSI. (2011). PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. In. London: British Standards Institution.

CEN. (2012). Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method. In *EN 15978:2011*. Dublin, Ireland: NSAI Standard.

CEN. (2019). EN 15804:2012+A2:2019 Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products. In. Brussels: European Committee for Standardization.

Collinge, W. O., Landis, A. E., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2013). Dynamic life cycle assessment: framework and application to an institutional building. *Int. J. Life Cycle Assess.*, *18*(3), 538-552. https://doi.org/10.1007/s11367-012-0528-2

Collinge, W. O., Liao, L., Xu, H., Saunders, C. L., Bilec, M. M., Landis, A. E., Jones, A. K., & Schaefer, L. A. (2011, 16-18 May 2011). Enabling dynamic life cycle assessment of buildings with wireless sensor networks. Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology,

Collinge, W. O., Rickenbacker, H. J., Landis, A. E., Thiel, C. L., & Bilec, M. M. (2018). Dynamic Life Cycle Assessments of a Conventional Green Building and a Net Zero Energy Building: Exploration of Static, Dynamic, Attributional, and Consequential Electricity Grid Models. *Environ Sci Technol*, *52*(19), 11429-11438. https://doi.org/10.1021/acs.est.7b06535

Crowther, P. (2005). Design for disassembly–themes and principles. *Environment design guide*, 1-7.

Davenport, P. (2003). Instrumental measures of earthquake intensity in New Zealand. Proceedings of the 7th Pacific conference on earthquake engineering, Christchurch, New Zealand, paper,

Diemer, A., Nedelciu, C. E., Morales, M. E., Batisse, C., & Cantuarias-Villessuzanne, C. (2022). Waste Management and Circular Economy in the French Building and Construction Sector [Review]. *Front. Sustain.*, *3*. https://doi.org/10.3389/frsus.2022.840091

Durmisevic, E., & Noort, N. (2003). Re-use potential of steel in building construction. CIB Publication,

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019a). Dynamic Benchmarking of Building Strategies for a Circular Economy. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012027. https://doi.org/10.1088/1755-1315/323/1/012027

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019b). Life cycle assessment of a Danish office building designed for disassembly. *Build. Res. Inf.*, *47*(6), 666-680. https://doi.org/10.1080/09613218.2018.1517458

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019c). Potential of Circular Economy in Sustainable Buildings. *IOP Conference Series: Materials Science and Engineering*, *471*(9), 092051. https://doi.org/10.1088/1757-899X/471/9/092051

Eberhardt, L., Birkved, M., & Birgisdottir, H. (2022). Building design and construction strategies for a circular economy. *Arch. Eng. Des. Manag.*, *18*(2), 93-113. https://doi.org/10.1080/17452007.2020.1781588

Eboh, F. C., Andersson, B.-Å., & Richards, T. (2019). Economic evaluation of improvements in a waste-to-energy combined heat and power plant. *Waste Manage. (Oxford)*, *100*, 75-83. https://doi.org/https://doi.org/10.1016/j.wasman.2019.09.008

ecoinvent. (2023). *Allocation, cut-off, EN15804 (EN15804)*. https://ecoinvent.org/

EMR Group. (2022). *Environmental Product Declaration Reusable Steel*.

European Commission. (2002). *Life-cycle assessment (LCA) for steel construction – Final report*. Publications Office. https://op.europa.eu/en/publication-detail/-/publication/25e4be8e-97c1-4e79-b37b-a51b7634ef7c

Finkbeiner, M., Roche, L., & Holzapfel, P. (2025). From analysis-LCA to message-LCA: a lost cause? *Int. J. Life Cycle Assess.*, 1-8.

Fouquet, M., Levasseur, A., Margni, M., Lebert, A., Lasvaux, S., Souyri, B., Buhé, C., & Woloszyn, M. (2015). Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. *Build. Environ.*, *90*, 51-59. https://doi.org/10.1016/j.buildenv.2015.03.022

Gallagher, J., Basu, B., Browne, M., Kenna, A., McCormack, S., Pilla, F., & Styles, D. (2017). Adapting Stand-Alone Renewable Energy Technologies for the Circular Economy through Eco-Design and Recycling. *J. Ind. Ecol.*, *23*(1), 133-140. https://doi.org/10.1111/jiec.12703

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *J. Clean. Prod.*, *143*, 757-768. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.048

Goldstein, B., & Rasmussen, F. N. (2018). LCA of Buildings and the Built Environment. *Life cycle assessment: theory and practice*, 695-722.

Guy, B., Shell, S., & Esherick, H. (2006). Design for deconstruction and materials reuse. *Proceedings of the CIB Task Group*, *39*(4), 189-209.

Hasanali, M., Andisheh, K., Mago, N., Taheri, H., ShahMohammadi, A., Karpenko, M., Jármai, K., Dong, P., Clifton, G. C., & MacRae, G. A. (2024). *Seismic response of sustainable, resilient eccentrically braced frames* New Zealand Society for Earthquake Engineering 2024 Annual Conference, Auckland.

Hawkins, W., Cooper, S., Allen, S., Roynon, J., & Ibell, T. (2021). Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure. *Structures*, *33*, 90-98. https://doi.org/https://doi.org/10.1016/j.istruc.2020.12.013

HERA. (2021). *Steel Recycling Report*. New Zealand Heavy Engineering Research Association. https://www.hera.org.nz/wp-content/uploads/R5-89-Steel-Recycling-Report-v2.pdf

Holappa, L. (2020). A General Vision for Reduction of Energy Consumption and CO2 Emissions from the Steel Industry. *Metals*, *10*(9).

Huang, Z., Zhou, H., Miao, Z., Tang, H., Lin, B., & Zhuang, W. (2024). Life-Cycle Carbon Emissions (LCCE) of Buildings: Implications, Calculations, and Reductions. *Engineering*. https://doi.org/https://doi.org/10.1016/j.eng.2023.08.019

InfraBuild Australia Pty Ltd. (2024). *Environmental Product Declaration Reinforcing Rod, Bar, Wire and SENSE 600®*.

Ishaq, M., Ghouse, G., Fernández-González, R., Puime-Guillén, F., Tandir, N., & Santos de Oliveira, H. M. (2022). From Fossil Energy to Renewable Energy: Why is Circular Economy Needed in the Energy Transition? [Original Research]. *Front. Environ. Sci.*, *10*. https://doi.org/10.3389/fenvs.2022.941791

ISO. (2017). ISO 21930:2017. In *Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services* (pp. 80).

Jørgensen, S. V., & Hauschild, M. Z. (2013). Need for relevant timescales when crediting temporary carbon storage. *Int. J. Life Cycle Assess.*, *18*(4), 747-754. https://doi.org/10.1007/s11367-012-0527-3

Larsen, V. G., Tollin, N., Sattrup, P. A., Birkved, M., & Holmboe, T. (2022). What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability

assessment, LCSA. *J. Build. Eng.*, *50*, 104203. https://doi.org/https://doi.org/10.1016/j.jobe.2022.104203

Lausselet, C., Dahlstrøm, O. A., Thyholt, M., Eghbali, A., & Schneider-Marin, P. (2023). Methods to Account for Design for Disassembly: Status of the Building Sector. *Buildings*, *13*(4).

Levasseur, A., Cavalett, O., Fuglestvedt, J. S., Gasser, T., Johansson, D. J. A., Jørgensen, S. V., Raugei, M., Reisinger, A., Schivley, G., Strømman, A., Tanaka, K., & Cherubini, F. (2016). Enhancing life cycle impact assessment from climate science: Review of recent findings and recommendations for application to LCA. *Ecol. Indic.*, *71*, 163-174. https://doi.org/https://doi.org/10.1016/j.ecolind.2016.06.049

Levasseur, A., Lesage, P., Margni, M., Deschênes, L., & Samson, R. (2010). Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environ Sci Technol*, *44*(8), 3169-3174. https://doi.org/10.1021/es9030003

Lima, A. T., Kirkelund, G. M., Lu, Z., Mao, R., Kunther, W., Rode, C., Slabik, S., Hafner, A., Sameer, H., Dürr, H. H., Flörke, M., Lowe, B. H., Aloini, D., Zerbino, P., & Simoes, S. G. (2024). Mapping circular economy practices for steel, cement, glass, brick, insulation, and wood – A review for climate mitigation modeling. *Renew. Sustain. Energy Rev.*, *202*, 114697. https://doi.org/https://doi.org/10.1016/j.rser.2024.114697

Lueddeckens, S., Saling, P., & Guenther, E. (2020). Temporal issues in life cycle assessment—a systematic review. *Int. J. Life Cycle Assess.*, *25*(8), 1385-1401. https://doi.org/10.1007/s11367-020-01757-1

MacArthur, E. (2013). Towards the circular economy. *J. Ind. Ecol.*, *2*(1), 23-44.

McDonough, W., & Braungart, M. (2010). *Cradle to cradle: Remaking the way we make things*. North point press.

McLaren, S. J. (2021). Linking Life Cycle Assessment to the wider circular economy. In A. Borrion & O. Mwabonje (Eds.), *Life Cycle Assessment: a metric for the circular economy,* . Royal Society of Chemistry.

Mestre, A., & Cooper, T. (2017). Circular Product Design. A Multiple Loops Life Cycle Design Approach for the Circular Economy. *Des. J.*, *20*(sup1), S1620-S1635. https://doi.org/10.1080/14606925.2017.1352686

Ministry for the Environment. (2022). *Measuring emissions: a guide for organisations: 2022 detailed guide*. https://environment.govt.nz/publications/measuring-emissions-a-guide-for-organisations-2022-detailed-guide/

Minunno, R., O'Grady, T., Morrison, G. M., Gruner, R. L., & Colling, M. (2018). Strategies for Applying the Circular Economy to Prefabricated Buildings. *Buildings*, *8*(9).

Mughrabi, O. (2026). In (Email ed., pp. 06-03-2026).

Negishi, K., Tiruta-Barna, L., Schiopu, N., Lebert, A., & Chevalier, J. (2018). An operational methodology for applying dynamic Life Cycle Assessment to buildings. *Build. Environ.*, *144*, 611-621. https://doi.org/10.1016/j.buildenv.2018.09.005

New Zealand Green Building Council. (2023). *Green Star Case Studies*. https://nzgbc.org.nz/green-star-case-studies

Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. *J. Build. Eng.*, *44*, 102704. https://doi.org/https://doi.org/10.1016/j.jobe.2021.102704

Oluleye, B. I., Chan, D. W. M., Saka, A. B., & Olawumi, T. O. (2022). Circular economy research on building construction and demolition waste: A review of current trends and future research directions. *J. Clean. Prod.*, *357*, 131927. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.131927

Ouellet-Plamondon, C., Ramseier, L., Balouktsi, M., Delem, L., Foliente, G., Francart, N., Garcia, A., Hoxha, E., Lützkendorf, T., Nygaard Rasmussen, F., Peuportier, B., Butler, J., Birgisdottir, H., Dowdell, D., Dixit, M., Silva, V., Silva, M., de Cózar, J., Kjendseth Wiik, M., & Frischknecht, R. (2022). *Carbon footprint assessment of a wood multi-residential building considering biogenic carbon*. https://doi.org/10.21203/rs.3.rs-2273783/v1

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *J. Clean. Prod.*, *143*, 710-718. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.055

Pongiglione, M., Calderini, C., & Guy, G. B. (2017). A new demountable seismic-resistant joint to improve industrial building reparability. *Int. J. Disaster Resil. Built Environ.*, *8*(3), 251-262. https://doi.org/10.1108/IJDRBE-06-2016-0026

Rios, F. C., Chong, W. K., & Grau, D. (2015). Design for Disassembly and Deconstruction - Challenges and Opportunities. *Procedia Engineering*, *118*, 1296-1304. https://doi.org/https://doi.org/10.1016/j.proeng.2015.08.485

Robertson, N., & Hurren, K. (2021). *New Zealand Steel Economic Impact Assessment*. https://www.aucklandcouncil.govt.nz/ResourceConsentDocuments/18DIS60376538%20AppH%20EIA.pdf

Rosenbaum, R. K., Hauschild, M. Z., Boulay, A.-M., Fantke, P., Laurent, A., Núñez, M., & Vieira, M. (2018). Life cycle impact assessment. *Life cycle assessment: theory and practice*, 167-270.

Sassanelli, C., Urbinati, A., Rosa, P., Chiaroni, D., & Terzi, S. (2020). Addressing circular economy through design for X approaches: A systematic literature review. *Comput. Ind.*, *120*, 103245. https://doi.org/https://doi.org/10.1016/j.compind.2020.103245

Schützenhofer, S., Kovacic, I., Rechberger, H., & Mack, S. (2022). Improvement of Environmental Sustainability and Circular Economy through Construction Waste Management for Material Reuse. *Sustainability*, *14*(17).

Selvaraj, S., & Chan, T.-M. (2024). Recommendations for Implementing Circular Economy in Construction: Direct Reuse of Steel Structures. *J. Constr. Steel Res.*, *214*, 108439. https://doi.org/https://doi.org/10.1016/j.jcsr.2023.108439

Spišáková, M., Mandičák, T., Mésároš, P., & Špak, M. (2022). Waste Management in a Sustainable Circular Economy as a Part of Design of Construction. *Appl. Sci.*, *12*(9), 4553. https://www.mdpi.com/2076-3417/12/9/4553

Stats NZ. (2024). *New Zealand International Trade*. Retrieved 8/15 from https://statisticsnz.shinyapps.io/trade_dashboard/

Su, S., Li, X., Zhu, Y., & Lin, B. (2017). Dynamic LCA framework for environmental impact assessment of buildings. *Energy Build.*, *149*, 310-320. https://doi.org/10.1016/j.enbuild.2017.05.042

Tiruta-Barna, L., Pigné, Y., Navarrete Gutiérrez, T., & Benetto, E. (2016). Framework and computational tool for the consideration of time dependency in Life Cycle Inventory: proof of concept. *J. Clean. Prod.*, *116*, 198-206. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.12.049

Tomić, T., & Schneider, D. R. (2018). The role of energy from waste in circular economy and closing the loop concept – Energy analysis approach. *Renew. Sustain. Energy Rev.*, *98*, 268-287. https://doi.org/https://doi.org/10.1016/j.rser.2018.09.029

UK Green Building Council. (2024). *Future Homes Standard*. https://ukgbc.org/policy-advocacy/new-build-standards/future-homes-standard/

United Nations Environment Programme. (2023). *Building Materials and the Climate: Constructing a New Future*. https://wedocs.unep.org/20.500.11822/43293

Vanegas, P., Peeters, J. R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., & Duflou, J. R. (2018). Ease of disassembly of products to support circular economy strategies. *Resour. Conserv. Recycl.*, *135*, 323-334. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.06.022

Ventura, A. (2023). Conceptual issue of the dynamic GWP indicator and solution. *Int. J. Life Cycle Assess.*, *28*(7), 788-799. https://doi.org/10.1007/s11367-022-02028-x

Walzberg, J., Lonca, G., Hanes, R. J., Eberle, A. L., Carpenter, A., & Heath, G. A. (2021). Do We Need a New Sustainability Assessment Method for the Circular Economy? A Critical Literature Review [Review]. *Front. Sustain.*, *1*. https://doi.org/10.3389/frsus.2020.620047

Webster, M., & Costello, D. (2006). Designing structural systems for deconstruction. Proceedings, greenbuild conference,

Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2026). Dynamic carbon budgets and carbon debts for Aotearoa New Zealand and its building sector. *Build. Environ.*, *287*, 113805. https://doi.org/https://doi.org/10.1016/j.buildenv.2025.113805

World Steel Association. (2024). *Steel recycling: Attributes and benefits*. World Steel Association. https://worldsteel.org/wider-sustainability/circular-economy/#recycle

Wu, H., Liang, H., Roy, K., Harrison, E., Fang, Z., De Silva, K., Collins, N., & Lim, J. B. P. (2022). Analyzing the Climate Change Potential of Residential Steel Buildings in New Zealand and Their Alignment in Meeting the 2050 Paris Agreement Targets. *Buildings*, *12*(3). https://doi.org/10.3390/buildings12030290

Xiao, J., Chen, Z., Ding, T., & Xia, B. (2021). Effect of recycled aggregate concrete on the seismic behavior of DfD beam-column joints under cyclic loading. *Adv. Struct. Eng*, *24*(8), 1709-1723. https://doi.org/10.1177/1369433220982729

Chapter 4

Enabling Circular Office Fit-Outs for a Sustainable Future

Preface

This chapter is based on a book chapter accepted for publication in "Circular Economy enabling the SDGs through assessment governance and multi-scale built environment strategies from waste to neighbourhood design". This book chapter was developed as part of this doctoral research. The version presented here is the accepted manuscript, with minor adjustments made to ensure consistency with the overall thesis.

Building on the temporal emission perspective established in Chapter 3, Chapter 4 broadens the assessment to consider how circular economy (CE) strategies and developments associated with Construction 4.0 can influence building sector decarbonisation. The chapter addresses Objective 1.2 by examining CE opportunities in office fit-outs and the role of Construction 4.0 in enabling their implementation. This conceptual assessment provides the basis for the quantitative prospective analysis in Chapter 5, where selected CE strategies are evaluated under evolving future technological, socio-economic, and policy pathways.

Book chapter citation:
Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2026). Enabling Circular Office Fit-Outs for a Sustainable Future. In S. M. E. Sepasgozar & R.J. Tumpa (Eds.), Accepted for publication in *Circular Economy enabling the SDGs through assessment governance and multi-scale built environment strategies from waste to neighbourhood design*

Abstract

The built environment is a major contributor to global resource consumption, greenhouse gas (GHG) and other emissions, and waste generation throughout the life cycle of buildings. While significant attention has been given to reduce the environmental impacts of building design and construction, and operational energy and energy refurbishments, the recurring impacts of office fit-outs are comparatively underexplored. Office fit-outs, which involve the frequent refurbishment of interior spaces through replacement of fixtures, fittings, and furniture, occur multiple times in a building's service life, contributing to unsustainable consumption patterns. This chapter explores the application of circular economy principles in office fit-outs, emphasising the opportunities to reduce impacts by maximising reuse of components, design for optimisation, using low impact materials, and minimising waste through integration of digital tools such as material passports. Drawing on examples from the industry, this chapter demonstrates how circular fit-outs can significantly reduce recurring emissions, and create additional economic and social value. Finally, the findings highlight circular fit-outs as a critical enabler of the Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

4.1 Introduction

The building sector is a major driver of anthropogenic climate change, accounting for approximately 37% of GHG emissions (United Nations Environment Programme, 2023, 2024). In the wider context, the built environment including buildings, infrastructure and constructed landscapes is the world's largest consumer of raw mineral resources, responsible for over 50% of global virgin material extraction - primarily in the form of aggregates, metals, and fossil feedstocks used in construction materials (ARUP, 2025). As buildings are critical for human well-being and economic development, it is imperative to reassess the ways in which buildings are designed, constructed, operated, refurbished and managed at the end of their life cycle.

Over the past decades, researchers and policymakers have responded to this challenge in part by developing international standards for accounting environmental impacts such as

ISO 14040/14044 (ISO, 2006a), green building certification systems such as Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM), and policies such as national GHG mitigation pathways for building sectors. To date, much of this attention has concentrated on alternative structural elements, operational energy efficiency, and large-scale refurbishment activities, supported by these international standards, and policies and regulatory frameworks (Balouktsi & Lützkendorf, 2016; Ghose et al., 2017; Hart et al., 2021; Pomponi et al., 2015; Pomponi & Moncaster, 2018). However, within this growing body of work, building interior refurbishments - commonly referred to as fit-outs - remain a particularly underexamined subset of the non-residential stock, despite their high frequency and high contribution to life cycle GHG emissions (Bui et al., 2023; Bullen & Dowdell, 2022; Ghose et al., 2019; Pomponi et al., 2015).

Fit-outs refer to the process of equipping the interior spaces of a building to make it suitable for occupation and use. It involves the installation or modification of non-structural elements such as fixtures, finishes and furniture (Carbon Leadership Forum, 2019). Fit-outs can be broadly categorised into shell and core (Shell/core), Category A (Cat A), and Category B (Cat B), each representing different levels of interior completion (RICS, 2024). Shell/core provides the base structure, envelope, life-safety systems, and shared amenities. Cat A is essential finishes and services, such as raised floors, ceilings, and mechanical, electrical and plumbing installations that make spaces functional but not tailored. Cat B is tenant-specific works, including partitions, tailored finishes, furniture, technology equipment, and service adjustments (RICS, 2024). While Shell/core and Cat A usually involve one-off processes at construction or during major refurbishment, Cat B is cyclical. These fit-outs can occur in different building typologies, including offices, retail, and restaurants etc. While all these types of fit-outs are significant in the context of building refurbishment, this chapter focuses particularly on tenant-driven Cat B office fit-outs due to their ubiquity and significant impact over the life cycle of office buildings.

Cat B office fit-outs are often driven by the goal of customising office spaces to meet the requirements of the tenants. Through their recurring cycles of replacement and refurbishment, these activities generate unsustainable patterns of consumption and contribute to substantial, yet often excluded, environmental impacts in the building life

cycle (Abtahi, 2006; Butler, 2024; Forsythe & Wilkinson, 2015). In this chapter, Cat B fit-outs are defined as tenant-driven interior modifications undertaken within existing office buildings to customise spaces according to organisational, functional, or aesthetic requirements. These works typically involve upgrading or replacement of fixtures, finishes, and furniture to align with corporate identity, functional demands, or aesthetic preferences (Carbon Leadership Forum, 2019; Rodriguez et al., 2020). While the term "refurbishment" is often used broadly in the literature to describe both structural and interior interventions, this chapter distinguishes Cat B fit-outs as a specific subset of refurbishment activities focused on interior spaces. Given their overlapping scope, the terms "interior refurbishment" and "office fit-out" are used interchangeably throughout this chapter to refer to Cat B fit-outs. Unlike structural refurbishments, office fit-outs are characterised by short and repetitive cycles, frequently triggered by tenant turnover, organisational restructuring, or shifting workplace design trends (Forsythe, 2010; Wilkinson & Reed, 2006). As a result, large volumes of interior components can be replaced before they reach the end of their service life, generating premature product turnover and waste.

This challenge presents a unique opportunity for targeted intervention. Office fit-outs, because of their repetitive nature, provide multiple points for embedding circular economy (CE) strategies. Unlike many other sectors, the building sector holds a particularly high potential for improved circularity due to the substantial material stocks it holds, the longevity of building service lives, and the frequency of interior refurbishment cycles that create opportunities for interventions (MacArthur, 2013; Pomponi & Moncaster, 2017). Therefore, this chapter aims to focuses particularly on office fit-outs to address this underexplored yet impactful phase of the office building life cycle, and to explore how the application of CE principles in office fit-outs can contribute to reducing embodied emissions and resource demand in the built environment. Given that office fit-outs represent a significant yet underexplored source of recurring emissions and material flows, the chapter seeks to bridge the gap between conceptual discussions on circularity and its practical implementation in interior office fit-out projects. The objectives of the chapter are as follows:

i. To review the climate change impact of office fit-outs

ii. To synthesise academic and industry evidence on circular strategies adopted in office fit-out practice
iii. To identify key technological enablers influencing the transition towards circular fit-outs
iv. To review how these strategies contribute towards the SDGs.

4.2 Methodological Approach

This chapter adopts a narrative literature review methodology to synthesise current knowledge and practice on the role of CE principles in office fit-outs and their contribution to achieving the SDGs. The narrative approach was chosen given the limited availability of scholarly research directly addressing this topic and the need to integrate insights across academic and industry sources. Relevant sources were identified through targeted database searches such as Scopus and Google Scholar using key terms such as fit-out, refurbishment, circular economy, embodied emissions, and sustainable strategies. To ensure comprehensive coverage, a snowballing approach was also applied, whereby reference lists of key publications were examined to identify additional studies and cases. Furthermore, industry reports and practitioner case studies were additionally reviewed to learn from real-world implementation of circular strategies in office fit-out projects.

The collected evidence was thematically analysed under four key themes: climate change impacts of office fit-outs (Section 4.3), circular economy as a pathway for sustainable office fit-outs (Section 4.4), enabling the transition to circular fit-outs in the built environment (Section 4.5), and achieving progress towards the sustainable development goals through circular fit-outs (Section 4.6).

4.3 Climate Change Impacts of Office Fit-Outs

The climate change impacts of office fit-outs arise primarily from embodied GHG emissions. While operational energy efficiency has historically dominated sustainability research on the built environment (Balouktsi & Lützkendorf, 2016; Hemmati et al., 2024; Singh & Lazarus, 2018), growing evidence highlights that embodied GHG emissions are becoming increasingly significant (Hart et al., 2021; Lützkendorf & Balouktsi, 2022; Pomponi & Moncaster, 2018; Zhang et al., 2024). Fit-out activities typify this problem:

although the fit-out activities appear minor compared to whole-building construction, their recurring nature over decades can translate into substantial cumulative climate impact from a whole-of-life, whole-of-building perspective (Forsythe & Wilkinson, 2015; Rodriguez et al., 2020). Studies indicate that office fit-outs typically recur every 2 to 10 years, and the frequency varies according to factors such as geographical context, the scale of the floor area, and the functional purpose of the intervention (Butler, 2024; Camilleri & Jaques, 2001; Dixit, 2019; Fieldson & Rai, 2009; Forsythe, 2017).

The recurrence emissions from office fit-outs have been quantified in recent studies. For instance, three case studies based on real-world fit-out projects have demonstrated that, over a 50-year building service life, office fit-outs can contribute an additional 480 $kgCO_2eq/m^2$ of net lettable area, representing approximately 25% of a building's whole-life carbon footprint in the Aotearoa New Zealand context, as calculated in a Building Research Association of New Zealand (BRANZ) case study (Butler, 2024). Notably, this additional impact is of a similar magnitude to a building's upfront embodied GHG emissions, underscoring the significance of these recurring refurbishments. Complementary findings reinforce this assessment: one study reported that the embodied energy associated with office interior equipment alone can increase the total embodied energy of a building by up to 35% (Abtahi, 2006). Furthermore, the impacts of tenant improvements range between 45 and 135 $kgCO_2eq/m^2$, with long-term analyses revealing that such frequent fit-outs can account for as much as 90% of the initial embodied emissions when considered over the full building lifespan (Carbon Leadership Forum, 2019). Collectively, these findings demonstrate that office fit-outs are not marginal contributors to the climate change impacts of a building but instead represent a substantial and recurrent source of GHG emissions.

4.4 Circular Economy as a Pathway for Sustainable Office Fit-Outs

The CE is increasingly recognised as a transformative framework for sustainable development, characterised by its restorative and regenerative design principles. In contrast to the linear take-make-dispose model, the CE aims to mimic natural systems in which waste is not created; instead, products, materials, and nutrients are kept in

circulation (Ellen MacArthur Foundation, 2024). It has been estimated that the built environment could reduce global CO_2 emissions of building materials by up to 38% by 2050 through applying CE principles, mainly through reductions in the demand for carbon-intensive materials such as steel, aluminium, cement, and plastics (Ellen MacArthur Foundation, 2024). Even though the application of CE principles in the built environment is widely discussed in the scholarly literature, with a strong emphasis on buildings, construction processes, and building materials (Akanbi et al., 2018; Broadbent, 2016; Eberhardt et al., 2019a, 2019c; Mestre & Cooper, 2017; Minunno et al., 2018; Norouzi et al., 2021; Pomponi & Moncaster, 2017; Tomić & Schneider, 2018), specific applications of CE in office fit-outs remain comparatively underexplored. This section discusses the documented case studies that are available on use of CE strategies in office fit-outs (see Table 4.1).

The examples in Table 4.1 show that the implementation of CE strategies in office fit-outs substantially reduces recurring embodied carbon emissions, with reductions ranging between 38% and 95% depending on the collection of strategies used and the gross internal floor area (GIA) in each case study. The strategies in Table 4.1 can be broadly categorised into three principles based on the CE principles for construction introduced by UKGBC (2022): (i) maximise reuse, (ii) design for optimisation and, (iii) minimise impacts and waste generation through low-impact material selection and design for waste prevention.

Table 4.1 Comparative summary of office fit-out case studies demonstrating circular economy strategies, associated emissions reductions and other benefits

Source	Description	Circular economy strategies applied	Emissions savings	Other benefits
(JLL Inc., 2025; UKGBC, 2022)	Relocate an existing office to Manchester, United Kingdom	1. Recover materials and products from on site or another site 2. Share or donate materials such as furniture 3. Design for flexibility- used 90% of fixtures and furnishings reconfigurable or demountable 4. Minimise waste through size standardisation 5. Use recycled content or secondary materials for tabletops, kitchen counters, carpets 6. Design out waste through material obviation, exposed ceilings, open plan workspaces, shared seating arrangements	1. 38% reduction of upfront embodied emissions compared to standard office fit-out 2. 116 $kgCO_2eq/m^2$ achieved compared to baseline of 185 $kgCO_2eq/m^2$	1. £47,300 of cost savings 2. Completed within 12 months
(ARUP, 2025)	Refurbish an existing office space in Utrecht, Netherlands	1. Design for flexibility- separate ceilings for technical and aesthetic ceilings 2. Design with low carbon, biobased materials 3. Design for disassembly	1. 50% reduction of embodied emissions compared to initial fit-out emissions	1. 56% reduction of renovation costs over the next 30 years 2. 67% higher reuse value generation forecast due to circular approach
(Workman LLP, 2024)	Merge two workplaces in Birmingham, United Kingdom	1. Reuse of existing furniture such as desks 2. Retain existing office layout including partitioning 3. Retain and reuse existing carpet, while replacing where necessary	1. 95% reduction of embodied emissions compared to baseline emissions 2. Limit office fit-out emissions at 3.4 $kgCO_2eq/m^2$ of GIA	No data

			compared to baseline of 78 $kgCO_2eq/m^2$	
(JLL Inc., 2025)	Refurbish an existing office space in London, United Kingdom	1. Reuse furniture, more than 80% 2. Use new and recycled low carbon materials 3. Design cellular spaces such as meeting rooms, huddle room and enclosed spaces at building's core to limit construction	No evidence on quantified emission savings But sent zero waste to landfill during the build stage	1. Completed within 24 weeks 2. SKA Gold and BREEAM Excellent ratings
(JLL Inc., 2025)	Merge two workplaces in Birmingham, United Kingdom	1. Identify carbon reduction opportunities at the design stage 2. Design for sustainability certifications 3. Design for shared workspaces	1. 53% reduction of embodied emissions compared to conventional fit-out	1. Completed within 16 weeks 2. Increased employee wellbeing
(JLL Inc., 2025)	Refurbish an existing office Leeds, United Kingdom	1. Reuse furniture 2. Remanufacture chairs 3. Design for sustainability certifications 4. Design for disassembly 5. Design for flexibility 6. Design with low carbon materials	1. 65% reduction of embodied emissions compared to the baseline case	1. Completed within 16 weeks 2. Increased employee wellbeing
(Morris & Spottiswood Limited, 2025)	Relocate an existing office to Glasgow, United Kingdom	1. Repurpose existing flooring finishes 2. Reuse second hand furniture through partner company 3. Design for flexibility with modular pod systems 4. Design for disassembly 5. Design for multi-purpose office spaces	1. 65% reduction of total embodied emissions compared to the UK Net Zero Carbon Building Standard which is 260 $kgCO_2eq/m^2$ 2. Limit upfront embodied carbon to 93 $kgCO_2eq/m^2$ 3. Total embodied carbon savings of 9.381 tCO_2eq	1. Shorter timescale compared to predicted (no quantified data available)
(Stathaki, 2025)	Refurbish an existing office	1. Reuse 60% of materials from existing fit-out	1. 75% reduction of embodied emissions compared to conventional fit-out	No data

	space in London, United Kingdom	2. Landfill only 1% of materials, others recycled and donated	2. Total carbon saving of 172 tCO_2eq	
(Nex-Architecture, 2021)	Refurbish an existing office space in London, United Kingdom	1. Remanufacture existing furniture and equipment- around 250 items of furniture (75% of existing) 2. Reuse existing materials 3. Design for multi-purpose office spaces 4. Zero to waste approach	1. 70% reduction of embodied emissions compared to a typical fit-out	1. Cost savings equal to 1-2 years' rent (no quantified data) 2. Shorter timescale compared to predicted 3. Increased employee wellbeing
(Better Buildings Partnership, 2023)	Design of new workplace in Sydney, Australia	1. Reuse 70% of existing furniture, carpet, and partitions	1. 50% reduction of embodied emissions compared to a typical fit-out	No data

First, the most widely adopted CE principle in office fit-outs is maximise **reusing and reconditioning** of furniture and partitions, which directly reduces demand for virgin materials and extends product lifespans. This has been recommended in several fit-out studies as one of the most effective ways of reducing recurring embodied carbon in the commercial offices (e.g. Butler, 2024; Carbon Leadership Forum, 2019; Forsythe & Ding, 2017; Rodriguez et al., 2020; UKGBC, 2022). Secondly, the **design for optimisation** principle includes strategies such as design for disassembly and flexibility (UKGBC, 2022). These two strategies ensure that existing interior elements such as partitions, flooring, ceiling and modular components are easily removed, or replaced and then reused in another life cycle without generating excessive waste. Design for disassembly not only enables the reuse of building components but also enhances their recyclability by facilitating materials to be separated, collected and recycled. Design for flexibility is balancing current user requirements with anticipated future needs by enabling flexible configuration of elements; it reduces the need for new material inputs during future refurbishments and thereby lowers cumulative embodied carbon over the building's service life (ARUP, 2025; López Ruiz et al., 2020; UKGBC, 2022). Thirdly, the principle of **minimising impacts and waste through low-impact material selection and design for waste prevention** includes strategies such as selection of low impact carbon materials, use of recycled materials or secondary materials, and designing out waste which leads to low environmental impacts, reduced demand for virgin materials and minimal waste during the process respectively. It also focuses on reducing onsite construction wastes such as packaging. This principle is inherently connected with the design for optimisation principle as these strategies together reduce resource consumption and extend the life cycle of materials.

Office fit-outs that incorporate CE strategies in their design and construction are commonly referred to as circular fit-outs (ARUP, 2025). These circular office fit-outs not only reduce embodied GHG emissions but also provide a wide range of co-benefits. For example, reuse of furniture and partitions significantly reduces costs by lowering the demand for virgin materials and minimising waste management expenses (ARUP, 2025; JLL Inc., 2025; UKGBC, 2022). One case study reported that a 1,291 m^2 GIA office fit-out achieved a total cost reduction of £47,300, of which £40,000 was attributable to the use of second-hand furniture (UKGBC, 2022). Furthermore, the use of reclaimed or

modular components can streamline installation processes compared with conventional construction methods (Morris & Spottiswood Limited, 2025; UKGBC, 2022). Circular fit-outs have also contributed to improved indoor air quality (Nex-Architecture, 2021); for example, they reduce reliance on new materials such as fabrics and plastics in furniture and carpets which are linked with emissions of volatile organic compounds (VOCs), a major source of indoor air pollution that can negatively impact occupant health (Harčárová et al., 2020; Holøs et al., 2019). Designing for optimisation of office places that prioritises shared and flexible spaces has been linked to enhanced employee well-being by advancing collaboration, connectivity, and providing a diversity of work settings (Nex-Architecture, 2021; Workman LLP, 2024).

Circular fit-outs also contribute towards achieving internationally recognised sustainability certifications, as many of the underlying principles are aligned with the assessment criteria for certification schemes such as BREEAM, SKA rating for commercial office fit-outs, National Australian Built Environment Rating System (NABERS), and WELL Building Standard (WELL). For example, many of circular office fit-out case studies listed in Table 4.1 were (JLL Inc., 2025) designed to achieve a BREEAM Excellent rating through reduced embodied carbon (JLL Inc., 2025), to target WELL Platinum certification through improved indoor air quality and wellbeing of occupants, or to achieve SKA Gold rating for overall office fit-out. Thus, the application of CE strategies in office fit-outs not only mitigates GHG emissions but also enables organisations to demonstrate their environmental sustainability credentials through certification systems.

Overall, these findings highlight that circular office fit-outs deliver a range of benefits including reducing GHG emissions, enhancing economic efficiency, shortening the project timeline, promoting user well-being, contributing to healthier indoor environments, and promoting reputations for organisations through sustainability certifications (Figure 4.1).

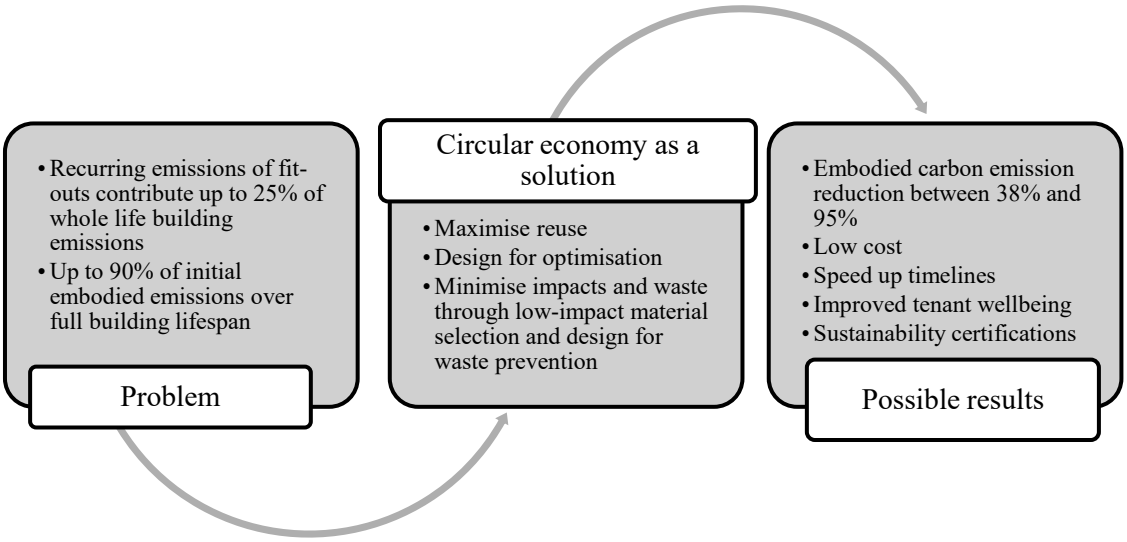


Figure 4.1 Summary of circular economy strategies as a solution for high office fit-out emissions and their multidimensional benefits

4.5 Enabling the Transition to Circular Fit-Outs in the Built Environment

Although CE principles have proven significant benefits and gained industry attention in the built environment, uptake in office fit-outs has been limited (Fierens, 2024). Circular office fit-out uptake in the industry is constrained by different barriers that hinder the practical implementation of circular practices. However, several strategies offer viable pathways to overcome these challenges. In alignment with the scope of this thesis, this section focuses specifically on technology-based solutions that facilitate the transition toward circular office fit-outs. It first discusses key barriers hindering the integration of CE principles in office fit-outs (Section 4.5.1) and then discusses corresponding strategies that can enable their implementation (Section 4.5.2).

4.5.1 Barriers to Circular Fit-Outs

While social, economic, and regulatory factors play a significant role in shaping the uptake of circular fit-outs, most of the challenges to uptake are interlinked and can be attributed to a fundamental technological limitation that constrains systemic progress. This limitation is the absence of an established, reliable and accessible secondary market

for reclaimed and reconditioned materials (Knoth et al., 2022; López Ruiz et al., 2020). The absence of established secondary markets is also linked with potential users' doubts around material quality and warranties; this discourages designers, contractors, and clients from specifying reused components. There is also a knock-on effect to this situation which is that related initiatives based on other CE strategies (such as design for optimisation) are not incentivised (Knoth et al., 2022). Moreover, even if the reconditioned products or reused materials are available, there can be issues of supply consistency and compatibility with modern aesthetic designs which limit their uptake in large scale fit-out projects (UKGBC, 2022). In many regions, infrastructure to support product and material recovery, storage, and redistribution remains non-existent or underdeveloped, thereby constraining the practical implementation of reuse strategies in office fit-outs. For instance, while the European market has experienced a rapid expansion of platforms that specialise in remanufactured and reclaimed building materials (Çetin et al., 2021; EEA, 2022), similar systems are underdeveloped in other regions. One of the main reasons for this is that European markets benefit from policy support, and availability of digital platforms and mechanisms (Çetin et al., 2021). Consequently, economic, social, and regulatory barriers such as higher transaction costs, limited market incentives, and ambiguous responsibilities among stakeholders can be viewed as extensions of this core technological barrier.

There are also common barriers for CE implementation in the context of the built environment arising from technical and material limitations, lack of collaboration between different stakeholders, and high labour involved with deconstruction processes (Rios et al., 2015; Tleuken et al., 2022). However, in the context of circular fit-outs, many of these challenges are less complicated than in structural elements. Fit-outs typically use interior elements such as fixtures, finishes, and furniture, which are comparatively easier to modify, replace, or disassemble without affecting the primary building structure. For instance, the integration of modular systems or reconditioned workspaces can be achieved with fewer technical constraints and lower safety risks compared to the retrofitting of structural elements in buildings. Therefore, circular fit-outs represent an accessible entry point for the adoption of CE practices within the built environment.

In summary, while the barriers to implementing circular office fit-outs seem multidimensional, they are fundamentally interconnected to the technological deficit of

traceable, high-quality secondary market systems. This foundational barrier underpins constraints in maximising reuse, such as the lack of reliable material traceability and secondary markets; in designing for optimisation, including limited digital support for modular and adaptive planning; and in minimising impact and waste, particularly through low-impact material selection and efficient resource management. Overcoming this limitation is pivotal to advancing circularity in office fit-outs. The following subsection therefore outlines key technological strategies that can facilitate the transition toward circular fit-out practices.

4.5.2 Technology-Based Strategies to Overcome Barriers

To overcome the above discussed barriers, the strengthening of infrastructure is essential for enabling CE in office fit-outs. One promising solution is the development and adoption of digital technologies into CE strategies in the built environment, such as additive manufacturing, Artificial Intelligence (AI), Building Information Modelling (BIM) and Geographical Information Systems (GIS) (Çetin et al., 2021). **Adopting additive manufacturing** into fit-outs enables design and three-dimensional (3D) printing of customised interior components with minimal waste. For instance, it allows the production of partition elements designed for disassembly, thereby enabling component repair and remanufacturing, while reducing material waste (Tibaut et al., 2016). **AI** driven tools and mechanisms facilitates designers to generate and evaluate multiple fit-out alternatives alongside predefined performance criteria, including embodied carbon, material efficiency, and disassembly potential (Çetin et al., 2021). For example, predictive models developed for the construction sector to estimate waste streams and material reusability (Akanbi et al., 2019; Armeni et al., 2024) can be directly applied to office fit-outs to eliminate wastes generating over frequent fit-out cycles. **BIM** allows integration of environmental performance, material flows, and optimisation strategies into the design and refurbishment process. It also provides a digital representation of building interiors where every component can be tracked, quantified, and assessed for embodied carbon, material composition, and future reuse potential (Akanbi et al., 2018; Charef & Emmitt, 2021). **GIS** enables the spatial mapping of material stocks and flows across urban areas, providing insights into the availability of reclaimed materials from ongoing demolition or refurbishment projects (Çetin et al., 2021). For fit-outs, GIS can be used to identify local sources of secondary materials such as furniture, partitions, ceiling, and flooring thereby reducing dependence on virgin materials and minimising

transportation-related emissions. This spatial intelligence is particularly relevant for high-density cities (Verhagen et al., 2021) where fit-out activities are frequent and material recovery potential is significant.

Material passports, also known as digital product passports (DPPs), have emerged as a key point of attention for operationalising circularity and ensuring long-term value retention of building components (Çetin et al., 2021; Çetin et al., 2023; Markou et al., 2025). By providing structured and accessible digital information on material composition, embodied emissions, repairability, and disassembly potential, material passports address one of the most critical challenges of CE implementation: the lack of transparency and sufficient information about materials over the whole life of a building. Material passports can be understood as an integrative solution that combines the strengths of various digital technologies such as BIM, AI, and GIS (Markou et al., 2025). When embedded within BIM models, material passports ensure that every fixture, finish, or furniture element is traceable and linked to life cycle data. Coupled with AI algorithms, these passports can predict the optimal reuse potential or recycling route based on condition assessments and historical performance data. At a larger scale, coupling GIS platforms with material passports enables city-level mapping of available reusable components, supporting urban mining strategies and reducing the environmental impacts associated with virgin material extraction and transport. For example, initiatives such as Madaster in the Netherlands (Heisel & Rau-Oberhuber, 2020), Upcyclea in France and Circuland in the United Kingdom (UKGBC, 2025) provide digital identities for building components, enabling designers and contractors to source reclaimed materials and share information about the composition of their products and buildings. By linking design and deconstruction stages through a digitally integrated passport system, office interiors can be designed for disassembly, maintained with predictive insights, and refurbished with readily available secondary materials. Notably, the uptake of material passports is beginning to shift to being a regulatory requirement. For example, the European Union (EU) implemented a new regulation mandating that almost all products sold in the EU incorporate a DPP (European Commission, 2022; European Union, 2024; Walden et al., 2021). This initiative aims to enhance transparency across product value chains by providing comprehensive information on each product's origin, material composition, environmental impacts, and disposal recommendations.

Enabling circular fit-outs can be positioned within the broader transition towards Construction 4.0, where advanced technologies and data-driven decision-making emphasise sustainability in the built environment (Balasubramanian et al., 2024; de Almeida Barbosa Franco et al., 2022; van der Heijden, 2023). The principles of CE in fit-outs closely align with Construction 4.0's emphasis on life cycle thinking, optimisation, and integration across different stakeholders in the built environment. Both circular fit-outs and Construction 4.0 challenge the traditional linear construction model in the context of a sustainable future. Therefore, research on enabling circular fit-outs provides a good example for investigating implementation of Construction 4.0, translating its technological and process innovations into environmental, economic, and social outcomes.

The strategies discussed in this section demonstrate how technology-based solutions can support the implementation of circular fit-outs. Construction 4.0 technologies, including additive manufacturing, AI, BIM, GIS, and DPPs, together support maximising reuse by facilitating precise tracking, recovery, and redistribution of fit-out components. These technologies also underpin design for optimisation by allowing for flexible, adaptable, and modular fit-out configurations, which can be efficiently reconfigured or repurposed over time. Furthermore, they contribute to minimising impact and waste by guiding the selection of low-impact materials, supported by life cycle assessment, and enabling efficient resource management throughout the fit-out process. Together, these strategies provide an integrated, technology-enabled pathway to operationalise circular office fit-outs, addressing both the central technological barrier and the multidimensional challenges associated with maximising reuse, design for optimisation, and minimising impact and waste in office fitouts. To clearly demonstrate how each technological strategy addresses specific barriers and aligns with the three CE principles, a summary mapping is presented in Table 4.2.

Table 4.2 Summary of technology-based strategies, barriers for circular fit-outs and their alignment with circular strategies

Technological Strategy	Barriers Addressed	CE Strategy Alignment
Additive manufacturing Design and 3D printing of customised interior components	Enable component remanufacture pathways Increase reuse potential	Design for optimisation Minimise waste
AI Predictive models development for predefined performance criteria	Enable data standardisation Increase reuse potential	Maximise reuse Design for optimisation Minimise waste
BIM Multicriteria integration to design and future refurbishment plans	Establish secondary material database Enable data standardisation Material traceability Material transparency Increase reuse potential Improve stakeholder relationship	Maximise reuse Design for optimisation Minimise impact and waste
GIS Spatial mapping of material stocks and flows	Material traceability Reduce inconsistency in supply chains	Maximise reuse Design for optimisation
DPPs Ensure long-term value retention	Establish secondary material database Enable data standardisation Increase reuse potential Enable data standardisation Material traceability Material transparency Enable material quality standardisation for secondary market	Maximise reuse Design for optimisation Minimise impact and waste

4.6 Achieving Progress Towards the Sustainable Development Goals Through Circular Fit-Outs

The SDGs, introduced by the United Nations in 2015, provide a universal framework to guide global action towards promoting prosperity while protecting the planet (United Nations, 2017). Comprising 17 goals and 169 targets, the SDGs emphasise the integration of environmental, social, and economic dimensions of sustainable development. Within this framework, the built environment has been widely recognised as a critical area due to its significant environmental footprint, high resource demand, and potential for systemic transformation (Fei et al., 2021; Goubran, 2019). Similarly, the contribution of the CE in the built environment and its role in contributing to the achievement of the SDGs has also been widely addressed in recent publications (Brandão & Verissimo, 2024; Ogunmakinde et al., 2022). However, within the broader context of the built environment, the role of office fit-outs in contributing to the achievement of SDGs has received limited attention. This section therefore discusses how the application of CE in office fit-outs can contribute to the achievement of the SDGs for a sustainable future.

In the context of office fit-outs, certain SDGs are particularly relevant given their direct relationship with material use, recurring emissions, and waste generation in the built environment. Among these, SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) are most directly aligned with circular fit-outs. By promoting sustainability through circular office fit-outs, the built environment makes a meaningful contribution to SDG 11, which seeks to make cities and human settlements inclusive, safe, resilient, and sustainable. Through the responsible use of natural resources and the reuse of existing products within the material loop, circular fit-outs illustrate the principles of resource efficiency. By reusing and refurbishing furniture and fixtures, circular fit-outs directly contribute to SDG 12 through reducing the reliance on virgin materials, limiting waste streams, and extending the service life of building components, thereby promoting sustainable consumption patterns within the built environment. Circular fit-outs directly reduce GHG emissions by lowering the embodied emissions associated with recurring fit-outs over the life cycle of buildings, and this is particularly the case for office buildings where they may occur frequently. It makes a significant contribution to SDG 13 by supporting climate change

mitigation. Each of these SDGs include specific targets, and the contribution of circular fit-outs toward achieving these targets are summarised in Table 4.3.

Table 4.3 Contribution of circular fit-outs to specific targets of SDGs 11, 12 and 13

SDGs	Specific targets	Contribution towards SDG Target
SDG 11	11.3- Enhance inclusive and sustainable urbanisation and capacity for participatory, integrated, and sustainable human settlement planning and management	Allow spaces to be reconfigured over time, reducing the need for resource-intensive refurbishment and enabling long-term urban resilience
	11.6- Reduce per capita environmental impact of cities including air quality and waste management	Material reuse, reconditioning, and recycling. Minimise the embodied GHG emissions and VOC emissions
	11.b- Increase uptake in cities and settlements of adopting integrated policies for inclusion, resource efficiency, climate change mitigation, and disaster resilience	Systematic application of CE principles, supported by digital tools such as material passports, which facilitate transparent, data-driven decision-making within urban cities
SDG 12	12.2- Achieve the sustainable management and efficient use of natural resources	Prioritise reuse and recycle over new material extraction
	12.4- Achieve the environmentally sound management of chemicals and all wastes throughout their life cycle	Reduce wastes including chemicals release to air, water, and soil to through reuse and recycle practices and thereby reducing adverse impacts on human health and the environment
	12.5- Reduce waste generation through prevention, reduction, recycling and reuse	Prevent, reduce, recycle, and reuse waste through modular design, deconstruction, and material recovery strategies

	12.6- Encourage companies to adopt sustainable practices	Provide cost benefits, accelerated timelines and employee wellbeing
	12.a- Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable resource consumption and production	Application of digital and technological innovations, such as BIM and material passports, which enhance scientific and technical capacity of countries
SDG 13	13.a- Commitment to the climate action through supporting towards meaningful mitigation actions	Promote mechanisms for building capacity for effective climate change-related planning and management

In addition to their direct contributions to SDGs 11, 12, and 13, circular fit-outs also generate important indirect benefits across a broader range of SDGs. For instance, circular fit-outs support SDG 3 (Good Health and Well-being) by improving indoor environmental quality, and by creating healthier, more comfortable workplaces that enhance employee well-being. Waste reduction and responsible material management contribute to SDG 6 (Clean Water and Sanitation) by reducing the risk of water pollution from material extraction and waste disposal processes. Furthermore, enabling circular fit-outs in industry also contribute to SDG 8 (Decent Work and Economic Growth) by creating new forms of employment, entrepreneurship, and economic productivity through enabling the establishment and expansion of functional secondary markets, and developing innovative business models that facilitate digital platforms, such as material passports. Circular fit-outs also contribute to SDG 9 (Industry, Innovation, and Infrastructure) by encouraging retrofitting practices, promoting sustainable construction industries, and driving the adoption of digital technologies for resource-efficient and environmentally sound industrial processes. Finally, by reducing reliance on virgin materials and minimising waste generation, circular fit-outs contribute to SDG 14 (Life Below Water) and SDG 15 (Life on Land) through biodiversity conservation and reduced ecosystem degradation. Collectively, these direct and indirect contributions highlight the systemic role of circular fit-outs in accelerating progress towards a wide range of interconnected SDGs, thereby emphasising their significance beyond immediate environmental benefits.

4.7 Conclusion

Office fit-outs represent a significant challenge in the built environment due to their recurring nature and high frequency of replacement cycles, which result in significant embodied carbon emissions, waste generation, and continued demand for virgin materials. Yet both the life cycle-based environmental impacts of office fit-outs, and the application of CE principles in this context, have received limited attention in academic research. Although quantitative data on circular office fit-outs remain limited, this chapter synthesises available case studies and highlights that adopting circular strategies can significantly reduce waste generation, lower demand for virgin materials, and mitigate GHG emissions. CE principles such as maximising reuse, design for optimisation, and minimising impacts and waste through low-impact material selection and design for waste prevention, provide pathways toward sustainable office fit-outs, potentially not only delivering GHG emission reductions but also additional value such as lower project costs, accelerated fit-out timelines, improved indoor air quality, enhanced employee wellbeing, and improved environmental reputation through achieving sustainability certifications. Importantly, the transition toward circular fit-outs can be enabled by emerging digital platforms and technologies, including additive manufacturing, BIM, GIS, AI, and material passport systems, which together facilitate tracking of resources, design optimisation, and secondary market development.

Drawing on the identified barriers, strategies, and practices, this chapter provides several actionable insights for advancing circular fit-outs in the built environment. For designers, the adoption of digital technologies enables data-informed decision-making across the design and refurbishment process. Use of such tools facilitates material efficiency, reuse planning, and low-impact material selection. For building owners, the insights highlight the financial and operational advantages of integrating circular strategies, including longer asset lifespans, enhanced adaptability, reduced material procurement costs and improved profile through building certification systems. Encouraging collaboration with suppliers and contractors to adopt digital traceability systems can further strengthen transparency and circular supply chains. For policy makers, it highlights the necessity to establish supportive frameworks that incentivise reuse-based procurement, develop secondary markets, and mandate life cycle data disclosure through DPPs.

Beyond GHG emission reduction, circular fit-outs also align directly and indirectly with the United Nations SDGs, thereby reinforcing their role as a holistic sustainability solution. They contribute directly to the goals of SDG 12 by reducing waste and extending product lifespans, SDG 13 through GHG emission reduction, and SDG 11 by fostering more resource-efficient, resilient, and inclusive office environments. Indirectly, circular fit-outs also contribute to SDGs such as SDG 3, SDG 6, SDG 8, SDG 9, SDG 14, and SDG 15, through their broader impacts on well-being, water, economic opportunities, innovation ecosystems and biodiversity.

References

Abtahi, S. (2006). *Embodied energy of a UK office fit-out* (Publication Number U593828) [M.Sc., University of London, University College London (United Kingdom)]. ProQuest Dissertations & Theses Global. England.

Akanbi, L., Oyedele, L., Davila Delgado, J. M., Bilal, M., Akinade, O., Ajayi, A., & Mohammed-Yakub, N. (2019). Reusability analytics tool for end-of-life assessment of building materials in a circular economy. *World Journal of Science, Technology and Sustainable Development*, *16*(1), 40-55. https://doi.org/10.1108/WJSTSD-05-2018-0041

Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Davila Delgado, M., Bilal, M., & Bello, S. A. (2018). Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation and Recycling*, *129*, 175-186. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.10.026

Armeni, I., Raghu, D., & De Wolf, C. (2024). Artificial Intelligence for Predicting Reuse Patterns. *A Circular Built Environment in the Digital Age*, 57-78.

ARUP. (2025). *Unlocking value in buildings: developing the business case for building circular*. https://www.arup.com/insights/unlocking-value-in-buildings-developing-the-business-case-for-building-circular/

Balasubramanian, S., Shukla, V., Islam, N., & Manghat, S. (2024). Construction Industry 4.0 and Sustainability: An Enabling Framework. *IEEE Transactions on Engineering Management*, *71*, 1-19. https://doi.org/10.1109/TEM.2021.3110427

Balouktsi, M., & Lützkendorf, T. (2016). Energy efficiency of buildings: the aspect of embodied energy. *Energy Technology*, *4*(1), 31-43.

Better Buildings Partnership. (2023). *Circular fitouts toolkit for offices*. https://www.betterbuildingspartnership.com.au/circular-fitout-toolkit-for-offices/

Brandão, R., & Verissimo, L. (2024). Circular Economy Adoption in Construction: A Pathway to Sustainable Development and UN SDG 11 Achievement. In W. Leal Filho, A. L. Salvia, & C. R. Portela de Vasconcelos (Eds.), *An Agenda for Sustainable Development Research* (pp. 213-230). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-65909-6_13

Broadbent, C. (2016). Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy. *The International Journal of Life Cycle Assessment*, *21*(11), 1658-1665. https://doi.org/10.1007/s11367-016-1081-1

Bui, T. T. P., Wilkinson, S., MacGregor, C., & Domingo, N. (2023). Decision making in reducing carbon emissions for building refurbishment: Case studies of university buildings in New Zealand. *Building and Environment*, *242*, 110557. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110557

Bullen, L., & Dowdell, D. (2022). Embodied carbon of New Zealand office and residential building services. *Study Report SR479. BRANZ Ltd*.

Butler, J. (2024). Carbon-friendly office fit-outs. *Build Magazine*, *JUN/JUL 2024*, 56-57. https://www.buildmagazine.org.nz/articles/show/carbon-friendly-office-fit-outs

Camilleri, M. J., & Jaques, R. A. (2001). *Implications of Climate Change for the Construction Sector: Office Buildings*. https://d39d3mj7qio96p.cloudfront.net/media/documents/SR96_Implications_of_climate_change_for_the_construction_sector_-_office_buildings.pdf

Carbon Leadership Forum. (2019). *LCA for low carbon construction: Estimates of embodied carbon for mechanical, electrical, plumbing and tenant improvement* (Summary document, Issue. https://carbonleadershipforum.org/download/3123/

Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular digital built environment: An emerging framework. *Sustainability*, *13*(11), 6348.

Çetin, S., Raghu, D., Honic, M., Straub, A., & Gruis, V. (2023). Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. *Sustainable Production and Consumption*, *40*, 422-437. https://doi.org/https://doi.org/10.1016/j.spc.2023.07.011

Charef, R., & Emmitt, S. (2021). Uses of building information modelling for overcoming barriers to a circular economy. *Journal of Cleaner Production*, *285*, 124854. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.124854

de Almeida Barbosa Franco, J., Domingues, A. M., de Almeida Africano, N., Deus, R. M., & Battistelle, R. A. (2022). Sustainability in the Civil Construction Sector Supported by Industry 4.0 Technologies: Challenges and Opportunities. *Infrastructures*, *7*(3).

Dixit, M. K. (2019). Life cycle recurrent embodied energy calculation of buildings: A review. *Journal of Cleaner Production*, *209*, 731-754. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.10.230

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019a). Dynamic Benchmarking of Building Strategies for a Circular Economy. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012027. https://doi.org/10.1088/1755-1315/323/1/012027

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019b). Potential of Circular Economy in Sustainable Buildings. *IOP Conference Series: Materials Science and Engineering*, *471*(9), 092051. https://doi.org/10.1088/1757-899X/471/9/092051

EEA. (2022). *Investigating Europe's secondary raw material markets*.

Ellen MacArthur Foundation. (2024). *Building Prosperity: Unlocking the potential of a nature-positive, circular economy for Europe*. https://content.ellenmacarthurfoundation.org/m/62e7613596a2d12f/original/Building-Prosperity-July-2024.pdf

European Commission. (2022). *Green Deal: New proposals to make sustainable products the norm and boost Europe's resource independence*

European Union. (2024). *REGULATION (EU) 2024/1781 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL*. Retrieved from https://eur-lex.europa.eu/eli/reg/2024/1781/oj

Fei, W., Opoku, A., Agyekum, K., Oppon, J. A., Ahmed, V., Chen, C., & Lok, K. L. (2021). The critical role of the construction industry in achieving the sustainable development goals (SDGs): Delivering projects for the common good. *Sustainability*, *13*(16), 9112.

Fieldson, R., & Rai, D. (2009). An assessment of carbon emissions from retail fit-out in the United Kingdom. *Journal of Retail & Leisure Property*, *8*(4), 243-258. https://doi.org/10.1057/rlp.2009.16

Fierens, T. (2024). *Bridging the fit-out gap* Delft University of Technology].

Forsythe, P. (2010). Office Buildings-The Importance Of" Make Good", Fitout and Recurring Embodied Energy. SB10: Innovation and Transformation, New Zealand Sustainable Building Conference,

Forsythe, P. (2017). Quantifying the recurring nature of fitout to assist LCA studies in office buildings. *International Journal of Building Pathology and Adaptation*, *35*(3), 233-246.

Forsythe, P., & Ding, K. (2017). Increasing wood based office fitout for sustainable life cycle benefits.

Forsythe, P., & Wilkinson, S. (2015). Measuring office fit-out changes to determine recurring embodied energy in building life cycle assessment. *Facilities*, *33*(3/4), 262-274.

Ghose, A., McLaren, S. J., Dowdell, D., & Phipps, R. (2017). Environmental assessment of deep energy refurbishment for energy efficiency-case study of an office building in New Zealand. *Building and Environment*, *117*, 274-287. https://doi.org/https://doi.org/10.1016/j.buildenv.2017.03.012

Ghose, A., Pizzol, M., McLaren, S. J., Vignes, M., & Dowdell, D. (2019). Refurbishment of office buildings in New Zealand: identifying priorities for reducing environmental impacts. *The International Journal of Life Cycle Assessment*, *24*(8), 1480-1495. https://doi.org/10.1007/s11367-018-1570-5

Goubran, S. (2019). On the role of construction in achieving the SDGs. *Journal of sustainability research*, *1*(2).

Harčárová, K., Vilčeková, S., & Balintova, M. (2020). Building materials as potential emission sources of VOC in the indoor environment of buildings. Key engineering materials,

Hart, J., D'Amico, B., & Pomponi, F. (2021). Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. *Journal of Industrial Ecology*, *25*(2), 403-418. https://doi.org/10.1111/jiec.13139

Heisel, F., & Rau-Oberhuber, S. (2020). Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. *Journal of Cleaner Production*, *243*, 118482. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.118482

Hemmati, M., Messadi, T., Gu, H., & Hemmati, M. (2024). LCA Operational Carbon Reduction Based on Energy Strategies Analysis in a Mass Timber Building. *Sustainability*, *16*(15).

Holøs, S. B., Yang, A., Lind, M., Thunshelle, K., Schild, P., & Mysen, M. (2019). VOC emission rates in newly built and renovated buildings, and the influence of ventilation–a review and meta-analysis. *International Journal of Ventilation*, *18*(3), 153-166.

ISO. (2006). *ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework*. ISO.

JLL Inc. (2025). *Circular design cuts carbon and transforms office fit-outs*. https://www.jll.com/en-uk/guides/circular-design-choices-are-cutting-carbon-and-transforming-office-fit-outs

Knoth, K., Fufa, S. M., & Seilskjær, E. (2022). Barriers, success factors, and perspectives for the reuse of construction products in Norway. *Journal of Cleaner Production*, *337*, 130494. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.130494

López Ruiz, L. A., Roca Ramón, X., & Gassó Domingo, S. (2020). The circular economy in the construction and demolition waste sector – A review and an integrative model approach. *Journal of Cleaner Production*, *248*, 119238. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.119238

Lützkendorf, T., & Balouktsi, M. (2022). Embodied carbon emissions in buildings: explanations, interpretations, recommendations. *Buildings and Cities*. https://doi.org/10.5334/bc.257

MacArthur, E. (2013). Towards the circular economy. *Journal of Industrial Ecology*, *2*(1), 23-44.

Markou, I., Sinnott, D., & Thomas, K. (2025). Current methodologies of creating material passports: A systematic literature review. *Case Studies in Construction Materials*, *22*, e04267. https://doi.org/https://doi.org/10.1016/j.cscm.2025.e04267

Mestre, A., & Cooper, T. (2017). Circular Product Design. A Multiple Loops Life Cycle Design Approach for the Circular Economy. *The Design Journal*, *20*(sup1), S1620-S1635. https://doi.org/10.1080/14606925.2017.1352686

Minunno, R., O'Grady, T., Morrison, G. M., Gruner, R. L., & Colling, M. (2018). Strategies for Applying the Circular Economy to Prefabricated Buildings. *Buildings*, *8*(9).

Morris & Spottiswood Limited. (2025). Modular Office Fit-Out Project Delivers Embodied Carbon Saving Equivalent to Circumnavigating the Glob. https://www.morrisandspottiswood.co.uk/blog/modular-office-fit-out-project-delivers-embodied-carbon-saving-equivalent-to-circumnavigating-the-glob

Nex-Architecture. (2021). *Interview: British Land's Circular Economy Workspace*. Nex-Architecture. https://www.nex-architecture.com/2021/09/case-study-british-lands-circular-economy-workspace/

Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. *Journal of Building Engineering*, *44*, 102704. https://doi.org/https://doi.org/10.1016/j.jobe.2021.102704

Ogunmakinde, O. E., Egbelakin, T., & Sher, W. (2022). Contributions of the circular economy to the UN sustainable development goals through sustainable construction. *Resources, Conservation and Recycling*, *178*, 106023. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.106023

Pomponi, F., Farr, E. R. P., Piroozfar, P., & Gates, J. R. (2015). Façade refurbishment of existing office buildings: Do conventional energy-saving interventions always work? *Journal of Building Engineering*, *3*, 135-143. https://doi.org/https://doi.org/10.1016/j.jobe.2015.07.003

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710-718. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.055

Pomponi, F., & Moncaster, A. (2018). Scrutinising embodied carbon in buildings: The next performance gap made manifest. *Renewable and Sustainable Energy Reviews*, *81*, 2431-2442. https://doi.org/https://doi.org/10.1016/j.rser.2017.06.049

RICS. (2024). Whole life carbon assessment for the built environment. In. London: Royal Institution of Chartered Surveyors (RICS),.

Rios, F. C., Chong, W. K., & Grau, D. (2015). Design for Disassembly and Deconstruction - Challenges and Opportunities. *Procedia Engineering*, *118*, 1296-1304. https://doi.org/https://doi.org/10.1016/j.proeng.2015.08.485

Rodriguez, B. X., Huang, M., Lee, H. W., Simonen, K., & Ditto, J. (2020). Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation. *Energy and Buildings*, *226*, 110324. https://doi.org/https://doi.org/10.1016/j.enbuild.2020.110324

Singh, R., & Lazarus, I. J. (2018). Energy-efficient building construction and embodied energy. In *Sustainability through energy-efficient buildings* (pp. 89-107). CRC Press.

Stathaki, E. (2025). A whopping 92% of this slick London office fit-out came from reused materials. *Wallpaper*. https://www.wallpaper.com/architecture/plp-architecture-circular-office-design-london-uk

Tibaut, A., Rebolj, D., & Nekrep Perc, M. (2016). Interoperability requirements for automated manufacturing systems in construction. *Journal of Intelligent Manufacturing*, *27*(1), 251-262. https://doi.org/10.1007/s10845-013-0862-7

Tleuken, A., Torgautov, B., Zhanabayev, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2022). Design for Deconstruction and Disassembly: Barriers, Opportunities, and Practices in Developing Economies of Central Asia. *Procedia CIRP*, *106*, 15-20. https://doi.org/https://doi.org/10.1016/j.procir.2022.02.148

Tomić, T., & Schneider, D. R. (2018). The role of energy from waste in circular economy and closing the loop concept – Energy analysis approach. *Renewable and Sustainable Energy Reviews*, *98*, 268-287. https://doi.org/https://doi.org/10.1016/j.rser.2018.09.029

UKGBC. (2022). *Insights on how circular economy principles can impact carbon and value*. https://ukgbc.org/wp-content/uploads/2022/08/Whole-Life-Carbon-Circular-Economy-Report.pdf

UKGBC. (2025). *Materials Passports Platforms*. UK Green Building Council. https://ukgbc.org/resources/materials-passports-platforms/

United Nations. (2017). *The sustainable development goals*. Stylus Publishing, LLC.

United Nations Environment Programme. (2023). *Building Materials and the Climate: Constructing a New Future*. https://wedocs.unep.org/20.500.11822/43293

United Nations Environment Programme. (2024). *Global Status Report for Buildings and Construction*. https://www.unep.org/resources/report/global-status-report-buildings-and-construction

van der Heijden, J. (2023). Construction 4.0 in a narrow and broad sense: A systematic and comprehensive literature review. *Building and Environment*, *244*, 110788. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110788

Verhagen, T. J., Sauer, M. L., van der Voet, E., & Sprecher, B. (2021). Matching demolition and construction material flows, an urban mining case study. *Sustainability*, *13*(2), 653.

Walden, J., Steinbrecher, A., & Marinkovic, M. (2021). Digital product passports as enabler of the circular economy. *Chemie Ingenieur Technik*, *93*(11), 1717-1727.

Wilkinson, S., & Reed, R. (2006). Office buildings and the environment: the increasing importance of ESD.

Workman LLP. (2024). *Embodied carbon: our office move delivers 95% savings*. Workman LLP. https://www.workman.co.uk/office-move-carbon-savings/

Zhang, Y., Sattar, S., Cook, D., Johnson, K., & Fung, J. (2024). *Systematic Review of Embodied Carbon Assessment and Reduction in Building Life Cycles*. US Department of Commerce, National Institute of Standards and Technology.

Chapter 5

Climate Change Impacts of Recurring Office Fit-Outs: A Prospective Life Cycle Assessment of Circular Economy-Based Improvements

Preface

Chapter 5 builds on the conceptual foundations established in Chapter 4 by providing a quantitative assessment of circular economy (CE) strategies in office fit-outs. It addresses objectives 1.2 and 1.3, and applies prospective life cycle assessment (pLCA) to address limitations in dynamic LCA accounting approach, enabling the evaluation of how emissions evolve under future technological, socio-economic, and policy conditions. The chapter extends the temporal perspective established in Chapter 3 from the timing of emissions within a building system to changes in emission trajectories under evolving future conditions.

The findings demonstrate how recurring building activities and changing background systems can influence the magnitude and timing of future emissions, providing a building-level basis for considering decarbonisation trajectories over time. This progression in time-differentiated emission accounting provides the foundation for the subsequent research area, which extends the temporal perspective from individual building systems to sectoral climate constraints through time-differentiated carbon budgeting in Chapter 6. Chapter 5 is based on a manuscript developed as part of this doctoral research, with minor adjustments made to ensure consistency with the overall thesis.

Article in under review:
Weerasinghe, S. N., McLaren, S. J., Sacchi, R., Boulic, M., Dowdell, D., & Chandrakumar, C. (forthcoming). Climate Change Impacts of Recurring Office Fit-Outs:

A Prospective Life Cycle Assessment of Circular Economy-Based Improvements. Submitted to International Journal of Life Cycle Assessment

Abstract

Purpose: Buildings with long service life are associated with recurring greenhouse gas (GHG) emissions arising from repeated activities such as refurbishments over time, which can significantly contribute to the cumulative climate change impact. In particular, multi-tenant office buildings, where fit-outs typically occur every 2-10 years, contribute approximately 25% of GHG emissions over the building service life. Such emissions are not adequately represented in conventional static life cycle assessment (LCA) as it does not model future scenarios with changed processes that affect future emissions. This study applies prospective LCA (pLCA) to quantify the climate change impact over the service life of a tenanted office building and assesses the effect of circular economy (CE) strategies using time-differentiated analysis.

Method: An office fit-out case study in Aotearoa New Zealand was modelled using LCA. The climate change impact was initially quantified using static LCA and hotspots were identified for applying CE strategies. Alternative CE strategies were then modelled using static LCA, related to maximising reuse, design for optimisation, and using low-impact materials. Then pLCA was conducted using the *premise* to quantify the future climate change impact by analysing office fit-outs across four fit-out cycles at 10-year intervals, with and without implementation of CE strategies. In addition to the global future scenarios in *premise*, a national electricity decarbonisation pathway was included in the scenario modelling. Sensitivity analyses were conducted to assess the robustness to key assumptions in the evaluated CE strategies and using alternative climate policy pathways.

Results and discussion: The static LCA results showed that office fit-outs in module B5 are dominated by GHG emissions arising from manufacture of replacement materials and components. Implementing all the evaluated CE strategies can reduce the net climate change impact of a single office fit-out - modelled using static LCA - by 17%. However, when modelled using pLCA, the net climate change impact of the final office fit-out is reduced by 56% relative to the same office fit-out modelled using static LCA.

Conclusion: The study shows that pLCA, through dynamic modelling of socio-economic, technology and climate policy pathways, enables a more comprehensive evaluation of future GHG emissions associated with recurring fit-outs in office buildings, and the future mitigation potential of CE strategies that target current GHG emission hotspots. The results highlight the importance of wider changes in socio-economic systems (supported by enabling climate change policy) in reducing the climate change impacts associated with recurring fit-outs of office buildings.

5.1 Introduction

Buildings are characterised by long service lives that often extend over several decades, during which time they continue to use resources as they undergo refurbishments and replacement of materials or components, in response to changing user needs. This is particularly noticeable in multi-tenant office buildings, where tenant turnover leads to more frequent changes compared to other building typologies (Huang, 2018; Rodriguez et al., 2020). Tenant improvements (TI) in multi-tenant office buildings are often driven by customisation of office spaces to meet the tenants' needs by upgrading fixtures, finishes and furniture (Carbon Leadership Forum, 2019; Rodriguez et al., 2020). The drivers include emerging aesthetic trends, corporate branding strategies, policy compliance, and a perceived need to enhance the appeal of spaces for prospective tenants in competitive leasing markets (Forsythe, 2010; Wilkinson & Reed, 2006). These drivers often lead to frequent and premature interior office fit-outs, resulting in significant environmental impacts including GHG emissions (Carbon Leadership Forum, 2019).

On average, studies indicate that office fit-outs typically recur every 2 to 10 years, and the frequency varies according to factors such as geographical location, the scale of the floor area, and the functional purpose of the intervention (Butler, 2024; Camilleri & Jaques, 2001; Dixit, 2019; Fieldson & Rai, 2009; Forsythe, 2017). Empirical studies show that between 46 and 70% of the office floor area in high-rise buildings undergoes refurbishment every 5 years in Melbourne, Australia (Forsythe & Wilkinson, 2015) and every 8.2 years in Sydney, Australia (Forsythe, 2017). Camilleri and Jaques (2001) suggest that in Aotearoa New Zealand, these renewal cycles typically occur in response

to market pressures related to asset value preservation, tenant retention, and operational performance.

Material replacement associated with office fit-outs constitutes a dominant driver of recurring GHG emissions in the lifetime of office buildings. As a consequence of these recurring fit-outs, the effective service life of many fit-out elements is substantially shorter than their technical or designed lifetimes (Casas-Arredondo et al., 2018). Moreover, recurring GHG emissions due to fit outs constitute a significant proportion, approximately 25% of a building's whole-of-life carbon footprint, in multi-tenant office buildings (Butler, 2024; Huang, 2018). Thus, they represent an opportunity for strategic interventions in support of decarbonisation of existing office buildings guided by CE principles (AlJaber et al., 2025; Mathew et al., 2020).

Recent studies have identified and proposed a range of CE strategies aimed at reducing the recurring GHG emissions associated with office fit-outs (Abtahi, 2006; Arredondo & Miguel, 2021; Fierens, 2024; Fini & Forsythe, 2020; Forsythe & Ding, 2017; Itanola et al., 2025; MacArthur, 2013). These strategies can be broadly categorised against the three CE principles introduced by The UK Green Building Council- UKGBC (2022) for construction: (i) maximise reuse, (ii) design for optimisation and, (iii) low-impact material selection. However, to understand the climate change mitigation potential of these different CE strategies, the potential GHG emissions need be quantified in real-world contexts. LCA is an established method for evaluating such emissions - but conventional "static" LCA, as detailed in ISO 14040 and ISO 14044, is limited in this context because it relies on present-day inventory background data. Current approaches using static LCA that simply multiply the emissions from a single fit-out event by the number of expected fit-out occurrences over the building's service life have inherent limitations, as this approach fails to capture the temporal dynamics of socio-economic systems (Collinge et al., 2013; Eberhardt et al., 2019a; McLaren et al., 2025; Negishi et al., 2019; Su et al., 2017). Instead, a time-differentiated methodology is more suitable for quantifying the cumulative climate change impact of recurring fit-outs.

pLCA addresses this limitation by evaluating the recurring emissions at the point of emission in the future based on specified socio-economic, technological and policy pathways (Arvidsson et al., 2018; Bruhn et al., 2023; Sacchi et al., 2022). pLCA has

recently gained attention amongst researchers, and has been used to assess the environmental impacts of building components and infrastructure due to its future-oriented approach in life cycle impact assessment (LCIA) (Bruhn et al., 2025; Horup et al., 2025; Rodrigues et al., 2023; Rodrigues et al., 2024). To operationalise pLCA, this study employed the *premise* software (Sacchi et al., 2022) which is a database modification tool for pLCA (Bruhn et al., 2023). *premise* couples integrated assessment model (IAM) outputs and user-defined scenarios with ecoinvent databases (Wernet et al., 2016) to generate time- and scenario-dependent background inventories. IAM models are used to create scenarios aligned with Shared Socio-economic Pathways (SSPs) and climate pathways developed by the Intergovernmental Panel on Climate Change (IPCC). User-defined scenarios such as country-specific scenarios are additionally useful to better represent national climate pathways. Therefore, this study used Aotearoa New Zealand specific scenario modelling for electricity systems in addition to the global IAM scenarios to improve the decision relevance of the study. Together, use of these models and scenarios enables exploration of climate mitigation strategies whilst accounting for temporal dynamics.

This study therefore investigates the climate change mitigation potential of different CE strategies for recurring office fit-outs, while assessing the effects of temporal dynamics related to socio-economic, technological and climate policy pathways. The study addresses two main objectives. First, it quantifies the climate change impact of a single office fit-out using static LCA and identifies hotspots in order to define specific CE strategies. Second, it assesses the prospective climate change impact of recurring office fit-outs throughout the life of a building and evaluates the mitigation potential of selected CE strategies over this time period.

5.2 Methods

5.2.1 Overview of the Case Study

This study uses data for a real-world office fit-out to quantify recurring GHG emissions over the reference service life (RSL) of the office building. The data were sourced from a Building Research Association of New Zealand (BRANZ) study (Butler, 2024). The inventory represents the actual material composition and quantities of the implemented

office fit-out. The selected office is located in Auckland, Aotearoa New Zealand; it is part of a multi-tenant commercial office building where the fit-out was undertaken at the end of a lease period.

The fit-out elements and materials included in the assessment were selected based on the office fit-out classification provided by the Carbon Leadership Forum (CLF) which categorises interior components according to their functional role (Carbon Leadership Forum, 2019; Huang, 2018). Using this framework, the fit-out was disaggregated into three primary categories: finishes, fixtures, and furniture. Each category was further subdivided into relevant sub-categories and associated materials/elements (Table 5.1).

Table 5.1 Summary of the office fit-out categories, sub-categories and elements assessed in the case study

Category	Sub-category	Material/Element
Finishes	Flooring	Wall tiles, floor sheets, carpet tiles
	Painting	Interior wall paint
Furniture	Office furniture	All types of chairs, tables, stools, workstations, sofas
	Shelving	Lockers
Fixtures	Casework	Benchtops, cabinets and cupboards including joinery
	Doors	Door panels, insulation
	Partition walls	Framing, insulation

5.2.1.1 Modelling Circular Economy Strategies

The CE strategies applied in the study were defined based on the characteristics of the assessed fit-out project, the functional requirements of the office space, and the dominant emission hotspots identified in the baseline assessment (Section 5.3.1). The CE strategies were grouped into three main categories: maximising reuse, design for optimisation, and selection of low-impact materials.

The **maximisation of reuse** strategies focused on fit-out elements with the highest contribution to embodied carbon in the office fit-out (as determined in the baseline assessment, Section 5.3.2). Office furniture and carpet tiles, which have high embodied

emissions, were identified as priority elements for reuse-based strategies. Reuse scenarios were modelled by retaining a proportion of existing elements in subsequent fit-out cycles, thereby avoiding the production of equivalent new elements.

The **design for optimisation** strategies addressed spatial efficiency and functional layout, aiming to reduce material demand without compromising service provision. In this category, shared workspaces and centralised functional areas were modelled as alternatives to conventional, space-intensive layouts. These strategies were modelled with reduced quantities of fit-out materials per net lettable area (NLA).

The **design with low-impact materials** targeted material substitution for high embodied carbon elements. In this category, low-carbon material alternatives were selected for fit-out elements such as caseworks and workstations, based on their reduced life cycle emission intensities. The specific CE strategies applied in each scenario are described in detail in the Results (Section 5.3).

A sensitivity analysis was conducted to examine the robustness of the climate change impact reductions with respect to key assumptions underlying the CE strategies. For each strategy, the most influential variables - such as reuse rates, material demand reduction, and emission intensity of alternative products - were varied using a low, medium, and high scenario. The method utilised was to change one variable while keeping all other variables constant, in order to assess its individual influence on the results. The sensitivity analysis results were analysed to identify which assumptions have the greatest influence on the outcomes.

5.2.1.2 Accounting for the Temporal Dynamics of Recurring Fit-Outs

To capture the influence of temporal dynamics on the recurring emissions of office fit-outs, this study adopts a pLCA approach. Unlike conventional static LCA, this study couples the recurring fit-out cycles with future-oriented life cycle inventories. Future-oriented emission factors were generated using the *premise* software tool (Sacchi et al., 2022), by modifying the ecoinvent life cycle inventories (Wernet et al., 2016) to align with the specific socio-economic climate scenarios from the IAM. In this study,

SSP2 scenarios from the REgional Model of INvestment and Development (REMIND, version 2.1) (Baumstark et al., 2021) were selected to modify the future-oriented life cycle inventories. REMIND was selected due to its detailed representation of global energy systems, technology transitions, and mitigation pathways, which are particularly relevant for construction related materials and energy supply chains. The socioeconomic pathway SSP2 was selected as it is a moderate and widely used baseline scenario, representing a continuation of current socio-economic trends without extreme assumptions. In the SSP2 scenario, a climate policy-based pathway aligned with current Nationally Determined Contributions (NDCs) was included. This pathway reflects the implementation of national mitigation commitments under the Paris Agreement and corresponds to a global mean surface temperature (GMST) increase limit to well below 2 ºC. The NDC scenario was selected because the study focuses on climate change impact and mitigation, and this policy-constrained scenario enables the evaluation of recurring emissions in a future that is consistent with a commonly cited climate target.

While *premise* primarily provides globally consistent scenarios, geographical relevance was enhanced by adjusting the model for country-specific scenarios in Aotearoa New Zealand. In this case study, Aotearoa New Zealand electricity generation projections were included in the model. This was the only activity modelled at the national level for three reasons: (i) electricity is a key input to foreground construction and deconstruction activities during the life cycle of the fit-out; (ii) 80% of materials (by weight) in the case study are imported, and their production is already modelled following IAM-derived regional decarbonisation pathways in the *premise* background system rather than in Aotearoa New Zealand-specific industrial production pathways; and (iii) sufficient, detailed and consistent Aotearoa New Zealand-specific projections for other industrial sectors are not available in a form compatible with IAM pathways. Spatial differentiation was therefore limited to electricity generation affecting foreground processes such as construction and deconstruction activities, and manufacturing of locally sourced elements. The Aotearoa New Zealand electricity generation projections for the years 2020 to 2060 were applied to better represent the country's energy transitions using data in the TIMES-NZ 2.0 developed by EECA (Energy Efficiency & Conservation Authority, 2025).

Finally, a scenario analysis was conducted to assess the influence of the uncertainty in modelling assumption for the selected climate change policy pathway i.e. the NDC scenario. Two other climate change policy pathways which are available in *premise* were modelled under REMIND-SSP2: (i) NPi which represents a continuation of current trends without introducing additional climate mitigation measures; and (ii) PkBudg1000 where cumulative emissions are limited to 1000 $GtCO_2$ by 2100, resulting in a 50% chance of limiting global warming to 1.5 ºC above pre-industrial levels. These scenarios represent different levels of climate policy ambition and were selected to capture a plausible range of future mitigation pathways and associated decarbonisation trajectories.

5.2.2 Life Cycle Assessment

5.2.2.1 Goal and Scope

The goal of this study was to quantify the recurring GHG emissions associated with office fit-outs over their RSL and to evaluate the impacts of CE strategies in reducing these emissions under future socio-economic, technological and policy pathways. The LCA aims to show how accounting for the timing of emissions and changes in emission factors over time influences the assessment of refurbishment-related impacts, compared to conventional static LCA approaches (ISO, 2006a, 2006b). The functional unit is defined as one office fit-out every 10 years in the reference multi-tenanted Aotearoa New Zealand office building with 1,684 m^2 of NLA over a 60-year building RSL, normalised to 1 m^2 NLA.

5.2.2.2 System Boundary

The life cycle of the office fit-out is modelled as a refurbishment activity in the building life cycle and is therefore assigned to module B5 (refurbishment) (CEN, 2019). For transparency, module B5 is disaggregated into study-specific sub modules representing material production (B5.1), transport and installation (B5.2), and end-of-life (EOL) processing (B5.3) associated with each fit-out cycle. This disaggregation is used solely for reporting and does not represent additional EN 15978 modules. Other use stage processes (modules B1-B4 and B6-B7) are outside the scope of this study. The module D potential benefits or loads are separately accounted in the background system (ISO,

2017). Recurring GHG emissions arising from repeated fit-out cycles were modelled dynamically by assuming each refurbishment event occurs every 10 years and applying time-dependent emission factors consistent with selected IAM, SSP and Aotearoa New Zealand electricity generation mix scenarios. The 10-year interval was selected to represent the fit-out replacement cycle because it is consistent with commonly reported service lives of office interior elements in the literature and industry practice (Butler, 2024; Camilleri & Jaques, 2001; Dixit, 2019; Fieldson & Rai, 2009; Forsythe, 2017), and it also aligns with the temporal resolution of the integrated assessment model implemented in *premise*, where future background databases are provided at 10-year time steps. CE strategies were modelled as alternative scenarios relative to the baseline case.

5.2.2.3 Life Cycle Inventory

The life cycle inventory (LCI) of the office fit-out was compiled using a combination of primary and secondary data. Primary data for materials and respective quantities of the fit-out elements were extracted directly from a BRANZ case study (Butler, 2024). These data were modelled using Activity Browser (Steubing et al., 2020), an open-source graphical interface for constructing and analysing LCA models based on the Brightway open-source software package (Mutel, 2017) for LCA written in Python. Activity Browser version 3 with Brightway 2.5 was used to develop the foreground system, link foreground processes with background inventories, and manage scenario-specific databases generated using *premise* 2.3.0 for pLCA.

Based on the material types and quantities extracted from the case study, the refurbishment stage of all assessed fit-out elements was modelled for material manufacturing, transport to construction, installation and deinstallation processes, transport of waste, waste processing and disposal stages. For module B5.1, all fit-out elements were modelled based on their material compositions. Where elements comprised multiple materials (e.g. floor carpets, furniture etc), material composition data were obtained from the Environmental Product Declarations (EPDs) available in the New Zealand National Embodied Carbon Repository ($NECO_2$) (CIL Masterspec, 2025) to disaggregate products into basic materials. These material-specific inventories were then linked to corresponding background processes and modelled using the ecoinvent version 3.11 database with the cut-off system model (Wernet et al., 2016). However, several

elements were excluded from the study to maintain consistency with the scope of the assessed fit-out project. Ceiling systems and finishes applied to the existing concrete floor were excluded as it was assumed they would not be replaced during the 60-year RSL of the building. Decorative paints applied to casework were excluded due to their minor contribution to embodied climate change impacts (Fieldson & Rai, 2009). Electronic equipment, including computers, monitors, and cabling, were excluded as these items are typically managed and replaced independent of fit-out cycles.

Transport associated with refurbishment activities was modelled based on whether elements were locally manufactured or imported, based on the actual fit-out project data. Imported elements were modelled using sea freight from the country of origin to Auckland harbour, followed by road transport to the project site. Sea freight distances were approximated using port-to-port distances derived from publicly available mapping tools, and road transport was modelled using a standard distance of 50 km from the Auckland harbour to the project site.

Installation during refurbishment was modelled including onsite waste generation and electricity consumption during installation. Waste generation rates for individual elements were based on reported values from the original case study and complemented with confirmation by an independent industry expert. Electricity consumption during installation was estimated assuming a six-week refurbishment period, based on a recent industry report (Office Insight, 2025), with national grid electricity used to meet the site demand. Installation energy use is strongly influenced by project management practices and project-specific metered data were not available, and so this assumption was adopted for modelling purposes.

The EOL of the refurbishment of office fit-out was modelled to include activities from de-installation of office fit-outs, transport to waste processing, waste processing and disposal of waste. Deinstallation was modelled following the same approach as in installation. This included transport of de-installed materials from the project site to waste treatment or recovery facilities. Transport was modelled using road freight, with a standard transport distance of 50 km.

Waste processing was modelled at the level of individual elements and their constituent materials, representing the operations required to prepare de-installed materials for

recycling, recovery, or disposal. Waste treatment processes were selected from ecoinvent and included sorting, shredding, pressing, and cleaning where applicable. Waste processing for furniture was not modelled because furniture items were assumed to be either directly reused or disposed of as whole products without intermediate mechanical processing; there is also no reliable data on standardised furniture dismantling processes. However, lockers which consist predominantly of steel, were assumed to be sorted and pressed as scrap prior to recycling. In waste disposal, 100% of timber, 90% of furniture and 15% of the other elements (except for paint) were assumed to be landfilled. All the reusing, recycling and disposal assumptions were aligned with the original case study and further validated by an office interior contractor as reflective of current average industry practices. Notably, the study assumes like-for-like replacement of elements at each refurbishment cycle to ensure the functional unit consistency and comparability, even though it does not fully capture the nature of real-world practice.

Module D was modelled using the cut-off (EN15804) approach to account for the potential benefits and burdens beyond the "end-of-waste state" due to material reuse and recycling. Reused furniture (10%) was assigned the benefits of avoided new furniture production. Recycled elements (85%) were assigned the benefits of avoided primary production minus the burdens for recycling processes. The waste paint was treated as hazardous waste and modelled as disposed via incineration. Module D was reported separately and not included in the aggregated life cycle results, following the EN 15978 standard.

5.2.2.4 Life Cycle Impact Assessment

The modelled LCI data were used to perform the LCIA using Activity Browser. The LCIA was conducted in accordance with ISO 14040, ISO 14044 and EN 15978 to quantify the climate change impact of the office fit-out. The Global Warming Potential over a 100-year time horizon (GWP100, expressed in $kgCO_2eq$) was selected as the primary impact category, and characterisation was performed using the IPCC 2021 characterisation factors relevant for fossil GHG emissions (i.e. GWP-fossil). Biogenic carbon flows associated with timber-based materials were not explicitly modelled in this study, as the primary analytical focus was on fossil GHG emission pathways, temporal dynamics, and technology-driven mitigation strategies in the office fit-outs.

The LCIA was conducted in three main steps. First, the climate change impact of one office fit-out cycle was calculated using the original LCI, representing the first fit-out project taking place in 2020. Second, the LCI was modified to reflect the selected CE strategies, and the corresponding LCIA was performed to quantify their potential mitigation effects. These first two steps represent static LCA using static background data. Third, the LCI was modified using the *premise* tool to reflect projected changes in background systems over time as set out in Section 5.2.1.1. LCIA was then performed for future years to assess the sensitivity of the results to future technological changes and different socio-economic pathways. Figure 5.1 shows the summary of the methodology using both static and prospective LCA.

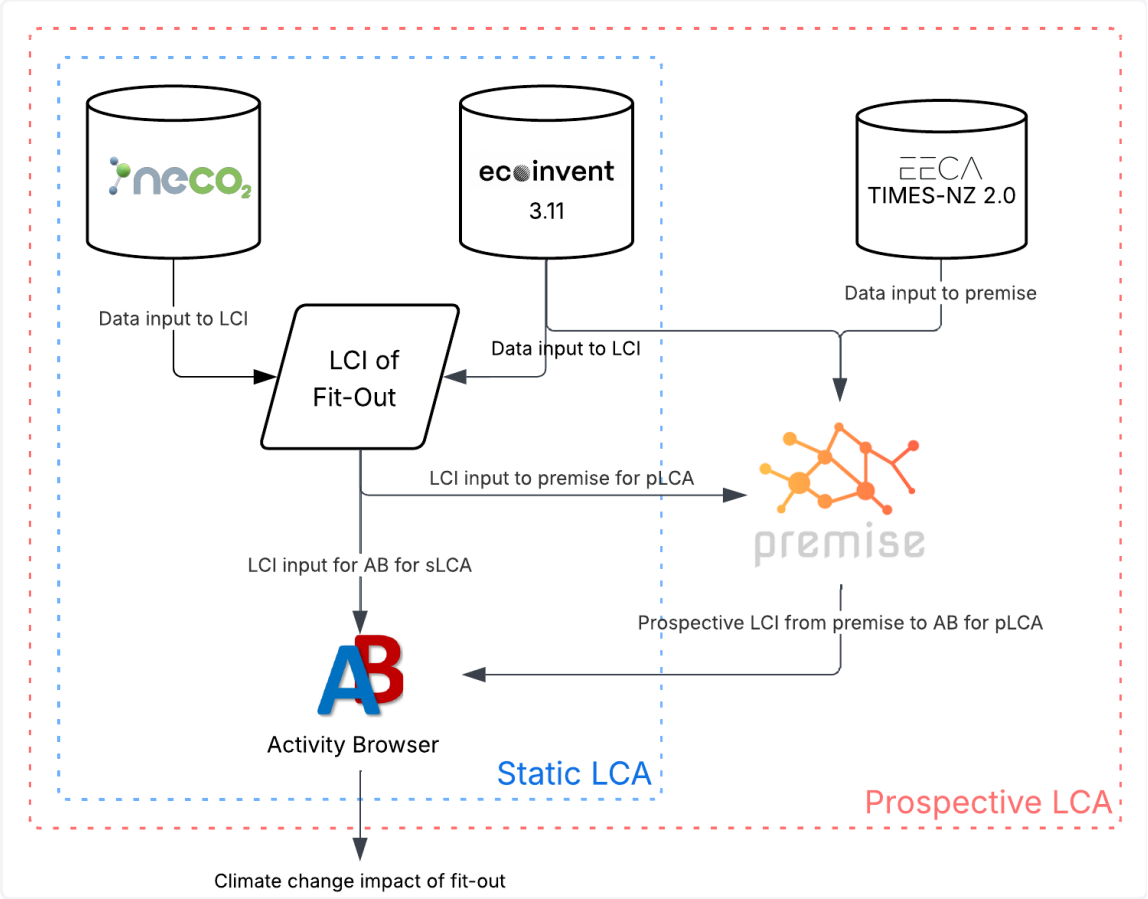


Figure 5.1 Summary of the tools and databases used in the life cycle assessment of the office fit-out

5.3 Results

This section presents the LCA of the office fit-out in four sections. Section 5.3.1 presents the climate change impact of one office fit-out cycle in module B5 and presents the contribution analysis of categories and subcategories of one fit-out to identify major contributors in materials and processes to determine climate change impact hotspots. Section 5.3.2 assesses the effectiveness of the selected CE strategies by quantifying their potential to reduce climate change impact relative to the conventional fit-out, and reports a sensitivity analysis to examine the robustness of the results with respect to key assumptions, including reuse rates and other parameters underlying the CE strategies. Section 5.3.3 assesses the effect of temporal dynamics on the climate change impact of the recurring office fit-out cycles by applying pLCA to account for future changes in background systems. Section 5.3.4 assesses the climate change impact of a circular office fit-out in the future using pLCA.

5.3.1 Identification of Climate Change Impact Hotspots in a Single Office Fit-Out Cycle

The climate change impact (GWP-fossil) of one office fit-out cycle using static LCA is presented in Table 5.2 for 1 m^2 NLA. Most of the emissions occur in the material production (B5.1), which contributes 93% of emissions in module B5. This reflects that the climate change impact of the office fit-out is dominated by the embodied GHG emissions associated with the production of materials and elements. The transport and installation activities (B5.2) and EOL processing (B5.3) contribute 6.5% and <1% respectively of module B5. These activities represent significantly smaller shares relative to B5.1 and thus a less dominant influence on the overall climate change impact. Module D has a net benefit of 24% relative to module B5, reflecting avoided emissions at the production stage due to material recycling and reuse beyond the system boundary.

Table 5.2 Climate change impact (GWP-fossil) of one office fit-out refurbishment cycle

Refurbishment activities	B5.1	B5.2	B5.3	B5.1-B5.3	D
Climate change impact of one fit-out cycle ($kgCO_2eq/m^2$ NLA)	196.30	13.82	1.72	211.84	-49.87

The results indicate that the climate change impact of a single office fit-out is mainly driven by material production rather than material transportation to the site, construction and EOL processes, highlighting the importance of targeting carbon-intensive elements when looking for mitigation opportunities.

To analyse the key contributors to these results, B5.1 was further disaggregated as it represents the largest share of emissions in the office fit-out. In line with the Carbon Leadership Forum (2019) classification, the contributions to B5.1 were classified under finishes, fixtures and furniture. The results show that furniture is the main contributor, accounting for 81% of GHG emissions at B5.1, followed by finishes at 11% and fixtures at 8%. Each of these categories was then further disaggregated to evaluate the subcategory contributions to identify the main hotspots. A summary of these disaggregated contributions of each category and subcategory is presented in Figure 5.2.

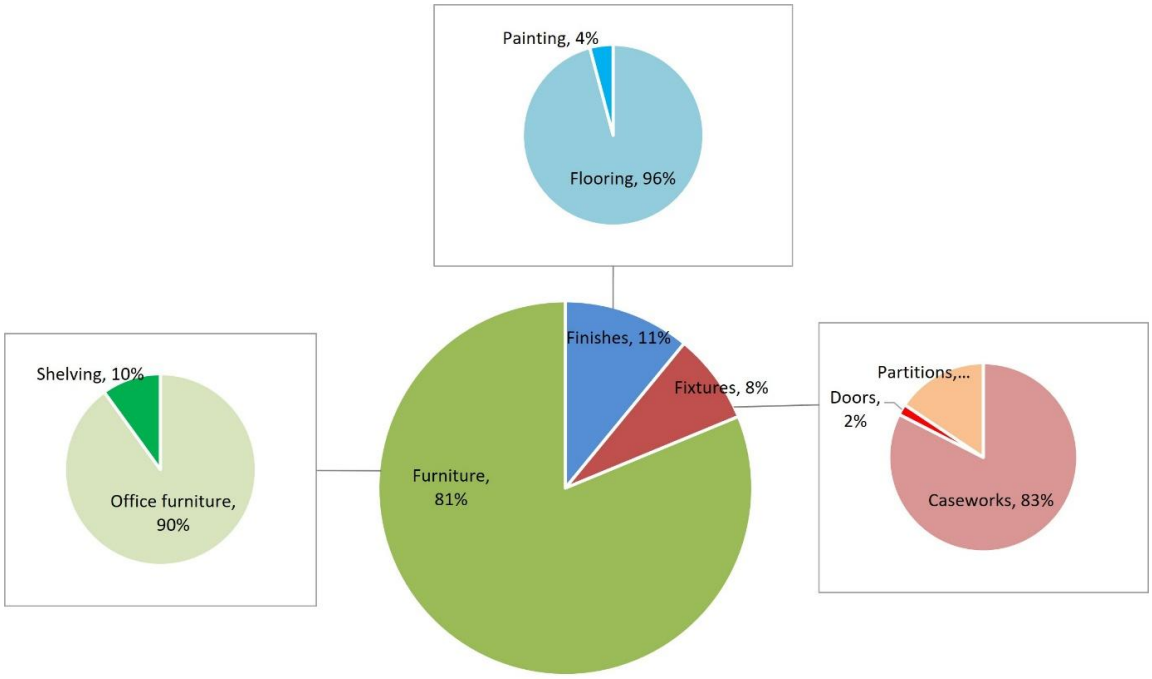


Figure 5.2 Contribution to the refurbishment material production emissions in each element of the office fit-out

Based on these contributions, the key elements driving fossil-GHG emissions at B5.1 were identified and summarised in Table 5.3.

Table 5.3 Percentage contributions of the key contributors to the climate change impact (GWP-fossil) of B5.1

Category	Element/Material	Percentage contribution to the B5.1 climate change (fossil) impact
Furniture	Workstations	22%
	Low seating chairs	39%
	Ergonomic chairs	10%
	Lockers	9%
Fixtures	Medium density fibreboard (MDF) used in caseworks	6%
Finishes	Floor carpet tiles	8%

All other elements individually contributed less than 2%. The dominant elements summarised in Table 5.3 were selected as the focus for the application of the CE strategies in Section 5.3.2.

5.3.2 Potential Climate Change Impact Reductions from CE Strategies

This section introduces the CE strategies modelled in the office fit-out (Section 5.3.2.1), and quantifies the climate change impacts of the modelled CE strategies relative to the baseline case (Section 5.3.2.2). This is followed by a sensitivity analysis to assess the influence of key assumptions underlying the CE strategies on the climate change impacts (Section 5.3.2.3).

5.3.2.1 Modelling of Circular Fit-Outs

Individual CE strategies were assigned to each element based on their technical feasibility and on functional constraints, organised according to the three CE principles introduced in Section 5.2. Table 5.4 summarises each individual CE strategy modelled under each CE principle, together with the modelling assumptions and the rationale for their selection. Each strategy was individually modelled, and then all the individual CE strategies were combined in the CE_ALL strategy in order to assess their cumulative climate change impact.

Table 5.4 Summary of the modelled circular economy strategies

CE principle	Individual strategies to reduce emissions	Elements modelled	Baseline assumption	Modification modelled for the CE strategy	Justification
Maximise reuse	Reuse furniture (CE1.1)	Low seating chairs, workstations, lockers and ergonomic chairs	Current reuse rate of 10%	Reuse rate of 20%	Moderate increase in reuse relative to current practice
	Reuse carpet tiles (CE1.2)	Interface carpet tiles	Current reuse rate of 10%	Reuse rate of 100%	Aligns with industry reuse programme-ReEntry (Interface Inc, 2025; Ministry for the Environment, 2020)
Design for optimisation	Shared workspaces (CE2.1)	Workstations	1:1 workplace to employee ratio	69 workspaces per 100 employees and no other elements changed	European average of hot-desking benchmarks (CBRE Inc, 2024, 2025)
	Centralised common areas (CE2.2)	Caseworks	Original casework	10% reduction in casework demand	Shared workspaces and centralised common areas were assumed to occur without

			demand in the case study		extensive organisational or behavioural change
Low impact materials	Use low carbon MDF boards (CE3.1)	MDF boards	Conventional MDF boards from Australia	Low carbon MDF boards	Sonae Aruco (2022)'s EcoBoard product imported from Europe
	Low carbon workstations (CE3.2)	Workstations	Conventional workstations	Low carbon workstations with 10% reduction in steel content	A moderate approximation while maintaining functional equivalence with the baseline product

5.3.2.2 Climate Change Impact (GWP-fossil) Associated with CE Strategies

Figure 5.3(a) presents the absolute climate change impact of a single office fit-out cycle as baseline case and all the assessed CE strategies in a single fit-out cycle, and Figure 5.3(b) shows the percentage changes relative to the baseline. The CE strategy results vary due to differences in material flows, location of origin, EOL pathways and benefits beyond the system boundary.

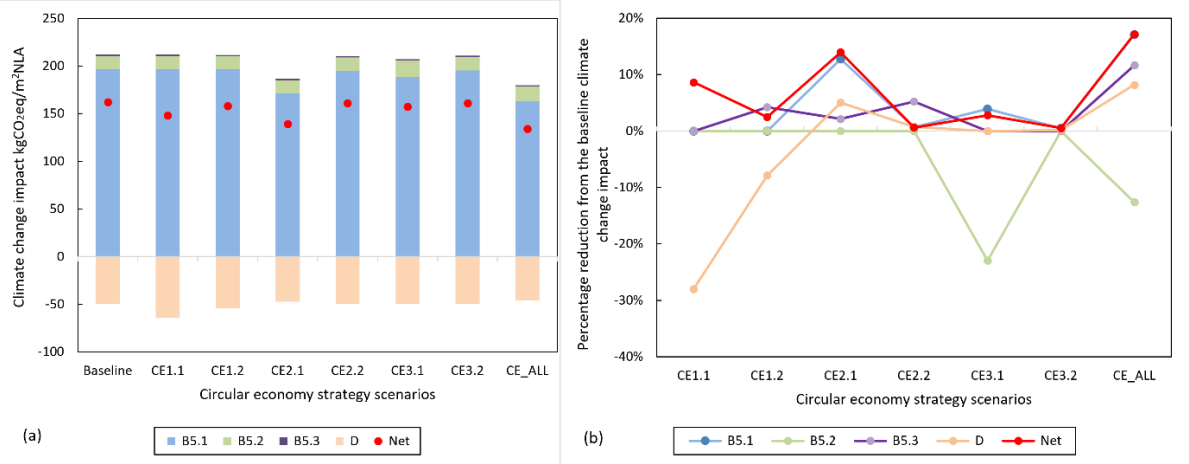


Figure 5.3 Climate change impact (GWP-fossil) of a single office fit-out cycle (a) absolute results of each circular economy strategy (b) percentage relative change of each circular economy strategy compared to baseline (for modules B5.1, B5.2 and B5.3, positive values indicate a reduction in climate change impact relative to the baseline; for module D, positive values indicate a net increase in climate change impact relative to the baseline). The acronyms used to denote the circular economy strategies are defined in Table 5.4

Applying the maximising reuse CE1.1 principle, representing increasing furniture reuse by an additional 10%, leads to a 28% increase in the benefit reported in module D, which reflects the assumption that reused furniture exits the system boundary and displaces new production, while other module B5 activities remain unchanged. As a result, the net climate change impact is reduced by approximately 9%. This reduction is primarily driven by the avoidance of primary material production through increased reuse. CE1.2, which

assumes full reuse of carpet tiles, increases the module D benefit by 8% and reduces emissions in B5.3 by 4%, reflecting the avoided waste processing and disposal associated with tile replacement. This results in an overall reduction of approximately 2% in the net climate change impact. Overall, strategies that focus on maximising reuse primarily influence the climate change impact of the office fit-out through increased benefits beyond the system boundary, while refurbishment emissions are unaffected, resulting in a reduction in net climate change impacts.

Applying the design for optimisation CE 2.1 principle, representing a hot-desking scenario with a reduced number of workstations, leads to a 13% reduction in B5.1 emissions, a 2% reduction in B5.3 emissions, and a 5% reduction in module D benefits, resulting in a net reduction of 14%. This comparatively large reduction reflects the relative magnitude of the contribution of workstations to refurbishment emissions. CE2.2, which reduces the casework and associated MDF products demand by 10% with centralised spaces in the office fit-out, results in only a 1% reduction in B5.1 emissions and corresponding reductions of 5% and 1% in B5.3 and D benefits, respectively, yielding an overall climate change impact reduction of approximately 1%. Overall, strategies that focus on the design for optimisation CE principle primarily influence the climate change impact of the office fit-out through reduced B5.1 emissions due to the reduction in demand for the quantity of materials.

Applying the low impact materials CE principle, CE3.1 which involves the substitution of MDF boards with low-carbon alternatives sourced from Europe, reduces B5.1 emissions by 4% but increases B5.2 emissions by 23% due to additional transport requirements. Despite this increase in transport-related emissions, the net climate change impact is reduced by approximately 3%, indicating that the material-related savings outweigh the additional transport burden. CE3.2, which replaces conventional workstations with low-carbon alternatives with 10% reduced steel content, results in reductions of less than 1% in both B5.1 and D, leading to a net reduction of approximately 1%. Overall, strategies that focus on low impact materials primarily influence the climate change impacts of the office fit-out through reduced B5.1 emissions due to the avoidance of carbon intensive material production.

For CE_ALL, where all individual CE strategies are combined into a single integrated scenario, the cumulative effect is significantly larger. The combined scenario results in a 17% reduction in B5.1 emissions, a 13% increase in B5.2 emissions, a 12% reduction in B5.3 emissions, and 8% reduction in module D benefits. Overall, the combined application of the CE strategies reduces the net climate change impact by approximately by 17% and total module B5 impact (excluding module D) by 15% for a single office fit-out. This highlights the relevance of addressing multiple hotspots simultaneously rather than in isolation.

5.3.2.3 Sensitivity Analysis

The results of the sensitivity analysis are presented for the six CE strategies in Figure 5.4, evaluated under low, medium, and high sensitivity scenarios.

Figure 5.4(a) and (b) represent maximising reuse strategies in CE1.1 and CE1.2 respectively. In CE1.1, the reuse rate of the selected furniture was varied from 10% (low) to 20% (medium) and 30% (high) scenarios. The results show that increasing reuse rates lead to a linear increase in the module D benefit of 56% from the low to high scenario, reducing the net climate change impact by 17% from the low to high scenario. In CE1.2, the reuse rate of floor carpet tiles was varied from 0% reuse with 85% recycling and 15% landfilling (low), to 50% reuse with the rest being recycled (85%) and landfilled (15%) (medium), and 100% reuse rate (high). The results show a 4% reduction in B5.3 emissions, while the module D benefit increases by 8% from the low to high scenario due to the increase in reuse rates. This reduces the net impact by 2% from the low to high scenario. Both CE1.1 and CE1.2 do not change the gross climate change impact for module B5, as the benefits are only accounted in module D. This confirms that direct reuse is significantly more effective than recycling in reducing the climate change impact. Figure 5.4(c) and (d) represents design optimisation strategies for CE2.1 and CE2.2 respectively. In CE2.1, the desk to employee ratio was varied from 83%, (low) to 69% (medium) and 50% (high) which correspond to 1.2, 1.45 and 2 employees per desk respectively. The results show that increases in the employee-to-desk ratio significantly lowers emissions; the B5.1 emissions reduce by 14% from the low to high scenario as fewer workstations are required, and also leads to a 2% reduction in the B5.3 emissions and a 5% reduction in the module D benefit. Overall, a 15% and 13% reduction in net and

gross climate change impact were observed respectively from the low to high scenario. In CE2.2, casework reductions of 0% (low), 10% (medium), and 20% (high) were assessed based on the centralised areas in the office fit-out. The results show a 1% reduction in both the B5.1 net and gross climate change impacts. This effect is smaller than for hot-desking (CE2.1) due to the comparatively lower emissions associated with caseworks compared to the workstations.

Figure 5.4(e) and (f) represents low-impact material strategies in CE3.1 and CE3.2 respectively. For CE3.1, the scenarios assumed use of conventional MDF (low), low-carbon Ecoboard (Sonae Aruco, 2022) imported from Europe (medium), and domestic low-carbon production similar to the Ecoboard (high). The results show that substitution reduces B5.1 emissions by 4% from the low to high scenario, and B5.2 emissions reduce by 10% with local production in the high scenario. The high scenario outperforms the medium scenario, demonstrating the importance of aligning material substitution with low-emission supply chains. The low to high scenario reduces net and gross emissions by 6% and 5% respectively. In CE3.2, the steel content in the workstation was varied with 0% reduction (low), 10% reduction (medium) and 20% reduction (high). The results show a decrease in B5.1 emissions with increasing steel reduction and overall, a 1% reduction from the low to high scenario, and a reduction in both the net and gross climate change impact by 1%.

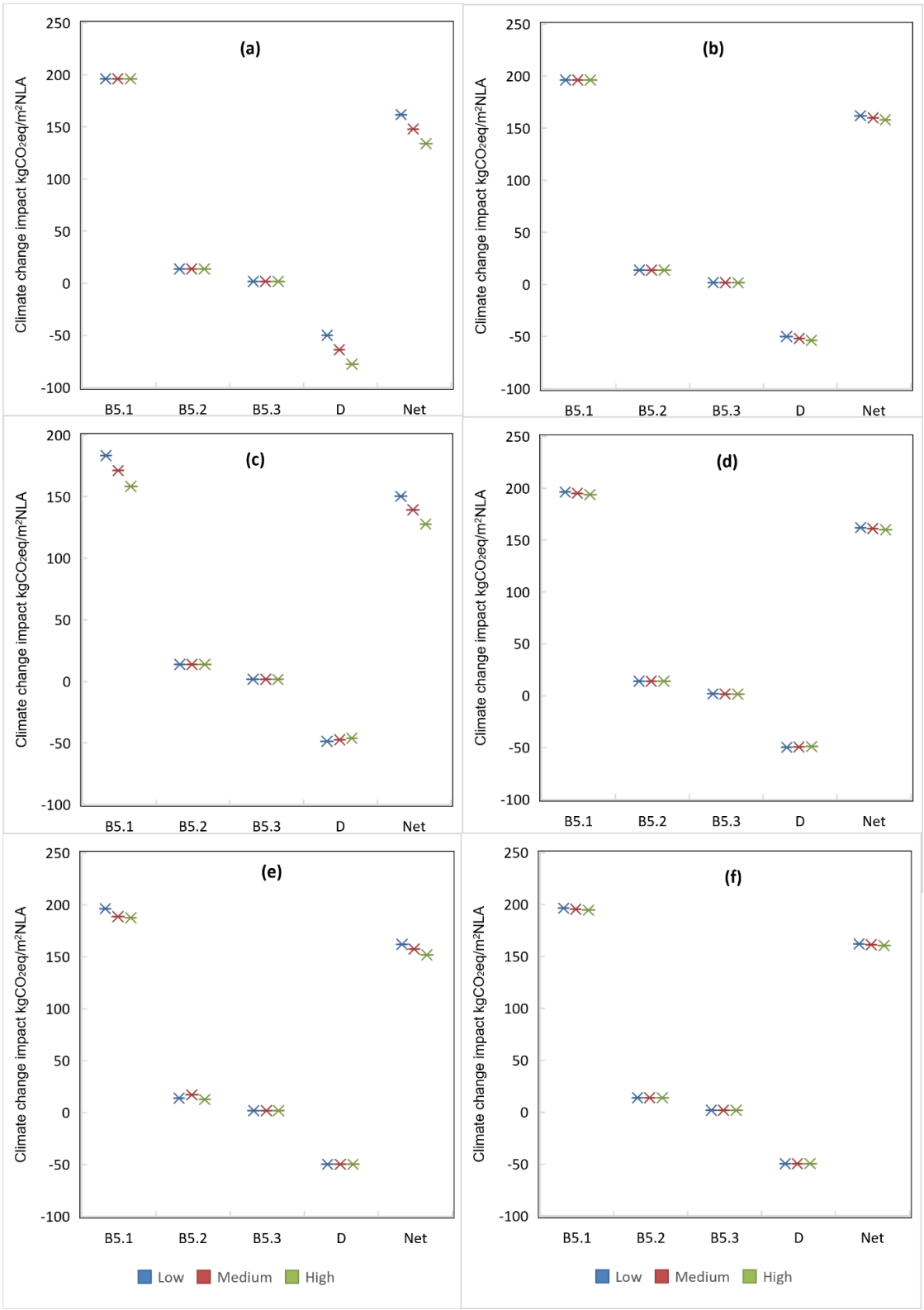


Figure 5.4 Sensitivity analysis results of each circular economy strategy: (a) and (b) maximising reuse strategies CE1.1 and CE1.2; (c) and (d) design for optimisation strategies CE2.1 and CE2.2; (e) and (f) low-impact material selection strategies CE3.1 and CE3.2

An expanded summary of the climate change impacts in the sensitivity analysis is provided in Appendix B. Across all six CE strategies, the reduction in net climate change impact from the low to high scenario varies from 1% to 17%. The largest changes are observed for CE1.1 (17%) and CE2.1 (15%), while CE2.2 and CE3.2 show the smallest change (1%). CE1.2 and CE3.1 show 2% and 6% reductions, respectively. Overall, the sensitivity analysis indicates that the climate change impact of the office fit-out is most sensitive to the reuse rate of office furniture and design optimisation of the office space. Material substitution, while beneficial, has a comparatively smaller effect and is more sensitive to supply chain characteristics such as transport distances from the countries of origin of the low-carbon alternatives.

5.3.3 Prospective Climate Change Impacts of Office Fit-Outs

This section presents the results of the pLCA of the recurring office fit-out cycles focusing on the temporal evolution of recurring emissions and their sensitivity to future decarbonisation pathways. Section 5.3.3.1 quantifies the climate change impact across four successive fit-out cycles and compares them with the static baseline over the same time period. Section 5.3.3.2 assesses the sensitivity of these impacts to alternative climate policy pathways through scenario analysis.

5.3.3.1 Prospective LCA Results of Recurring Office Fit-Outs

Figure 5.5 shows the climate change impact (GWP-fossil) of each successive fit-out cycle under the pLCA modelling. It shows the climate change impact associated with recurring office fit-out cycles for baseline and four subsequent refurbishment cycles over the RSL of office building.

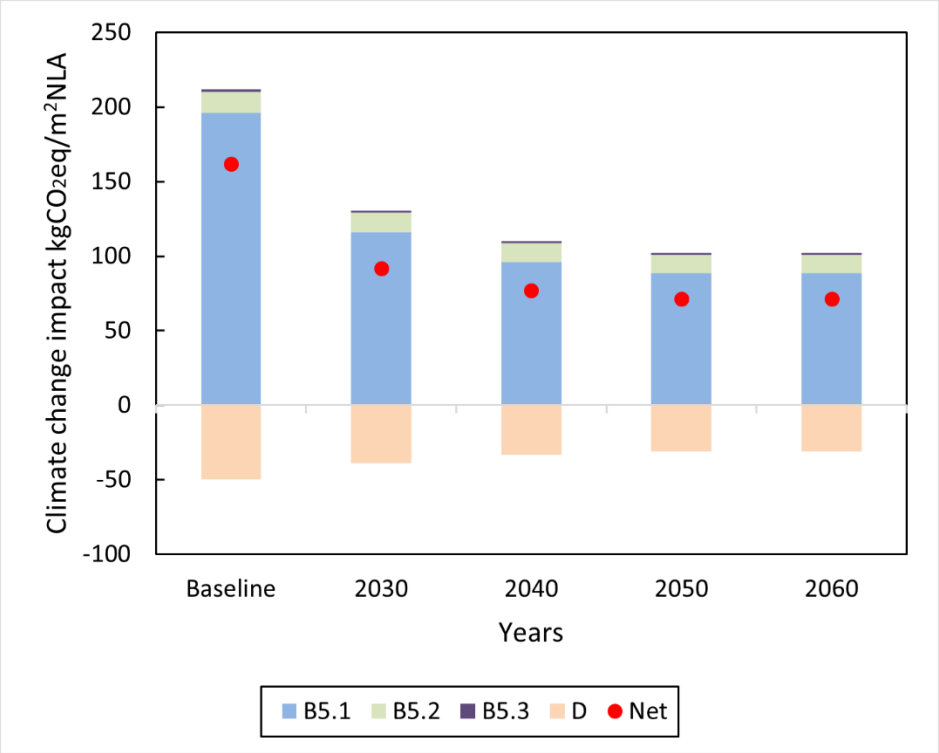


Figure 5.5 Prospective climate change (GWP-fossil) results of each fit-out cycle over the reference service life of the office building

The results show a progressive decline in per-cycle GHG emissions over the years, reflecting the decarbonisation of background system. B5.1 remains the dominant contributor to climate change impact in all fit-out cycles, although its relative contribution decreases substantially over the RSL (by 55%). However, this reduction is not constant over time. The largest decrease occurs between the first two cycles (baseline, 2030), during which the total reduction is 41%, reflecting the rapid decarbonisation of background production processes in this period. In contrast, over the subsequent four fit-out cycles, the rate of reduction slows considerably, with only a further 24% decrease observed. This pattern reflects the rapid early decarbonisation of energy and material supply chains, followed by progressively smaller marginal improvements as the system transitions toward lower-carbon economic systems aligned with the SSP2-NDC pathway. A similar pattern is observed for the other sub-modules of module B5. Emissions from the B5.2 decrease by approximately 10% over the modelled period, reflecting improvements in transport efficiency, logistics, and energy systems under the SSP2-NDC pathway. B5.3 emissions decline by around 25%, driven by increasing decarbonisation of waste treatment processes and low-carbon energy in dismantling, transport, and

treatment operations. In contrast, the benefits reported in module D decrease by 38% over time as background production processes become less emission-intensive, thereby reducing the relative benefit of material recycling and reuse. Consequently, the net climate change impact of the fit-out decreases by about 56% across successive fit-out cycles over the RSL. Notably, between the final two fit-out cycles, changes in all modules remain below 1%, indicating a convergence towards a steady-state emission intensity. This stabilisation reflects the saturation of decarbonisation opportunities under the SSP2-NDC pathway, in which major transitions in energy systems and technologies have largely occurred earlier, and subsequent improvements become incremental. Overall, the results highlight that the long-term climate performance of office fit-outs is greatly affected by the socio-economic and technological transitions represented in the SSP2-NDC scenario.

Comparison between static and prospective LCA results

The GWP-fossil impacts aggregated over all fit-out cycles using the static and prospective LCA approaches, are summarised in Table 5.5. The static LCA results are 71% higher than the pLCA results. This difference arises because the static LCA does not account for anticipated future reductions in the carbon intensity of material production, energy supply, and waste treatment. In contrast, the pLCA incorporates temporal dynamics, including decarbonisation of industrial processes, technological improvements, and socio-economic changes that are represented in the SSP2-NDC pathway. Thus, pLCA highlights the overestimation inherent in static LCAs when potential future changes are ignored.

Table 5.5 Cumulative climate change impact of the office fit-out over the reference service life of office building using static and prospective life cycle assessments

	Climate change impact (GWP-fossil) in kg CO_2eq/m^2 NLA	
Module	**Static LCA**	**Prospective LCA**
B5.1	981.52	585.81
B5.2	69.11	64.09
B5.3	8.61	7.04
D	- 249.35	- 183.27
Gross (B5)	1,059.24	656.94
Net	809.89	473.67

5.3.3.2 Climate Policy Pathway Analysis

Figure 5.6 presents the prospective climate change impact of the office fit-out over successive cycles under three policy pathways: SSP2-NDC, PkBudg1000, and NPi (as described in Section 5.2.1.2). All climate policy pathways show reductions in climate impact over time due to decarbonisation of energy, industrial processes, and socio-economic development, although the magnitude of reduction varies across pathways and sub-modules of module B5.

In B5.1, the cumulative reduction from the baseline case (assumed at year 2020) to the final fit-out cycle is 55% under both NDC and PkBudg1000 climate policy pathways. The NPi pathway shows a slightly lower reduction of 51%, reflecting moderate improvements in global material production efficiencies and energy decarbonisation even in the absence of new additional climate policies. For B5.2, all three pathways exhibit similar reductions (10%), driven primarily by improvements in energy and, transport and logistics efficiency. For B5.3, the climate change impacts are reduced by 25% under the NDC and PkBudg1000 pathways, whereas the NPi pathway achieves a slightly lower reduction of 24%. In module D, which accounts for the benefits of material reuse and substitution, the NDC and PkBudg1000 scenarios show a 38% reduction, while the NPi pathway exhibits a slightly smaller reduction of 33%, reflecting a similar reduction pattern as in B5.1. Overall, the net climate change impact of the successive office fit-outs is reduced by approximately 56% in both the NDC and PkBudg1000 pathways, whereas the NPi pathway achieves a slightly lower reduction of 53%. These differences illustrate the influence of global climate policy pathways on pLCA outcomes: while all pathways benefit from ongoing technological and socio-economic transitions, stronger mitigation policies under the NDC and PkBudg1000 pathways accelerate decarbonisation of production, energy, transport, and EOL processes, thereby enhancing cumulative reductions and module D benefits. However, it is worth noting that both the NDC and PkBudg1000 pathways have similar warming trajectories up to 2060, after which PkBudg1000 stabilises while NDC continues to increase (albeit by only a small amount). As the LCA modelling period of this office fit-out ends in 2060, post-2060 differences do not affect the results, leading to minimal divergence between the NDC and PkBudg1000 pathways within the study timeframe.

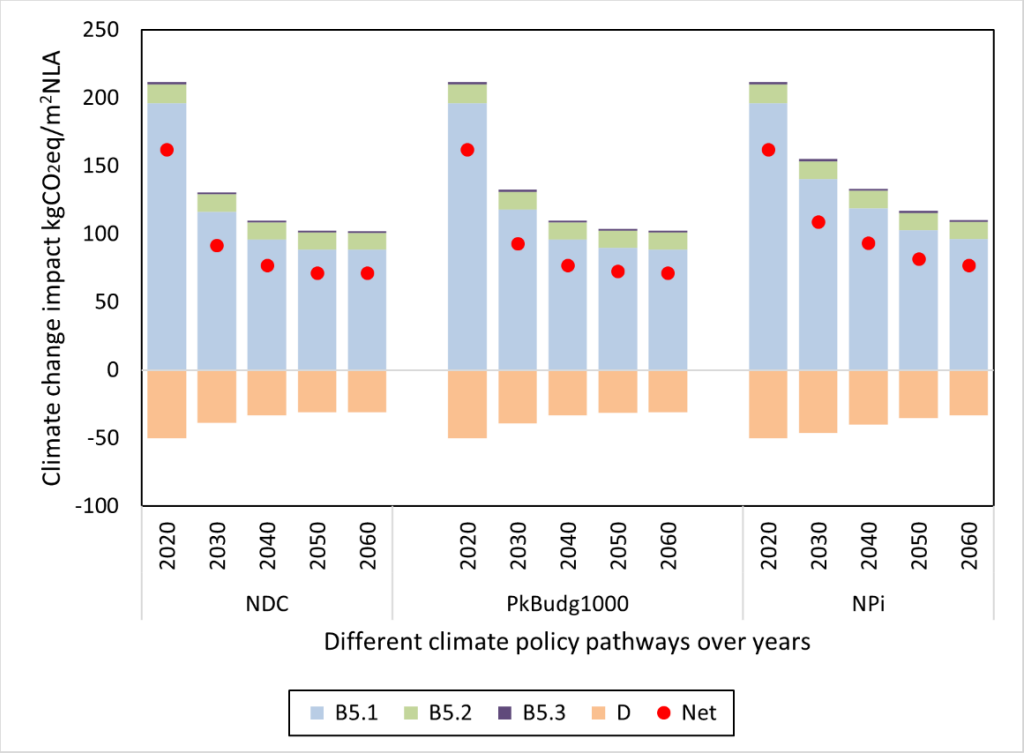


Figure 5.6 Climate change impacts of each office fit-out cycle under different climate policy pathways

5.3.4 Comparison of Future Circular and Conventional Office Fit-Outs

Figure 5.7 shows the temporal evolution of the climate change impact for the conventional fit-out and the combined CE strategy-based fit-out (circular fit-out), all modelled using pLCA under the SSP2-NDC pathway.

The results indicate that circular fit-outs can achieve substantially lower climate change impacts over time compared to a conventional office fit-out, due to the combined effects of increased reuse, design optimisation, low impact materials and background decarbonisation of energy and industrial systems. Relative to the conventional fit-out in the baseline year (assumed to occur in 2020), the circular fit-out in 2060 exhibits a reduction of approximately 60% in B5.1 as a larger fraction of material value is retained within the system through reuse rather than being transferred to subsequent life cycles. B5.2 shows an increase of about 2%, primarily due to longer transport distances associated with selected low-carbon material alternatives. B5.3 reduces by approximately 37%, while the benefits accounted for in module D decrease by about 54%. Overall, these

changes result in a 57% reduction in the net climate change impact of the circular fit-out in another 40 years compared to a conventional fit-out in 2020. These findings highlight that the combination of circular design strategies with long-term technological and socio-economic transitions amplify mitigation potential beyond what can be achieved through background decarbonisation alone, reinforcing the importance of integrating circular economy principles into future office fit-out practices.

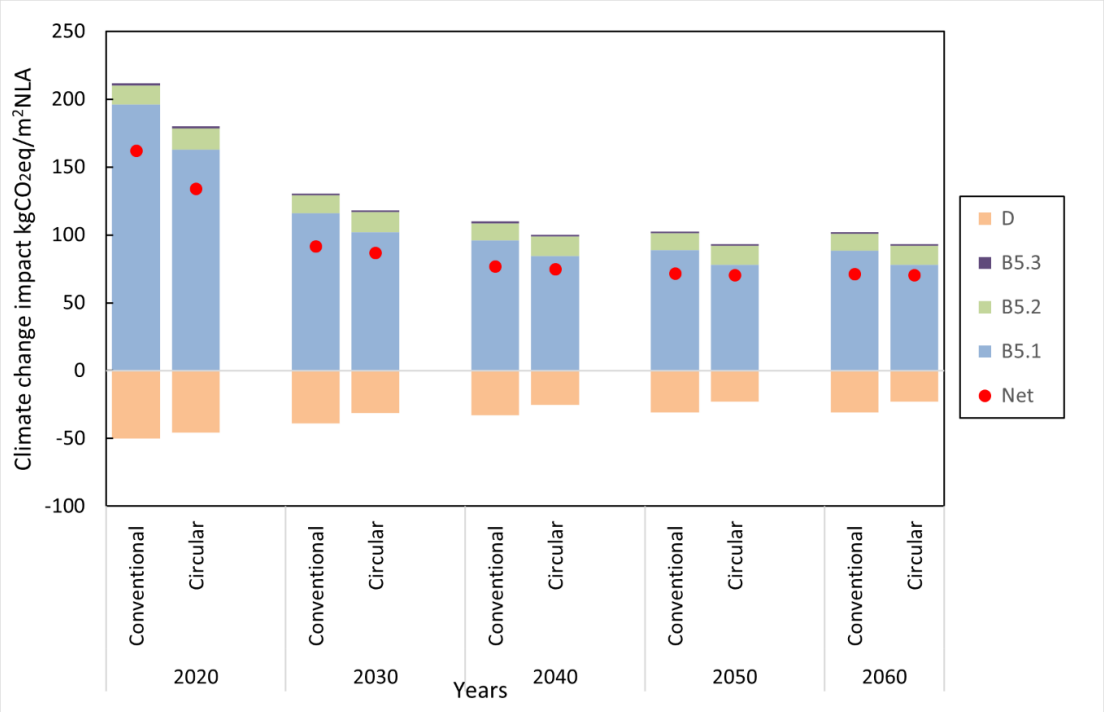


Figure 5.7 Climate change impact of conventional and combined CE strategy-implemented office fit-out cycles under SSP2-NDC scenario using prospective life cycle assessment

5.4 Discussion

5.4.1 Climate Change Impacts of Recurring Office Fit-Outs

Office fit-outs represent a significant and often underestimated source of fossil-GHG emissions in an office building. A single fit-out cycle can have a gross climate change impact of 211.85 $kgCO_2eq/m^2NLA$ (Table 5.2) in a multi-tenant office building, and 93% of this impact is associated with B5.1 rather than B5.2 or B5.3. This is explained by the fact that office fit-outs rely heavily on carbon-intensive elements such as office furniture,

floor finishes, partitions, and casework, which have energy-intensive manufacturing processes and use carbon-intensive materials such as metals, polymers, composites, and engineered wood products. Furthermore, more than 80% of the elements are imported to Aotearoa New Zealand, representing GHG emissions from global manufacturing and transport that are not directly influenced by Aotearoa New Zealand building efficiency improvements. As a result, even highly energy-efficient office buildings may remain carbon-intensive with recurring fit-out emissions. Notably, previous Aotearoa New Zealand research reports total building embodied carbon (excluding office fit-out, mechanical, electrical and plumbing, and module D) in the range of 509-881 $kgCO_2eq/m^2$ gross floor area over a 50-year RSL (Bullen & Dowdell, 2022), whereas the present study estimates 1059 $kgCO_2eq/m^2$ NLA (Table 5.5) attributable solely to office fit-outs across five cycles within a 60-year RSL (using static LCA, excluding temporal dynamics and module D).

Comparing with international studies, Liljenström and Malmqvist (2016) reported 74.5 $kgCO_2eq/m^2$ for an office fit-out in Stockholm, and a subsequent Swedish study of four office fit-out cases reported 93-96 $kgCO_2eq/m^2$ (embodied carbon only) per fit-out (Budiyani, 2023). More recently, a United Kingdom industry study based on 76 projects established a benchmark of approximately 190 $kgCO_2eq/m^2$ GIA (gross internal area) for an office fit-out, with minor and major fit-outs ranging from approximately 164-172 and 208-214 $kgCO_2eq/m^2$ (Overbury, 2024). Kılıç Bakırhan and Tuna (2025), in contrast, reported substantially different cumulative impacts across four office configurations over a 50-year period, ranging from 43.2-365.8 $kgCO_2eq/m^2$, depending on the office configuration and fit-out strategy. Their assessment included interior walls, floors and ceilings and recurring replacement and refurbishment activities, but did not include furniture as a major fit-out component, whereas furniture is included in the present study and contributes substantially to B5.1. The present study estimates 211.85 $kgCO_2eq/m^2$ NLA for a single fit-out cycle, which is comparable in magnitude with the recent United Kingdom benchmark and falls within the reported range for major fit-outs, although it is higher than the earlier Swedish studies. Differences among the reported values are likely to reflect variations in fit-out scope, functional unit, material quantities, inclusion of furniture, geographical context, databases, life cycle modules and refurbishment assumptions. The comparison therefore indicates that the per-cycle impact estimated in

this study is within the range of international evidence when differences in scope and modelling assumptions are considered.

Throughout the RSL of the office building, this study accounted for recurring fit-out cycles at 10-year intervals which corresponds to both the upper (Fieldson & Rai, 2009) and lower (Carbon Leadership Forum, 2019; Huang, 2018) ranges of values reported in the literature. Over such long-time horizons, and particularly when considering buildings with service lives of several decades, it is not realistic to assume that technologies, energy, industrial processes, or supply chains remain the same as those modelled during the first office fit-out. Static LCA, which estimates cumulative impacts by multiplying the impacts of a single fit-out by the number of cycles, therefore risks misrepresenting climate change impacts due to the assumption that background conditions remain unchanged over time. Use of pLCA enables the quantification of each fit-out cycle using time-specific background data and enables exploration of how recurring emissions may change over time, rather than treating them as temporally constant. This methodological approach in quantifying recurring emissions over long time scales represents a key contribution of this study, as most existing studies address recurring emissions through extrapolation, without explicitly modelling temporal dynamics. However, even under ambitious climate policy scenarios, fit-outs will remain a significant contributor to building-related emissions in the future, mainly due to their use of carbon-intensive materials (Figure 5.7). Thus, a reliance on decarbonisation of background systems alone is insufficient to achieve deep reductions in GHG emissions from fit-outs.

The GWP-fossil impact results of this study rely on the data from the ecoinvent database (Wernet et al., 2016) as the pLCA modelling in *premise* requires future-oriented emission factors to be derived consistently from ecoinvent inventories (Sacchi et al., 2022). Therefore, all foreground processes in module B5 including material extraction and processing, manufacturing, transportation, energy use, and EOL were modelled using harmonised ecoinvent datasets rather than manufacturer-reported emission factors for each element. This approach ensures internal consistency across scenarios and enables the representation of future dynamics. However, it also involves generalisation in modelling of the B5.1 elements; real-world product-specific variations - such as manufacturing efficiencies, manufacturer-specific logistics chains, and manufacturer-specific electricity mixes - are not accurately represented. In particular,

furniture production was modelled based on manufacturer-specific EPDs, including material composition and electricity consumption. However, when modelling these in LCI with ecoinvent processes, manufacturer-specific parameters such as their energy sources and process efficiencies could not be represented precisely, particularly regarding process-specific electricity use, material formulations, and local manufacturing practices. Therefore, the actual magnitude of the results should be interpreted with caution, as they are subject to underlying modelling, database, and scenario choices. Nevertheless, the approach allows for exploratory comparison of strategies, assessment of temporal dynamics, and evaluation of mitigation potential under varying socio-economic and technological pathways, which aligns with the primary objectives of this study.

5.4.2 Circular Office Fit-Outs as a Mitigation Strategy in the Building Sector

The findings of this study reinforce the growing evidence that CE principles are aligned with climate mitigation strategy in the building sector (Akanbi et al., 2018; Eberhardt et al., 2019c; Eberhardt et al., 2022; Gallagher et al., 2017; MacArthur, 2013; Minunno et al., 2018; Norouzi et al., 2021; Pomponi & Moncaster, 2017). The CE strategies assessed in this study showed mitigation potentials although their magnitudes are depended upon underlying assumptions. The study shows that their effectiveness is highly dependent on context-specific factors, including reuse rates, transport distances to manufacturing facilities, and working-from-home practices. Thus, circular fit-out strategies operate through distinct mechanisms whose effectiveness is strongly context-dependent. However, rather than acting through a single dominant mechanism, the greatest mitigation benefits arise from implementing a range of CE strategies. The success of CE strategies is, moreover, driven not only by technological change, but also in many cases additionally by organisational and individual stakeholder decisions. These influence, for example, facility management practices including whether elements are reused or discarded, and workplace policies and behaviour including the willingness of office workers to co-share workspaces. And the effectiveness of these measures is enabled by the availability of appropriate infrastructure, supportive governance mechanisms, and climate-aligned building policies. Consequently, circular fit-outs should be understood less as an isolated technical intervention and more as a collaborative effort that reshapes

material flows, procurement practices, and standardisations within the building sector (Bui et al., 2023; Eberhardt et al., 2022; Kanters, 2020).

Importantly, this study focused on climate change impacts arising from fossil fuel emissions only, and did not include consideration of biogenic carbon storage and emissions. Accounting for biogenic carbon could make a substantial difference to the results depending upon the methodology used, and whether timber is sourced from sustainable or unsustainable forestry systems (see, for example, building studies by (Hoxha et al., 2020; Ouellet-Plamondon et al., 2023)). Also, the investigated CE strategies may involve trade-offs with other environmental impact categories which could influence the overall sustainability performance.

Maximising reuse strategies

The importance of reuse as a mitigation strategy in this study reflects the importance of extending material lifetimes in reducing embodied GHG emissions (Mequignon et al., 2013; Palacios-Munoz et al., 2019). By deferring the need for new production, reuse shifts the dominant climate benefit beyond the system boundary and into future life cycles. Therefore, for reuse to be effective as a near-term mitigation strategy, it must be implemented in current practices. In other words, use of second-hand furniture, reclaimed components, or repurposed elements should be prioritised immediately as opposed to manufacturing new items that are designed for future reuse. This highlights the importance of having effective reuse and repurposing infrastructure, such as furniture reuse schemes (Gondaliya et al., 2023) and second-hand marketplaces. Initiatives such as ReEntry (Interface Inc, 2025; Ministry for the Environment, 2020) play a critical role in operationalising CE strategies by connecting supply and demand for reusable components. Moreover, public policy support is essential to scale such systems, for example by supporting robust and regulated digital product passport schemes (Çetin et al., 2023; Markou et al., 2025; UKGBC, 2025; Walden et al., 2021), providing incentives for reuse, and developing standards that facilitate the certification and acceptance of reused products. Without these enabling conditions, the theoretical climate benefits associated with reuse may not be realised on the timescales required for addressing the climate change crisis.

At the same time, however, it should be noted that higher reuse rates may be associated with increased maintenance, repair, or replacement during the use phase. These were not accounted for in this study and could partially offset the estimated climate benefits.

Design for optimisation strategies

Strategies aimed at optimising design, such as improving workplace layouts and centralised common areas, were also found to reduce net emissions by 14% and 1% respectively, primarily by decreasing the overall quantity of materials required for each office. Unlike reuse, which reallocates emissions across subsequent life cycles, demand reduction directly reduces GHG emissions in the B5.1 and B5.2 sub-modules without changing the product composition and production technology. This highlights the importance of facility management in organisations for implementing circularity (Lundgren et al., 2024). While such measures may be constrained by organisational culture and user acceptance (Rotimi & Rasheed, 2024), they offer a convenient pathway to reduce GHG emissions that do not depend on downstream recycling or reuse markets. The results of this study therefore imply that shared workspaces and functional optimisation should be considered core CE strategies for office fit-outs, rather than secondary or optional measures.

At the same time, however, it should be noted that this study was limited to modelling a reduced demand for workstations as a single variable. The study excluded potential rebound effects which may arise from increased residential energy use associated with working-from-home practices (Sepanta et al., 2024), and reduced commuter-related transport (thinkstep Ltd, 2022) Capturing such effects would require a broader system boundary that integrates commercial, residential and transport-related energy use and a revised functional unit (e.g. the number of employees associated with an office over a year). The relevance of such rebound effects is supported by guidance from the Ministry for the Environment (2024a), which provides dedicated emission factors for employees working from home that include electricity use for home office equipment, lighting, and additional heating, where applicable. It is clear that the magnitude of such effects is context dependent.

Previous studies suggest that increased remote and hybrid working can reduce the demand for traditional office space and potentially displace the need for future office construction

by enabling workspace downsizing or consolidation (Hensher et al., 2023). For example, an empirical study in the United States found that the relationship between teleworking and building space requirement showed work-from-home can significantly lower the average office floor area required per worker by 44%, implying a potential contraction in future office space requirements if remote working becomes a sustained practice (Liu et al., 2024). However, this study only modelled the reduced number of workstations and excluded consideration of the "spared" space to ensure comparability across the scenarios. This approach reflects a conservative system boundary and avoids introducing additional assumptions regarding long-term organisational space utilisation, or rebound effects, which remain highly context dependent.

Low impact material strategies

Low impact material substitution strategies deliver mitigation benefits immediately and entirely within the life cycle of a single office fit-out (Cabeza et al., 2013). Their uptake is therefore based on technological innovation rather than also requiring systemic organisational and user behavioural changes, as occurs with maximising reuse strategies and design for optimisation strategies. However, this study also shows that the mitigation effectiveness of material substitution depends on the geographical location of low-carbon material production, as long-distance sourcing may have potential to offset the climate benefits through additional transport emissions. Moreover, the use of lower-carbon alternatives may introduce trade-offs with other environmental impact categories such as ecotoxicity and human toxicity (Rey-Álvarez et al., 2022). For example, alternative materials may involve more intensive chemical processing, have reduced durability, and require different EOL management options, potentially merely shifting burdens rather than reducing them.

5.4.3 Prospective LCA for Modelling Future Background Systems

This study shows that additional insights are gained by incorporating temporal dynamics into the assessment of recurring building emissions. When emissions recur and buildings deliver services over multiple decades, both foreground and background systems are subject to change. The technological dynamics are coupled with socio-economic and political dynamics, including shifts in climate policies, economy, and social conditions.

Therefore, a single assumption of static emission intensities is misaligned with the likely reality of future scenarios. Static life cycle approaches that extrapolate current impacts across future cycles therefore over- or under-state cumulative emissions and potentially misinform decisions about mitigation strategies.

The pLCA adopted in this study enables recurring emissions of buildings to be aligned dynamically with changes in both foreground and background systems. Furthermore, the *premise* tool enhances the accuracy of pLCA modelling by integrating IAM, SSPs and climate change policy pathways into background system (Sacchi et al., 2022). In the absence of such automated coupling, pLCA of recurring building processes would require extensive manual adjustment of emission factors across future energy, material, and transport systems, which is both resource-intensive and difficult to implement consistently. *premise* therefore constitutes a key enabling infrastructure for applying pLCA at the building scale, where long lifetimes and recurring interventions interact with rapidly evolving background system (Bruhn et al., 2023). At the same time, this approach has several limitations. IAMs, due to their global scale, are necessarily based on relatively generic spatial, sectoral and technological assumptions, and model scenarios rather than accurate predictions. Consequently, the data does not represent local, sector-specific variables - which could be significant for real-world building emissions.

To partially address this limitation, this study introduced country-specific electricity generation forecast (Energy Efficiency & Conservation Authority, 2025) within *premise* to better reflect the national energy policy context. This refinement improves the representativeness of foreground system energy data in the case study, particularly in B5.2 and B5.3 sub-modules where electricity-related processes have a central role. Incorporating localised electricity scenarios therefore enhances the policy relevance and contextual validity of pLCA results.

5.4.4 Temporal Assessment of Mitigation Pathways

In addition to representing future technological and socio-economic transitions, the pLCA approach enables a time-differentiated interpretation of emissions. By coupling recurring foreground activities with temporally evolving background systems generated via *premise*, emissions are quantified according to their timing. This temporal resolution is imperative to assess the achievability of finite carbon budgets, including remaining

carbon budgets under climate policy pathways, where the timing of emissions influences the accumulation of carbon debt and when budgets are exceeded (Weerasinghe et al., 2026). Strategies that shift, delay, or reduce emissions at different points in time may have distinct climate change implications despite similar cumulative totals. Current strategies that delay or shift emissions along timelines can be assessed by modelling time-differentiated emissions using pLCA, and comparing them with remaining carbon budgets over different time horizons.

5.5 Conclusions

This study demonstrates how pLCA can be used to assess GHG emissions from recurring office fit-outs over long time periods, and the future impacts of CE strategies that target current climate change impact hotspots. By integrating LCI modelling with forward-focused foreground and background scenarios, the study provides insights beyond static representation of office fit-outs.

First, the study demonstrates that effective CE implementation in office fit-outs must prioritise material-intensive elements, as approximately 93% of the gross climate change impact is concentrated in the manufacturing of fit-out elements (B5.1). This finding indicates that mitigation potential is not evenly distributed across the fit-out life cycle, but is dominated by repeated production of fit-out elements. Second, this study shows that accounting for future changes in technology and socio-economic systems can significantly alter the climate change impact of recurring office fit-outs; static whole-of-life building LCA results may overstate the climate change impact by assuming static emission intensities persist into the future whereas pLCA demonstrates how both the magnitude and timing of emissions change when background systems decarbonise (or not) over time. Third, the pLCA results show that the relative effectiveness of CE strategies is not fixed, but is dependent on when emissions occur and how strongly they interact with future background system improvements. Thus, pLCA provides information that extend beyond conventional static LCA to highlight the critical importance of realising ambitious climate policy pathways as well as supporting more informed choices about implementation of alternative CE strategies.

Based on the contributions and limitations of this study, priorities for future research are: (i) assessing the whole-of-life building climate change impacts using pLCA; (ii) assessing the wider environmental trade-offs associated with CE strategies; (iii) incorporating more localised modelling dynamics into pLCA modelling (e.g. for Aotearoa New Zealand-based sectors such as cement, steel and glass); (iv) exploring alternative socio-economic and policy pathways; and (v) integrating biogenic carbon storage and emissions into the analysis alongside fossil emissions to provide a more comprehensive understanding of the climate impacts of office fit-outs and their CE strategies. Moreover, future research could explore the transferability of this approach beyond the Aotearoa New Zealand context and to other product systems.

References

Abtahi, S. (2006). *Embodied energy of a UK office fit-out* (Publication Number U593828) [M.Sc., University of London, University College London (United Kingdom)]. ProQuest Dissertations & Theses Global. England.

Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Davila Delgado, M., Bilal, M., & Bello, S. A. (2018). Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resour. Conserv. Recycl.*, *129*, 175-186. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.10.026

AlJaber, A., Martinez-Vazquez, P., & Baniotopoulos, C. (2025). Exploring Circular Economy Strategies in Buildings: Evaluating Feasibility, Stakeholders Influence, and the Role of the Building Lifecycle in Effective Adoption. *Appl. Sci.*, *15*(3), 1174. https://www.mdpi.com/2076-3417/15/3/1174

Arredondo, C., & Miguel, J. (2021). *Circular economy and office fit-out: an analysis for office fit-out processes based on material flows* UCL (University College London)].

Arvidsson, R., Tillman, A. M., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D., & Molander, S. (2018). Environmental assessment of emerging technologies: recommendations for prospective LCA. *J. Ind. Ecol.*, *22*(6), 1286-1294.

Baumstark, L., Bauer, N., Benke, F., Bertram, C., Bi, S., Gong, C., Dietrich, J., Dirnaichner, A., Giannousakis, A., Hilaire, J., Klein, D., Koch, J., Leimbach, M., Levesque, A., Madeddu, S., Malik, A., Merfort, A., Merfort, L., Odenweller, A., & Luderer, G. (2021). *REMIND2.1: Transformation and innovation dynamics of the energy-economic system within climate and sustainability limits*. https://doi.org/10.5194/gmd-2021-85

Bruhn, S., Sacchi, R., Cimpan, C., & Birkved, M. (2023). Ten questions concerning prospective LCA for decision support for the built environment. *Build. Environ.*, *242*, 110535. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110535

Bruhn, S., Sacchi, R., Horup, L. H., Zindel, A., & Birkved, M. (2025). Historical and Future Lca Insights on Residential Buildings in Denmark. *Available at SSRN 5101422*. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5101422

Budiyani, A. G. (2023). Embodied carbon and waste generation of building refurbishment: Case studies of office fit out in Sweden. In.

Bui, T. T. P., Wilkinson, S., MacGregor, C., & Domingo, N. (2023). Decision making in reducing carbon emissions for building refurbishment: Case studies of university buildings in New Zealand. *Build. Environ.*, *242*, 110557. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110557

Bullen, L., & Dowdell, D. (2022). Embodied carbon of New Zealand office and residential building services. *Study Report SR479. BRANZ Ltd*.

Butler, J. (2024). Carbon-friendly office fit-outs. *Build Magazine*, *JUN/JUL 2024*, 56-57. https://www.buildmagazine.org.nz/articles/show/carbon-friendly-office-fit-outs

Cabeza, L. F., Barreneche, C., Miró, L., Morera, J. M., Bartolí, E., & Inés Fernández, A. (2013). Low carbon and low embodied energy materials in buildings: A review. *Renew. Sustain. Energy Rev.*, *23*, 536-542. https://doi.org/https://doi.org/10.1016/j.rser.2013.03.017

Camilleri, M. J., & Jaques, R. A. (2001). *Implications of Climate Change for the Construction Sector: Office Buildings*. https://d39d3mj7qio96p.cloudfront.net/media/documents/SR96_Implications_of_climate_change_for_the_construction_sector_-_office_buildings.pdf

Carbon Leadership Forum. (2019). *LCA for low carbon construction: Estimates of embodied carbon for mechanical, electrical, plumbing and tenant improvement* (Summary document, Issue. https://carbonleadershipforum.org/download/3123/

Casas-Arredondo, M., Croxford, B., & Domenech, T. (2018). Material and decision flows in non-domestic building fit-outs. *J. Clean. Prod.*, *204*, 916-925. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.08.328

CBRE Inc. (2024). *Office occupier bennchmark report*.

CBRE Inc. (2025). *2024-2025 CBRE Global Workspace & Occupancy Insight*.

CEN. (2019). EN 15804:2012+A2:2019 Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products. In. Brussels: European Committee for Standardization.

Çetin, S., Raghu, D., Honic, M., Straub, A., & Gruis, V. (2023). Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. *Sustainable Production and Consumption*, *40*, 422-437. https://doi.org/https://doi.org/10.1016/j.spc.2023.07.011

CIL Masterspec. (2025). *National Embodied Carbon Repository*. https://www.neco2.co.nz/

Collinge, W. O., Landis, A. E., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2013). Dynamic life cycle assessment: framework and application to an institutional building. *Int. J. Life Cycle Assess.*, *18*(3), 538-552. https://doi.org/10.1007/s11367-012-0528-2

Dixit, M. K. (2019). Life cycle recurrent embodied energy calculation of buildings: A review. *J. Clean. Prod.*, *209*, 731-754. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.10.230

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019a). Dynamic Benchmarking of Building Strategies for a Circular Economy. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012027. https://doi.org/10.1088/1755-1315/323/1/012027

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019b). Potential of Circular Economy in Sustainable Buildings. *IOP Conference Series: Materials Science and Engineering*, *471*(9), 092051. https://doi.org/10.1088/1757-899X/471/9/092051

Eberhardt, L., Birkved, M., & Birgisdottir, H. (2022). Building design and construction strategies for a circular economy. *Arch. Eng. Des. Manag.*, *18*(2), 93-113. https://doi.org/10.1080/17452007.2020.1781588

Energy Efficiency & Conservation Authority. (2025). *New Zealand Energy Scenarios TIMES-NZ 2.0*. Energy Efficiency & Conservation Authority,. https://www.eeca.govt.nz/insights/data-tools/new-zealand-energy-scenarios-times-nz/

Fieldson, R., & Rai, D. (2009). An assessment of carbon emissions from retail fit-out in the United Kingdom. *Journal of Retail & Leisure Property*, *8*(4), 243-258. https://doi.org/10.1057/rlp.2009.16

Fierens, T. (2024). *Bridging the fit-out gap* Delft University of Technology].

Fini, A. A. F., & Forsythe, P. (2020). Barriers to reusing and recycling office fit-out: An exploratory analysis of demolition processes and product features [Journal Article]. *Construction Economics and Building*, *20*(4), 42-62. https://doi.org/10.5130/AJCEB.v20i4.7061

Forsythe, P. (2010). Office Buildings-The Importance Of" Make Good", Fitout and Recurring Embodied Energy. SB10: Innovation and Transformation, New Zealand Sustainable Building Conference,

Forsythe, P. (2017). Quantifying the recurring nature of fitout to assist LCA studies in office buildings. *International Journal of Building Pathology and Adaptation*, *35*(3), 233-246.

Forsythe, P., & Ding, K. (2017). Increasing wood based office fitout for sustainable life cycle benefits.

Forsythe, P., & Wilkinson, S. (2015). Measuring office fit-out changes to determine recurring embodied energy in building life cycle assessment. *Facilities*, *33*(3/4), 262-274.

Gallagher, J., Basu, B., Browne, M., Kenna, A., McCormack, S., Pilla, F., & Styles, D. (2017). Adapting Stand-Alone Renewable Energy Technologies for the Circular Economy through Eco-Design and Recycling. *J. Ind. Ecol.*, *23*(1), 133-140. https://doi.org/10.1111/jiec.12703

Gondaliya, A., Ong, E., Wu, J., Jepsen, S., & Saatchi, S. (2023). Towards Zero Waste: An Environmental Life Cycle Analysis of New Furniture vs Participation in the Furniture Reuse Program.

Hensher, D. A., Wei, E., & Beck, M. J. (2023). The impact of COVID-19 and working from home on the workspace retained at the main location office space and the future use of satellite offices. (0967-070X (Print)).

Horup, L., Bruhn, S., Hoxha, E., Birgisdottir, H., Secher, A. Q., Ohms, P., & Hauschild, M. (2025). Absolute sustainability assessment of the Danish building sector through prospective LCA. *Science of The Total Environment*, *966*, 178780. https://doi.org/https://doi.org/10.1016/j.scitotenv.2025.178780

Hoxha, E., Passer, A., Saade, M. R. M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., & Habert, G. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. *Build. Cities*, *1*(1), 504-524.

Huang, M., Simonen, K., Ditto, J. (2018). *Life Cycle Assessment (LCA) for Low Carbon Construction: Tenant Improvements in Commercial Office Buildings, Final Report*.

Interface Inc. (2025). *REENTRY*. https://www.interface.com/AU/en-AU/sustainability/recycling.html

ISO. (2006a). *ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework*. ISO.

ISO. (2006b). ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines. In.

ISO. (2017). ISO 21930:2017. In *Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services* (pp. 80).

Itanola, M., Griffiths, P., & Motawa, I. (2025). Closing the loop in building services: A systematic review of circular economy applications [Review]. *Build. Serv. Eng. Res. Technol.*, *46*(3), 293-315. https://doi.org/10.1177/01436244241296762

Kanters, J. (2020). Circular building design: An analysis of barriers and drivers for a circular building sector. *Buildings*, *10*(4), 77.

Kılıç Bakırhan, E., & Tuna, M. (2025). Mitigating fit-out waste in rentable offices: The role of flexible design strategies. *Journal of Construction Engineering, Management & Innovation*, *8*, 521-541. https://doi.org/10.31462/jcemi.2025.04521541

Liljenström, C., & Malmqvist, T. (2016, 2016). *Resource use and greenhouse gas emissions of office fit-outs - A case study* Central Europe Towards Sustainable Building 2016: Innovations for Sustainable Future, CESB 2016, 22 June 2016 through 24 June 2016, http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-195453

Liu, K., Guhathakurta, S., Han, C., Hittinger, E., Phoung, S., & Williams, E. (2024). How much is US office building space reduced per teleworker? *Findings*.

Lundgren, R., Kyrö, R., Toivonen, S., & Tähtinen, L. (2024). Enabling circular futures of workspaces through facility management: a backcasting approach. 23rd EuroFM Research Symposium,

MacArthur, E. (2013). Towards the circular economy. *J. Ind. Ecol.*, *2*(1), 23-44.

Markou, I., Sinnott, D., & Thomas, K. (2025). Current methodologies of creating material passports: A systematic literature review. *Case Studies in Construction Materials*, *22*, e04267. https://doi.org/https://doi.org/10.1016/j.cscm.2025.e04267

Mathew, P., Regnier, C., Shackelford, J., & Walter, T. (2020). Energy Efficiency Package for Tenant Fit-Out: Laboratory Testing and Validation of Energy Savings and Indoor Environmental Quality. *Energies*, *13*(20).

McLaren, S., Elliot, T., Dowdell, D., Wakelin, S., Kouchaki-Penchah, H., Levasseur, A., & Hoxha, E. (2025). Policy implications of time-differentiated climate change analysis in life cycle assessment of building elements in Aotearoa New Zealand. *Int. J. Life Cycle Assess.*, 1-23. https://doi.org/10.1007/s11367-025-02444-9

Mequignon, M., Adolphe, L., Thellier, F., & Ait Haddou, H. (2013). Impact of the lifespan of building external walls on greenhouse gas index. *Build. Environ.*, *59*, 654-661.

Ministry for the Environment. (2020). *Interface ReEntry Programme*. https://environment.govt.nz/what-you-can-do/stories/interface-reentry-programme/

Ministry for the Environment. (2024). *Measuring emissions: A guide for organisations: 2024 detailed guide*.

Minunno, R., O'Grady, T., Morrison, G. M., Gruner, R. L., & Colling, M. (2018). Strategies for Applying the Circular Economy to Prefabricated Buildings. *Buildings*, *8*(9).

Mutel, C. (2017). Brightway: an open source framework for life cycle assessment. *Journal of Open Source Software*, *2*(12), 236.

Negishi, K., Lebert, A., Almeida, D., Chevalier, J., & Tiruta-Barna, L. (2019). Evaluating climate change pathways through a building's lifecycle based on Dynamic Life Cycle Assessment. *Build. Environ.*, *164*, 106377. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106377

Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. *J. Build. Eng.*, *44*, 102704. https://doi.org/https://doi.org/10.1016/j.jobe.2021.102704

Office Insight. (2025). Office fit-out cost guide. officeinsight.co.uk/wp-content/uploads/2025/05/OFFICE-FIT-OUT-COST-GUIDE-PRINTING-VERSION.pdf

Ouellet-Plamondon, C. M., Ramseier, L., Balouktsi, M., Delem, L., Foliente, G., Francart, N., Garcia-Martinez, A., Hoxha, E., Lützkendorf, T., & Rasmussen, F. N. (2023). Carbon footprint assessment of a wood multi-residential building considering biogenic carbon. *J. Clean. Prod.*, *404*, 136834.

Overbury. (2024). *Counting the upfront carbon in Cat B office fit-out*. https://d31fl6kv41tqjh.cloudfront.net/v2/accreditations/Counting-the-upfront-carbon-in-Cat-B-office-fit-out-Overbury-2024.pdf

Palacios-Munoz, B., Peuportier, B., Gracia-Villa, L., & López-Mesa, B. (2019). Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach.

Build. Environ., *160*, 106203. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106203

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *J. Clean. Prod.*, *143*, 710-718. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.055

Rey-Álvarez, B., Sánchez-Montañés, B., & García-Martínez, A. (2022). Building material toxicity and life cycle assessment: A systematic critical review. *J. Clean. Prod.*, *341*, 130838. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.130838

Rodrigues, C., König, J., & Freire, F. (2023). Prospective life cycle assessment of a novel building system with improved foam glass incorporating high recycled content. *Sustainable Production and Consumption*, *36*, 161-170. https://doi.org/https://doi.org/10.1016/j.spc.2023.01.002

Rodrigues, C., Rodrigues, E., S. Fernandes, M., & Tadeu, S. (2024). Prospective life cycle approach to buildings' adaptation for future climate and decarbonization scenarios. *Applied Energy*, *372*, 123867. https://doi.org/https://doi.org/10.1016/j.apenergy.2024.123867

Rodriguez, B. X., Huang, M., Lee, H. W., Simonen, K., & Ditto, J. (2020). Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation. *Energy Build.*, *226*, 110324. https://doi.org/https://doi.org/10.1016/j.enbuild.2020.110324

Rotimi, J. O. B., & Rasheed, E. O. (2024). The "Other" Workplace Design Factors: An Insight into What New Zealand Workers Want. *Sustainability*, *16*(19), 8381. https://www.mdpi.com/2071-1050/16/19/8381

Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., & Luderer, G. (2022). PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renew. Sustain. Energy Rev.*, *160*, 112311. https://doi.org/https://doi.org/10.1016/j.rser.2022.112311

Sepanta, F., Sirati, M., & O'Brien, W. (2024). Quantifying the net impact of hybrid work on greenhouse gas emissions associated with workplace and residential energy consumption.

Sonae Aruco. (2022). *Environmental Product Declaration of Oriented Strand Board*.

Steubing, B., De Koning, D., Haas, A., & Mutel, C. L. (2020). The Activity Browser—An open source LCA software building on top of the brightway framework. *Software Impacts*, *3*, 100012.

Su, S., Li, X., Zhu, Y., & Lin, B. (2017). Dynamic LCA framework for environmental impact assessment of buildings. *Energy Build.*, *149*, 310-320. https://doi.org/10.1016/j.enbuild.2017.05.042

thinkstep Ltd. (2022). *The carbon benefits of working from home*. https://www.thinkstep-anz.com/resrc/case-studies/carbon-benefits-wfh/

UKGBC. (2022). *Insights on how circular economy principles can impact carbon and value*. https://ukgbc.org/wp-content/uploads/2022/08/Whole-Life-Carbon-Circular-Economy-Report.pdf

UKGBC. (2025). *Materials Passports Platforms*. UK Green Building Council. https://ukgbc.org/resources/materials-passports-platforms/

Walden, J., Steinbrecher, A., & Marinkovic, M. (2021). Digital product passports as enabler of the circular economy. *Chemie Ingenieur Technik*, *93*(11), 1717-1727.

Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2026). Dynamic carbon budgets and carbon debts for Aotearoa New Zealand and its building sector. *Build. Environ.*, *287*, 113805. https://doi.org/https://doi.org/10.1016/j.buildenv.2025.113805

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.*, *21*(9), 1218-1230. https://doi.org/10.1007/s11367-016-1087-8

Wilkinson, S., & Reed, R. (2006). Office buildings and the environment: the increasing importance of ESD.

This page is intentionally left blank

Chapter 6

Towards Dynamic Carbon Budgets for Aotearoa New Zealand Building Sector

Preface

Chapter 6 is based on a conference paper published in the 2025 Sustainable Built Environment (SBE) conference proceedings. This article was developed as part of this doctoral research and contributes to achieve the objectives 2.1 and 2.2. It focuses on the development of time-differentiated carbon budgeting approaches for the building sector, addressing the alignment of emission pathways with climate targets. The version presented here reflects the conference paper, with minor adjustments made to ensure consistency with the overall thesis.

Chapter 6 extends the perspective developed in Chapter 3-5 to the sectoral scale by addressing the complementary question of how emission trajectories can be constrained by time-differentiated climate budgets. As the original conference paper was subject to the page limitations specified in the conference proceedings, the methodological description and associated calculations were necessarily presented at a limited level of detail. Accordingly, Chapter 6 introduces the conceptual and methodological framework for time-differentiated carbon budgeting, while the detailed methodology, calculations, assumptions and application of the framework are presented and further developed in Chapter 7.

Conference article reference:
Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2025, 25.06.2025-27.06.2025). Towards Dynamic Carbon Budgets for Aotearoa New Zealand Building Sector. SBE Conference Series, Zurich, Switzerland.

6.1 Introduction

The building sector is a major contributor of global greenhouse gas (GHG) emissions. In Aotearoa New Zealand (ANZ), the building sector accounts for more than 15% of national consumption-based (CB) GHG emissions (Chandrakumar et al., 2019). Addressing these emissions requires a methodological approach that aligns with targets like the Paris Agreement, which aims to limit warming to well below 2°C, and to pursue efforts to limit global warming to 1.5 °C above pre-industrial levels. Progress towards these climate targets can be assessed using different criteria, such as the remaining carbon budget (RCB) concept for setting carbon budgets for nations and sectors. The latest Intergovernmental Panel for Climate Change (IPCC) report also provided RCBs based on the climate targets (IPCC, 2023). However, it is evident that these carbon budgets are already exhausted or rapidly approaching exhaustion at the global scale (Li et al., 2025) and the ANZ scale (Bullen, McLaren, et al., 2021; McLaren et al., 2020). Therefore, this study examines the options for assessing timely interventions to avoid budget overshoots by setting dynamic carbon budgets.

6.2 Methods

Given the significant contribution of carbon dioxide (CO_2) to global warming and its predominant role in building sector emissions, this study focuses on CO_2. The global RCB for CO_2 from the beginning of 2020 for a 50% chance of limiting global warming to 1.5 °C (which is 500 $GtCO_2$) (IPCC, 2023) is used to calculate ANZ's share, and is further downscaled to the ANZ building sector for the period 2020 to 2050, assuming net zero emissions are achieved by 2050. The RCB is derived based on the assumption that future non-CO_2 warming aligns with stringent mitigation scenarios. However, a range of adjustments to the RCB were included to account for non-CO_2 emissions differing from this assumption, adding 100 $GtCO_2$ for the upper-bound estimate and subtracting 200 $GtCO_2$ for the lower-bound estimate based on IPCC (2023, p. 82).

Since there are different sharing principles for downscaling, we used several approaches to reduce the potential bias of using one single sharing approach. To establish a comprehensive range of RCB, we used equal per capita (EPC) and grandfathering (GF) sharing approaches for global to national downscaling to represent the typical range of

downscaled results using different sharing approaches. EPC was chosen for the lower bound primarily because the relatively small population in ANZ compared with other countries results in a proportionately lower allocation. GF was chosen for the higher bound because ANZ has relatively high production-based (PB) emissions associated with its economy relative to many other countries due to its large livestock-based agricultural sector.

These sharing approaches mostly rely on static data, typically accounting for the population or emissions taken based on a single year, and not accounting for potential dynamic changes that influence future emissions. Examples of dynamic changes include population growth and reduction in CO_2 emissions due to the future climate policies. Therefore, in this research we used the EPC and GF sharing approaches to allocate dynamic national shares by considering both the population dynamics over future years and the forecasted CB emissions provided by the Ministry for the Environment (2024d) based on IPCC's fifth assessment report (AR5) (IPCC, 2013). We calculated the RCB available from 2024 onwards by subtracting the CB CO_2 emissions for 2020-2023 from the downscaled carbon budget calculated at the beginning of 2020. Then we derived annual shares based on the proportion of the annual population to the total population over 2024-2050, and annual forecasted emissions to the total emissions over 2024-2050, for EPC and GF sharing approaches, respectively. Finally, we calculated the possible years remaining until the RCBs for ANZ are exhausted based on the assumption that CB emissions in year 2022 will continue at the same rate over future years.

For sectoral allocations, the economic value added (EVA) and GF sharing approaches were used. These reflect the average economic contribution of the building sector to the national Gross Domestic Product and the forecasted CB emissions over future years respectively. This results in four combinations of sharing approaches (EPC+EVA, EPC+GF, GF+EVA, and GF+GF). Sectoral annual shares were derived similarly to the method used in national shares derivation.

6.3 Results and Discussion

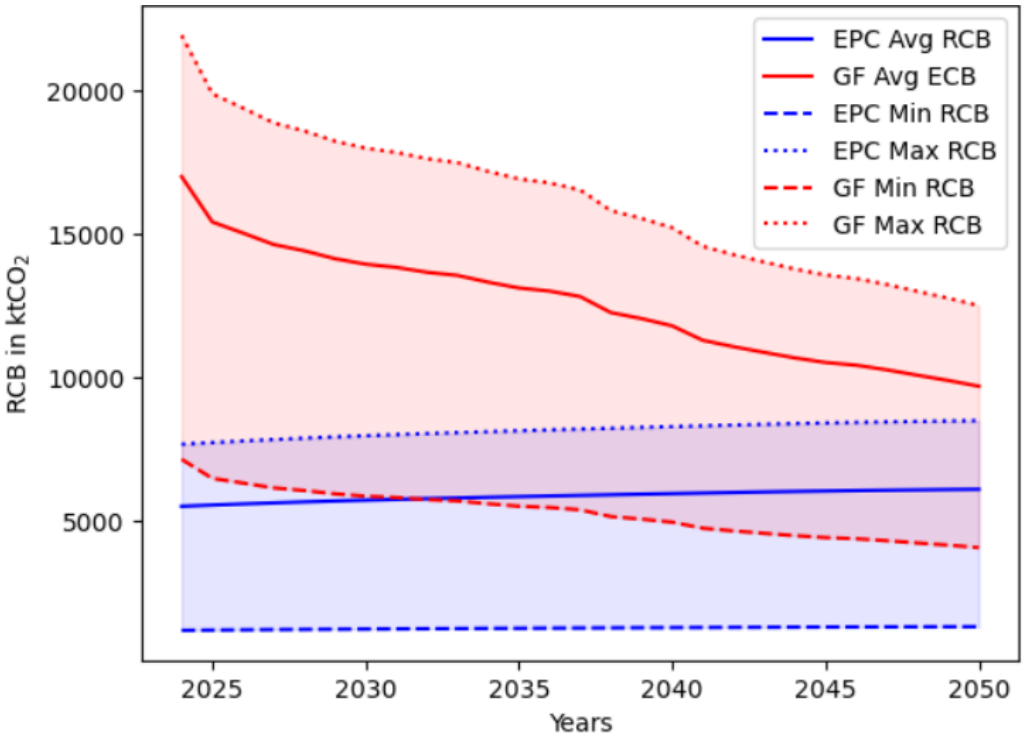


Figure 6.1 Dynamic remaining carbon budgets for Aotearoa New Zealand from 2024-2050 based on equal per capita (EPC) and grandfathering (GF) approaches

Based on the EPC and assuming CB emissions in year 2022 will continue to occur over future years, the national RCB is exhausted in 2024 for the minimum RCB scenario in ANZ. It varies from year 2027 to 2029 for the average and maximum RCB scenarios using the EPC. Based on GF, the minimum RCB will be exhausted in 2027, and varies from 2032 to 2035 for the average and maximum RCB scenarios respectively. It is evident that the two approaches result in different RCBs for ANZ, and Figure 6.1 shows the national dynamic RCB up to 2050 using both approaches. For the EPC, the dynamic RCB gradually increases due to the population growth forecast. For the GF, the dynamic RCB decreases reflecting the economic conditions and policies of the forecasted emission pathway in ANZ (Ministry for the Environment, 2024d). There is almost no overlap in the RCBs using the two alternative sharing approaches in the 2020s but the range difference decreases over time so that the ranges are about 50% overlapping by 2050.

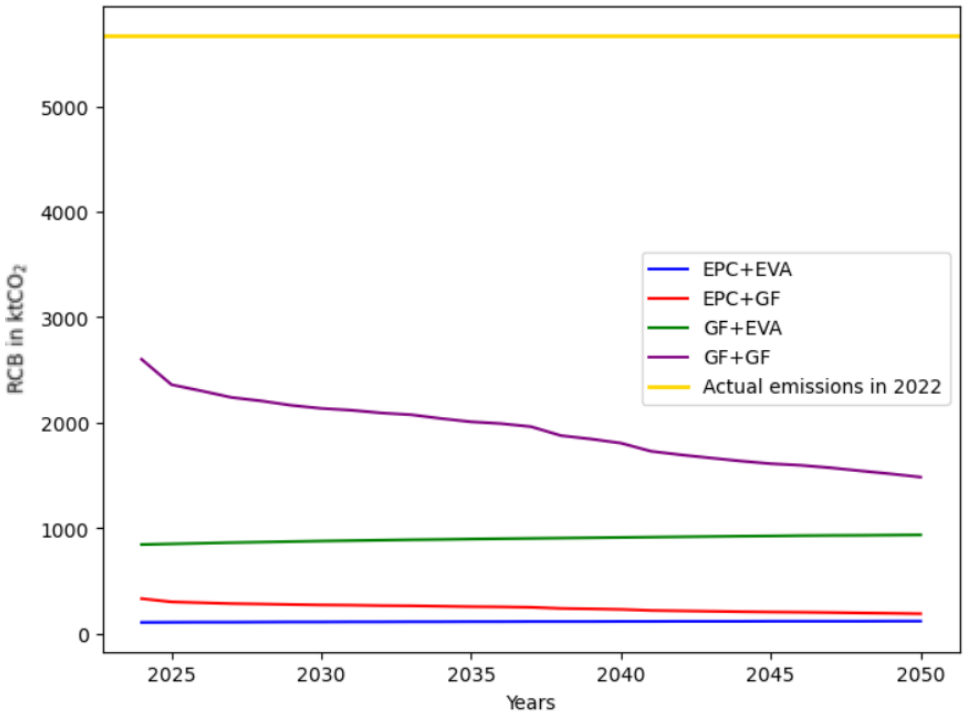


Figure 6.2 Dynamic remaining carbon budgets for Aotearoa New Zealand building sector from 2024-2050 based on four different approaches and actual emissions in year 2022

For the ANZ building sector, the RCBs using the four approaches are presented in Figure 6.2 alongside the actual CB sectoral emission in 2022 (yellow line). The results show that the derived annual RCBs using the different approaches are significantly lower than the actual emissions in 2022 (5147-118%). It will be extremely challenging to meet these carbon budgets; therefore, the ANZ building sector is highly likely to overshoot its RCB within the next few years.

Different sharing approaches result in varying allocated shares due to the different assumptions regarding fairness, responsibility and capability. However, irrespective of the sharing approach used, this study emphasises the urgency of implementing rapid decarbonisation strategies at national and building sector level in ANZ to realign with climate targets. By using this dynamic approach, timely interventions can be introduced to transform ambitious goals into achievable milestones and to identify and prioritise the necessary decarbonisation strategies to achieve climate goals. We suggest complementary negative carbon budgets should be set for ANZ and its building sector allowing for implementation of alternative initiatives to remove CO_2 from the atmosphere.

References

Bullen, L., McLaren, S. J., Dowdell, D., & Chandrakumar, C. (2021). Absolute sustainability of New Zealand office buildings in the context of climate targets. *Building and Environment*, *205*. https://doi.org/10.1016/j.buildenv.2021.108186

Chandrakumar, C., McLaren, S. J., Malik, A., Ramilan, T., & Lenzen, M. (2019). Understanding New Zealand's consumption-based greenhouse gas emissions: an application of multi-regional input-output analysis. *The International Journal of Life Cycle Assessment*, *25*(7), 1323-1332. https://doi.org/10.1007/s11367-019-01673-z

IPCC. (2013). *Climate Change 2013: The Physical Science Basis*. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf

IPCC. (2023). *Climate Change 2023: Synthesis Report*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

Li, M., Pelz, S., Lamboll, R., Wang, C., & Rogelj, J. (2025). A principle-based framework to determine countries' fair warming contributions to the Paris Agreement. *Nature Communications*, *16*(1), 1043. https://doi.org/10.1038/s41467-025-56397-6

McLaren, S. J., Chandrakumar, C., Dowdell, D., Bullen, L., & Jaques, R. (2020). Application of Absolute Sustainability Assessment to New Zealand Residential Dwellings. *IOP Conference Series: Earth and Environmental Science*, *588*(2). https://doi.org/10.1088/1755-1315/588/2/022064

Ministry for the Environment. (2024). *New Zealand's projected greenhouse gas emissions to 2050*. Retrieved from https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/emissions-reductions/emissions-reduction-targets/new-zealands-projected-greenhouse-gas-emissions-to-2050/

Chapter 7

Dynamic Carbon Budgets and Carbon Debts for Aotearoa New Zealand and Its Building Sector

Preface

This chapter is based on a peer-reviewed journal article developed and built directly on the methodological framework established in Chapter 6 with detailed methodological development and calculations. It advances the application of time-differentiated carbon budgeting by quantifying and assessing the alignment of Aotearoa New Zealand's building sector emissions with climate targets. The chapter addresses the objectives 2.2 and 2.3, and introduces and operationalises the concept of dynamic carbon debt, enabling the evaluation of the implications of delayed mitigation over time. It moves from the methodological framework established in Chapter 6 to its detailed implementation and national sectoral application. The version presented here is the published article, with minor adjustments made to ensure consistency with the overall thesis.

Article citation:
Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2026). Dynamic carbon budgets and carbon debts for Aotearoa New Zealand and its building sector. *Building and Environment*, *287*, 113805. https://doi.org/10.1016/j.buildenv.2025.113805

Abstract

The remaining carbon budget (RCB) is a crucial parameter when setting carbon budgets for nations and economic sectors that want to measure their progress in climate change mitigation. The Paris Agreement is the most widely used and accepted climate change mitigation target, and the global RCB specified by the Intergovernmental Panel for Climate Change (IPCC) provides the carbon budget remaining from the beginning of

2020 that can be emitted as CO_2 before the Paris Agreement's target is exceeded. This research investigates the global RCB allocation to the national and building sector level in Aotearoa New Zealand, including consideration of different sharing approaches and modelling of potential future dynamic parameters for the RCB allocation, that are required to stay below 1.5 °C warming between the years 2024 and 2050. The average national RCB ranges from 159 to 339 $MtCO_2$ from year 2024; based on an average annual emissions rate of 38 $MtCO_2$, it will be depleted in 4-8 years. Therefore, this study proposed a dynamic carbon debt framework that provides a more realistic representation of dynamic RCBs and the carbon debt over future years. Key findings include the urgency of timely interventions, the need for additional mitigation strategies beyond the current policy approach which is largely focused on increased plantation forestry, and the usefulness of time-disaggregated carbon budgeting to address exhaustion of the RCB. Overall, this study demonstrates the relevance of dynamic budgeting to guide effective climate policy at both the national and building sector levels.

7.1 Introduction

The building and construction sector is a major contributor to global greenhouse gas (GHG) emissions, accounting for approximately 37% of emissions when considering both operational and embodied carbon (United Nations Environment Programme, 2024). In Aotearoa New Zealand (ANZ), GHG emissions from building and construction sector is increasing over years, accounting for 11.5 $MtCO_2eq$ in the year 2021, which is an increase of 5.3% from the year 2020 based on consumption-based accounting approach (Ministry of Business Innovation and Employment, 2024). Overall, the built environment accounts for 20% of GHG emissions in ANZ (thinkstep Ltd, 2018). The ANZ built environment's consumption-based emissions comprise: 8.7% for embodied emissions arising from building products, 8.6% for operational energy use, 2.1% for imported embodied emissions, and 0.5% for building and garden waste (thinkstep Ltd, 2018). There is therefore a need for both global and more local mitigation efforts related to this sector, and an important question concerns how much this sector must reduce its GHG emissions to meet the global climate targets set under the Paris Agreement (UNFCCC, 2015).

Science-based carbon budgets are widely accepted as a way of measuring progress to stay within climate targets. These budgets are quantified at the global scale and then allocated

to national and/or sectoral scales, supporting policymakers to set emission reduction pathways (Lahn, 2020). Recent literature has explored carbon budgets for ANZ (Chandrakumar, Malik, et al., 2020) and for specific building typologies such as residential buildings (Chandrakumar, McLaren, et al., 2020; McLaren et al., 2020) and non-residential buildings (Bullen, McLaren, & Dowdell, 2021; Bullen, McLaren, et al., 2021; Ghose et al., 2020). These studies used a static accounting approach to set budgets without considering temporal dynamics over the years. In this paper, we include temporal dynamics by considering global and national population growth, economic growth in the building sector, and policy changes with associated emission reduction pathways in ANZ over the next few decades.

This dynamic LCA approach provides more informative modelling of future emissions by integrating consideration of temporal dynamics over time. Additionally, it enables calculation of dynamic carbon debts arising from ongoing GHG emissions and budgets, thereby enabling timely interventions to inform policies and strategies for the decarbonisation of the building sector. Unlike conventional approaches that represent GHG emissions and carbon budgets over extended periods as a single aggregate value, this dynamic approach identifies critical moments for intervention. Alongside the dynamic carbon debts, the main additional carbon removal strategy that is practically available at a national scale - carbon removal through planting exotic forests - is quantified in this study, showing that additional decarbonisation pathways are required for the building sector to align with the 1.5 °C climate goal.

7.2 Background

7.2.1 Global Carbon Budgets Concepts and Definitions

Aotearoa New Zealand's GHG emission profile in 2022 comprised 40.3% carbon dioxide (CO_2), 48.9% methane (CH_4), 8.8% nitrous oxide (N_2O) and 2% fluorinated gases (F-gases), and was dominated by the agriculture and energy sectors' emissions (Ministry for the Environment, 2024b). The climate target for 2050 is to achieve net zero GHG emissions except for biogenic CH_4 where the target is to achieve a reduction of 24% to 47% in CH_4 emissions (New Zealand Legislation, 2019). Measuring progress towards

achieving climate targets require the development of specific methodologies, among which the concept of the carbon budget has gained significant prominence (Lahn, 2020). The IPCC define the carbon budget as "*the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a specified level with a specified likelihood*" (IPCC, 2023). Therefore as CO_2 accounts for more than 90% of GHG emissions contributed by both the global building sector (Cabeza et al., 2022) and the ANZ building sector (Ministry for the Environment, 2024f), this study focuses on CO_2 rather than including all GHGs; this also aligns with the carbon budget accounting of the IPCC (IPCC, 2023).

The carbon budget concept has led to several budgetary calculations that use specific parameters. These parameters include limiting temperature rise to a certain degree, limiting temperature rise to align with a certain historical period or base year, limiting radiative force to a certain level, incorporating confidence levels, inclusion/exclusion of non-CO_2 warming, and with reference to a target year in the future (Matthews et al., 2020). The proposed budgets include: the total carbon budget, total GHG budget, remaining carbon budget (RCB), and remaining GHG budget. These budgets are intended to guide mitigation strategies at global, local, and sectoral levels, assisting in understanding of the appropriate scale of required responses to align with global climate targets. The total carbon budget is defined as the maximum amount of cumulative net global anthropogenic CO_2 emissions from pre-industrial times up to the present (or to some future year) that can be emitted whilst limiting global warming to a given temperature level with given probability. When these emissions are accounted from a more recent specified date, then the carbon budget is defined as the RCB (IPCC, 2023).
Researchers have derived carbon budgets using different methods in the scientific literature. Matthews and colleagues (Matthews et al., 2021) calculated the RCB based on the Transient Climate Response to Cumulative CO_2 Emissions (TCRE) metric for 1.5 °C warming with 33%, 50% and 67% likelihood from year 2020 as 670 $GtCO_2$, 440 $GtCO_2$ and 230 $GtCO_2$ respectively. Rogelj and colleagues (Rogelj et al., 2018) estimated annual CO_2 budgets to limit global warming to 1.5 °C using different scenarios based on five Shared Socio-economic Pathways (SSPs) and six different integrated assessment models that will limit radiative forcing to 1.9 Wm^{-2}. From 13 different scenarios, the average CO_2 emissions were estimated as 725 $GtCO_2$ from year 2016 to 2050. Rogelj and colleagues (Rogelj et al., 2019) then developed a further approach to determine the RCB for specific

temperature change limit considering five variables: historical human-induced warming up to date, non-CO_2 warming (net additional contribution of aerosols and non-CO_2 GHGs) to future temperature rise, net-zero commitments, TCRE, and Earth system feedback. The RCBs using this framework were estimated to limit global warming to 1.5 °C with 33%, 50% and 66% likelihood as 740 $GtCO_2$, 480 $GtCO_2$ and 320 $GtCO_2$ respectively, and to limit global warming to 2°C with 33%, 50% and 66% likelihood as 1930 $GtCO_2$, 1400 $GtCO_2$ and 1070 $GtCO_2$ respectively (Rogelj et al., 2019).

However, the IPCC established the global RCB from the beginning of 2020 as 500 $GtCO_2$ for a 50% chance of limiting global warming to 1.5 °C, and 1150 $GtCO_2$ for a 67% chance of limiting it to 2 °C (IPCC, 2023, p. 82). These RCB estimates are derived with the assumption that future non-CO_2 warming aligns with stringent mitigation scenarios, meaning that non-CO_2 GHG and aerosols make a net additional contribution of around 0.1°C above the 2010-2019 level (Mengis & Matthews, 2020). However, Rogelj and Lamboll (2024) note that if actual non-CO_2 emissions differ from this assumption, the RCB estimation will need to be adjusted accordingly i.e. if non-CO_2 emissions are higher than expected, the RCB will needs to be reduced (and vice versa). According to the IPCC (2023, p. 82), if this occurs, the RCB for a 50% chance of limiting warming to 1.5 °C could decrease to around 300 $GtCO_2$. Conversely, if the global warming associated with non-CO_2 warming is reduced to 0.05 °C, the RCB for limiting warming to 1.5 °C with 50% chance could increase to around 600 $GtCO_2$ (IPCC, 2023, p. 82).

The 1.5 °C target has been endorsed by most of the world leaders, in view of the IPCC's warning that exceeding this threshold could lead to significantly more severe climate change impacts, including more frequent and intense droughts, heatwaves, and heavy rainfall (IPCC, 2023; UNFCCC, 2015). Therefore, we use the IPCC's calculated RCB for limiting global warming to 1.5 °C with a 50% chance (500 $GtCO_2$) for this research. We also investigate the significant influence of non-CO_2 emissions on the RCB, again using the IPCC's estimated range between 300 $GtCO_2$ (scenarios with higher non-CO_2 global warming) and 600 $GtCO_2$ (scenarios with lower non-CO_2 warming).

7.2.2 Allocating Shares

Numerous sharing approaches have been used in the literature to downscale global carbon budgets to national and then sectoral levels, each informed by a distinct distributive justice theory and unique assumptions (Ryberg et al., 2020). Existing studies have used a variety of methodologies for budget allocation that are informed by these theories (Bjørn et al., 2020; Ryberg et al., 2020; Sandin et al., 2015). However, there is no consensus to date on a preferred downscaling approach, and the choice of sharing approach can significantly influence the magnitude of the downscaled budgets (Dao et al., 2018; Lucas et al., 2020; Ryberg et al., 2020; Sandin et al., 2015).

Three main distributive justice theories are mostly employed in the literature to allocate global budgets: egalitarian, libertarianism, and utilitarian (Ryberg et al., 2020). The egalitarian distributive justice theory is commonly used in downscaling global budgets to national level; it emphasises that everyone should be treated equally and have equal opportunities (equity-based). The equal per capita (EPC) sharing principle, based on egalitarian distributive justice theory, is the most frequently used sharing principle (Ryberg et al., 2020) to downscale from the global budget to national budgets (Bullen, McLaren, et al., 2021; Chandrakumar, McLaren, et al., 2020; Horup et al., 2023; Priore et al., 2023; Williges et al., 2022). Following libertarianism distributive justice theory, grandfathering (GF) is a common sharing principle which is based on historical emissions in a reference year (Bjørn et al., 2020; Horup et al., 2023). This sharing principle can be applied to downscaling efforts not only at national level but also at other levels, including sectoral and product levels, based on respective historical emissions (Chandrakumar, McLaren, et al., 2020; McLaren et al., 2020; Priore et al., 2023). A problem with this approach is that it provides an advantage to historically high GHG emitters. The utilitarian distributive justice theory emphasises that products and services can be prioritised based on their value in an economy. The utilitarian approach is commonly applied to downscale the budget from national to sector level (Ryberg et al., 2020), after downscaling from global to the national level using the egalitarian approach.

In addition to these three distributive justice theories and their derived sharing principles, two other sharing principles, ability to pay (AP) and economic value added (EVA), are commonly used in the literature to allocate shares to sectoral levels. The AP sharing

principle is classified under prioritarianism distributive justice theory, which prioritises emission allocation based on nations' wealth rather than other parameters such as historical emissions and population. AP is applied based on a country's capability to reduce emissions represented through its Gross Domestic Product (GDP) (Horup et al., 2023). For AP, less RCB is allocated to countries with high GDP because they have a greater capability to reduce their climate change impacts (Bjørn et al., 2020). The EVA sharing principle also falls under prioritarianism distributive justice theory, where the fair share is determined based on the economic gross value added by an industry sector to the national economy. Algunaibet et al. (2019) applied this principle to allocate the planetary boundaries to stay within the safe operating space when downscaling from national scale to the energy sector in the United States. Similarly, Horup et al. (2023) used this principle to allocate the carbon budget for the building sector to new buildings based on the contribution of economic activities associated with new buildings to overall economic activity in the construction sector.

As there is currently no universally agreed sharing principle, individual nations and/or sectors can choose their most favourable approaches and this risks compromising the credibility of downscaled budgets (Bai et al., 2024). This has led to researchers using a number of different approaches in their studies. For example, combination of AP, EPC and GF sharing principles were used for a framework to allocate budgets (and associated reduction targets) to different countries in the EU to derive national budgets (Steininger et al., 2022). When downscaling global GHG budgets to Denmark, Tilsted and Bjørn (2023) used five different sharing principles to add more perspective to their study. In our study, we have also used multiple approaches to allocate carbon budgets from the global to national and building sector levels. This allows for direct comparison of outcomes under different principles, thereby highlighting the sensitivity of budget allocations to the choice of sharing principle.

7.2.3 Temporal Dynamics

Current approaches for allocating the global carbon budget largely neglect the time-dependency within any time horizons defined for these budgets. For instance, GF generally allocates global share based on historical emissions. However, when setting emission targets over a long time period, reliance on historical emissions may not

accurately reflect the carbon budget for future years, as it fails to account for anticipated changes in emissions trajectories that are likely to be affected by dynamic economic, technological, and policy conditions. Additionally, when budgets are set as cumulative values applicable over extended time periods, the policies and strategies required to manage these budgets become complicated. Dividing the total budget equally between number of years is inaccurate as it assumes that emissions and budgets will remain consistent year-on-year, which is not realistic. Similarly, the building sector's contribution to the country's economy over time or a country's capacity to pay based on GDP may fluctuate due to economic growth or contraction, and demographic dynamics such as population growth or decline over years. These dynamics may affect the carbon budgets over a long period. Therefore, the allocation methods should be integrated with dynamic factors that reflect a range of evolving socio-economic and demographic conditions. Also, cumulative budgets need to be distributed over future years to align with modelled future dynamics; provision of just cumulative values do not provide information on the timing and scale of interventions needed, and thus hinders development of phased and manageable mitigation measures. By distributing the budget over time, decision-makers gain transparent understanding into when mitigation measures must be intensified, and thereby are supported to design time-differentiated, responsive strategies.

7.2.4 Carbon Budget Exhaustion and the Concept of Negative Budgets

Recent literature on national carbon budgets in different countries show that their fair share is already exhausted or soon to be exhausted. For example, Li et al. (2025) found that around 84 to 90 countries in the world, including all major developed nations, had already exhausted their national GHG budgets by 2021 to limit warming to 1.5 °C with 50% chance. Gueret et al. (2018) showed that the carbon budgets of major European Union (EU) member states are nearly exhausted, with several countries on the boundary of exceeding their shares in the coming years under the 2°C climate target. Particularly for Denmark, Horup et al. (2023) showed that Danish legislation allows emissions up to 220% higher than the average of their downscaled national budgets and they would need to reduce their climate impacts of new building activity by 20-70% compared to recent performance to align with 1.5 °C target. Similarly, Chandrakumar et al. (2020a) found that ANZ and most of its economic sectors had exceeded their GHG budgets regardless

of the sharing approach used, based on 2011 consumption- and production-based emissions. The ANZ office building sector for 2018-2050 exceeded their GHG budget by a factor of 4.0 and newly built offices exceeded their budget by a factor of 5.3 based on 2012 consumption-based emissions (Bullen, McLaren, et al., 2021). New-built residential dwellings also exceeded their GHG budget by a factor of 6.7, 6.8 and 10.9 for detached, medium density housing and apartments, respectively (McLaren et al., 2020). Therefore, additional strategies for achieving climate targets for the ANZ building sector must be investigated.

As carbon budgets are now either exhausted or rapidly approaching depletion, the concept of net-negative emissions has emerged as a focus area for both academia and policy making. By removing more emissions than are emitted, net negative emissions can help mitigate the cumulative effects of past emissions (Smith et al., 2024; Tokarska et al., 2019). In response, studies have emphasised the need for robust economic and political instruments to support the transition toward net-negative emissions. Among the proposed mechanisms, Carbon Removal Obligations (CROs) have emerged as a novel approach that holds emitters accountable for the removal of their historical emissions (Bednar et al., 2021; Bednar et al., 2019). In parallel, there is a growing interest in political reforms that embed the concept of negative carbon budgets in policy agendas. Peters and Geden (2017) argued that there needs to be a political shift from low carbon to net negative carbon in climate policies. This negative emission approach has been adopted in practice in several economically advanced nations - mainly through implementation of carbon dioxide removal (CDR) technologies (Shukla et al., 2022). Current CDR practices are mostly concerned with afforestation and reforestation (particularly in China and Brazil), direct air capture and storage (DACS) (in the United States (US), EU state members, the UK and Canada), and bioenergy with carbon capture and storage (BECCS) in Denmark and the US (Pilorgé et al., 2021; Schenuit et al., 2025; Schenuit et al., 2021).

ANZ mostly relies on forestry for CDR, and accounts for only the carbon removal from exotic forests in their international climate commitment reporting for the Paris Agreement (Ministry for the Environment, 2023b). This reliance on exotic forests (e.g. *Pinus radiata*) in current carbon removal calculations is primarily driven by the fast growth rates and rapid carbon sequestration capacity of exotic compared to native species (Acosta et al.,

2020). However, the ANZ government intends to include other CDR strategies into the emission reduction plan including activities such as biological processes storing carbon in vegetation, wood products, marine sediments and organic oils including rewetting of drained peatlands, restoring wetlands, and engineered chemical and geochemical processes for DACS in minerals (Ministry for the Environment, 2023a, 2023b). Although CDR from exotic forestry is more widely implemented and aligns with nature-based approaches, it is constrained by limitations such as land availability, risks like fire and disease, adverse impacts on biodiversity, and relatively slower rates of carbon sequestration compared to technological alternatives (Dooley & Kartha, 2018; Evison & Mason, 2017).

Given the near exhaustion of RCBs, along with existing gaps in incorporating temporal dynamics into budget allocation methodologies, and recent attention to potential CDR strategies in ANZ, this study examines the use of RCBs in ANZ using two dynamic lenses: (i) use of CDR strategies to stay within carbon budgets at the national level, and (ii) decarbonisation pathways for the building sector to stay within its carbon budget(s). The first approach primarily focuses on how implementation of CDR strategies in ANZ affects the exhaustion of carbon budgets over time. The second approach focuses on how the carbon budgets and carbon debts of ANZ building sector change over time and their implication for a building sector decarbonisation pathway.

7.3 Methodology

7.3.1 Downscale Global Remaining Carbon Budgets for Aotearoa New Zealand

This study adopts the IPCC's global RCB to allocate ANZ's fair share for a 50% chance of limiting warming to 1.5 °C from 2020, using an average value of 500 $GtCO_2$, and considering a lower and an upper bound of 300 and 600 $GtCO_2$ to reflect scenarios with higher and lower non-CO_2 warming, respectively (see Section 7.2). Since ANZ has committed to achieving net zero status by 2050 for long-lived gases, we allocate the RCB across 2020 to 2050 in this study i.e. assuming net zero emissions by 2050.

For downscaling the RCB from global to national level, we used both the EPC and GF sharing principles. The EPC sharing principle was chosen as it gives a low value for the RCB due to the relatively small population of ANZ: in 2020, ANZ's population was approximately 5.03 million, which represents only about 0.064% of the global population of 7.85 billion (UNPD, 2024). The GF sharing principle was chosen as it gives a high value for the RCB primarily based on ANZ's emissions relative to the global scale: in 2020, ANZ's CO_2 emissions were 0.11% of the global production-based CO_2 emissions (Crippa et al., 2022). In addition to EPC and GF, AP is generally used to allocate national shares. However, a smaller share of global RCBs can be expected for ANZ with its higher GDP ranking in the world (52nd globally) (World Bank, 2025).Therefore, AP yields a relatively low carbon budget allocation, although not as low as that derived from the EPC method (Horup et al., 2023) due to ANZ's small share of the global population (ranked 119th by population size (UNPD, 2024)).

First, the EPC was used to allocate the RCB to ANZ (see Equation 1), reflecting equity in that carbon budgets should be distributed among individuals regardless of geographical scope, a country's wealth or its historical emissions (Ryberg et al., 2020). Conventionally, this is calculated using the existing global and national populations in a selected year (Ryberg et al., 2020). To introduce dynamic accounting into this sharing principle, the forecasted global and national populations from 2020 to 2050 were calculated (UNPD, 2024).

$$RCB_{(EPC)National,2020-2050} = \frac{Pop_{National,2020-2050}}{Pop_{Global,2020-2050}} \times RCB_{Global,2020-2050}$$

Equation 1

Where, $Pop_{National,2020\text{-}2050}$ is the cumulative annual population of ANZ during 2020-2050, $Pop_{Global,2020\text{-}2050}$ is the cumulative annual population of the world during 2020-2050, $RCB_{Global,2020\text{-}2050}$ is the global RCB for 2020-2050, and $RCB_{(EPC)National,2020\text{-}2050}$ is the national RCB for 2020-2050 based on the EPC principle.

Similarly, the GF sharing principle was used to allocate the RCB to ANZ (see Equation 2). The year 2023 was chosen as the GF year to allocate a national share for

2020-2050 as the COVID-19 pandemic would have affected the usual emissions pattern during the 2020-2021 period (Wilson et al., 2020).

$$RCB_{(GF)National,2020-2050} = \frac{Emissions_{National,2023}}{Emissions_{Global,2023}} \times RCB_{Global,2020-2050}$$

Equation 2

Where, $Emissions_{National,2023}$ is ANZ's consumption-based CO_2 emissions in 2023 extracted from Ministry for the Environment (2024d), $Emissions_{Global,2023}$ is the global consumption-based CO_2 emissions in 2023 extracted from Crippa et al. (2022) and $RCB_{(GF)National,2020-2025}$ is the national RCB for 2020-2050 based on GF principle. The consumption-based CO_2 emissions include CO_2 emissions generated domestically and those embodied in imports and excludes CO_2 emissions from goods and services produced domestically but exported for consumption elsewhere.

To obtain the national annual RCB from 2024 onwards, the national CO_2 emissions in 2020, 2021, 2022 and 2023 (from 2020-2023) were subtracted from the calculated RCB (see Equation 3) (Stats NZ, 2023) for both the EPC and GF sharing principles.

$$RCB_{National,2024-2050} = RCB_{National,2020-2050} - Emissions_{National,2020-2023}$$

Equation 3

Where, $Emissions_{National,2020-2023}$ is the cumulative national annual consumption-based CO_2 emissions from 2020-2023.

Then, for the EPC sharing principle, the RCB from the beginning of 2024 was distributed over the years 2024 to 2050 (including 2050) to obtain national annual RCBs (see Appendix C) (Equation 4):

$$RCB_{(EPC)National,t} = \frac{Pop_{National,t}}{Pop_{National,2024-2050}} \times RCB_{National,2024-2050}$$

Equation 4

Where, $RCB_{(EPC)National,t}$ is the national annual RCB of year t based on the EPC sharing principle.

For the GF sharing principle, a dynamic approach was adopted based on the annual emissions forecasted by the Ministry for the Environment (2024d) up to the end of 2050 (see Appendix C). Then, the national annual RCB was calculated considering the forecasted consumption-based emissions in each year (Equation 5):

$$RCB_{(GF)National,t} = \frac{Emissions_{National,t}}{Emissions_{National,2024-2050}} \times RCB_{National,2024-2050}$$

Equation 5

Where, $RCB_{(GF)National,t}$ is the national annual RCB of year t based on the GF sharing principle.

Allocation of RCB from the national level to the building sector was performed using the GF and EVA principles for both the downscaled national annual RCBs (using EPC and GF), resulting in four different combinations of RCB allocations for the building sector: EPC+GF, EPC+EVA, GF+GF, and GF+EVA). In this study, the building sector refers to both residential and non-residential buildings, and the building sectoral emissions and carbon budgets in the analysis covers the entire life cycle of buildings. For the GF sharing principle, the sectoral RCB from 2024-2050 is allocated based on the share of the emissions by the building sector relative to national consumption-based emissions in 2023 (Equation 6):

$$RCB_{(GF)Sector,2024-2050} = \frac{Emissions_{Sector,2023}}{Emissions_{National,2023}} \times RCB_{National,2024-2050}$$

Equation 6

Where $RCB_{(GF)Sector,2024-2050}$ is the sectoral RCB for 2024-2050 based on the GF sharing principle, and $Emissions_{Sector,2023}$ is the sectoral consumption-based emissions for the reference year (2023).

For the EVA sharing principle, it was assumed that the building sector's carbon budget for 2024-2050 reflects the sectoral economic value added to the national GDP in 2023 (Equation 7):

$$RCB_{(EVA)Sector,2024-2050} = EVA_{Sector} \times RCB_{National,2024-2050}$$

Equation 7.

Where $RCB_{(EVA)Sector,\ 2024\text{-}2050}$ is the sectoral RCB from 2024-2050 based on the EVA sharing principle, and EVA_{Sector} is the average building sector's economic value added to the national GDP in 2023 (Stats NZ, 2024a).

Finally, using the GF sharing principle, annual sectoral RCBs were calculated (Equation 8):

$$RCB_{Sector,t} = \frac{Emissions_{Sector,t}}{Emissions_{Sector,2024-2050}} \times RCB_{National,t}$$

Equation 8

Where, $RCB_{Sector,t}$ is sectoral RCB at year t, $RCB_{National,t}$ is national RCB at year based on either EPC or GF, $Emissions_{Sector,t}$ is forecasted consumption-based sectoral emissions at year t, and $Emissions_{Sector,2024\text{-}2050}$ is forecasted consumption-based sectoral emissions from 2024-2050.

And using the EVA sharing principle, sectoral annual RCBs were calculated assuming the EVA from the building sector to the national GDP continues for 2024-2050 the same as the EVA in 2023 (Equation 9):

$$RCB_{Sector,t} = EVA_{Sector} \times RCB_{National,t}$$

Equation 9

7.3.2 National Carbon Debts and Building Sector Decarbonisation

In this section, we calculate the carbon debt for ANZ when emissions exceed the fair share of the RCB based on the carbon debt concept (Matthews, 2016). Dynamic carbon debts for ANZ are derived using annually assessed RCBs. For the first time in ANZ, we propose this dynamic carbon debt framework to assess the feasibility of carbon removal strategies available within the country, mainly focusing on forestry. We evaluate the extent to which land use, land use and change and forestry (LULUCF) can contribute to pay off the national carbon debt and realign national RCB with forecasted emissions. For that, ANZ government projections on LULUCF removals data were used in this study.

These projections are based on the central estimate from the Ministry for the Environment (2024d)'s official projections under its first Nationally Determined Contribution (NDC). These projections assume afforestation on Crown-owned land in ANZ of up to 320,000 hectares from year 2027-2050 (Ministry for the Environment, 2024c) which is guided by existing environmental regulations, including the National Environmental Standards for Commercial Forestry (NES-CF), which manage potential negative impacts such as biodiversity loss, water quality degradation, wildfire risk, and downstream hazards, thereby incorporating land-use constraints and ecological considerations into the afforestation scenarios (Ministry for the Environment, 2024e).Furthermore, this analysis is extended to the building sector, examining its potential role in avoiding the overshoot of RCB through sector-specific timely interventions.

First, we calculated the national annual carbon debt during 2024-2050 taking the difference between the forecasted annual CO_2 emissions and the annual RCB (for both EPC and GF methods) (Equation 10). We then calculated the requirement of additional CDR to stay within the allocated RCB after accounting for the forecasted LULUCF removals by Ministry for the Environment (2024d) in each year (Equation 11).

$$Carbon\ debt_t = RCB_t - Emissions_t$$

Equation 10

$$Additional\ CDR_t = Carbon\ debt_t - LULUCF\ Removal_t$$

Equation 11

Where, $Carbon\ debt_t$ is national carbon debt at year t, RCB_t is RCB at year t, $Emissions_t$ is consumption-based emissions at year t, $Additional\ CDR_t$ is CDR that is needed in addition to the forecasted LULUCF removals at year t, and $LULUCF\ Removal_t$ is forecasted LULUCF removal at year t.

For the building sector's annual carbon debt, we used the same approach as in Equation 10, i.e. taking the difference between sector's annual RCB and sector's forecasted annual consumption-based emissions. We present this sectoral annual carbon debt as the sectoral decarbonisation pathway up to 2050 to stay below 1.5 °C.

7.3.3 Sensitivity Analysis

Sensitivity analysis was undertaken to quantify the influence of key dynamic parameters on the estimated RCBs and associated carbon debts at both national and building sectoral levels. The selection of parameters was informed by their relevance to carbon budget allocation principles and the uncertainties linked with their future trajectories (see Table 7.1).

Table 7.1 Summary of the parameters used in sensitivity analysis

Parameter	Sensitivity analysis	Description
Population	Base Case	ANZ population growth rate will increase by 14% from 2020 to 2050 based on UNPD (2024)
	Sensitivity Analysis 1.1 (SA 1.1)	ANZ population growth rate will increase by 25% from 2020 to 2050
	Sensitivity Analysis 1.2 (SA 1.2)	ANZ population growth rate will decrease by 10% from 2020 to 2050
EVA	Base Case	Building construction EVA to national GDP remains on average rate of 1.96%
	Sensitivity Analysis 2.1 (SA 2.1)	Building construction EVA to national GDP and forecast increases by 10%
	Sensitivity Analysis 2.2 (SA 2.2)	Building construction EVA to national GDP and forecast decreases by 10%
CO_2 emission projection	Base case	Central estimation
	Sensitivity Analysis 3.1 (SA 3.1)	High estimation
	Sensitivity Analysis 3.2 (SA 3.2)	Low estimation

For population, sensitivity bounds were defined by applying a 25% increase (approximately another 11% increase with current predictions) and a 10% decrease to the baseline population growth. For EVA from the building sector to the national GDP, sensitivity bounds were selected by applying a ±10% from the baseline projections. For the GHG emissions forecast, high- and low- estimation scenarios were applied based on

projections by the Ministry for the Environment (2024d). High- and low-projections of future carbon budgets and debts were calculated based on these changes, assuming climate change policies and other measures remained the same as modelled for the base case (Ministry for the Environment, 2024d). For each sensitivity analysis, the RCB and carbon debt were recalculated using the allocation procedures described in Sections 7.2.1. and 7.2.2.

7.4 Results

Section 7.4.1 presents the RCBs for ANZ and its building sector from the year 2020 to 2050, and from the year 2024 to 2050 after the consumption of the RCB during 2020-2023, based on the chosen different sharing principles. The time available to exhaust these RCBs for each approach is presented, based on the forecasted emissions (Ministry for the Environment, 2024d) with existing measures to mitigate these emissions, which reflects the economic conditions and policies in late 2024.

Section 7.4.2 examines the carbon debts at national and building sectoral levels, and shows the additional CDR needed at national scale to stay within the allocated RCBs.

Section 7.4.3 examines the influence of dynamic parameters on the RCBs and carbon debts at national and building sectoral levels and how selection of sharing principles to downscale budgets influence the development of policies and strategies in countries and sectors.

7.4.1 National and Sectoral RCBs

National RCBs based on EPC and GF from year 2020 and from year 2024 are presented in Figure 7.1. The results show that EPC allocates national RCB that are lower than those allocated based on GF, primarily due to the lower ANZ population, and the higher consumption-based CO_2 emissions associated with ANZ's economy, relative to other countries in the world. Furthermore, using EPC, the RCBs from 2024 show a 41-81% reduction range compared to RCBs from 2020, highlighting the significant impact of consumption-based emissions in ANZ from 2020-2023 on RCB. Similarly, for GF, RCBs from 2024 are 26-51% lower than RCBs from 2020. These results highlight how fast

current emission trajectories are exhausting the RCBs. Based on these RCBs up to 2050, it is important to understand the decarbonisation pathway that ANZ needs to follow over these future years to stay within the RCBs.

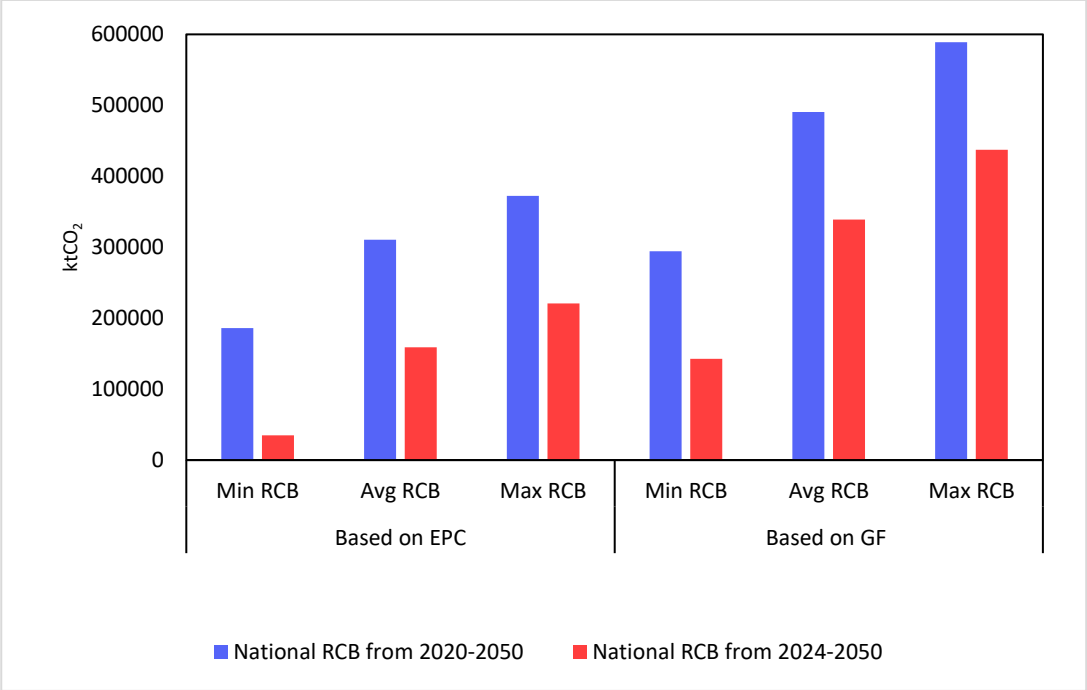


Figure 7.1 Remaining carbon budgets of Aotearoa New Zealand from 2020-2050 and from 2024-2050 using equal per capita and grandfathering sharing approaches

The RCB exhaustion timelines based on the forecasted consumption-based emissions are presented in Figure 7.2 for both EPC and GF sharing principles, showing the variations between the exhaustion years based on RCBs from 2020 and from 2024. Figure 7.2 highlights the extent to which the actual consumption-based emissions from 2020-2023 affect the exhaustion timeline. Following the consumption of the allocated RCB from 2020-2023, the exhaustion years occur significantly earlier. This contraction suggests that current rate of emissions in ANZ may continue to contract the timeline even more after 2023. The RCB for the lower bound derived using EPC has already been exceeded in 2024. Across all the RCBs analysed, the budget exhaustion has now drawn significantly closer, with current emission trends indicating exhaustion of the lower bound RCB within the next 10 years.

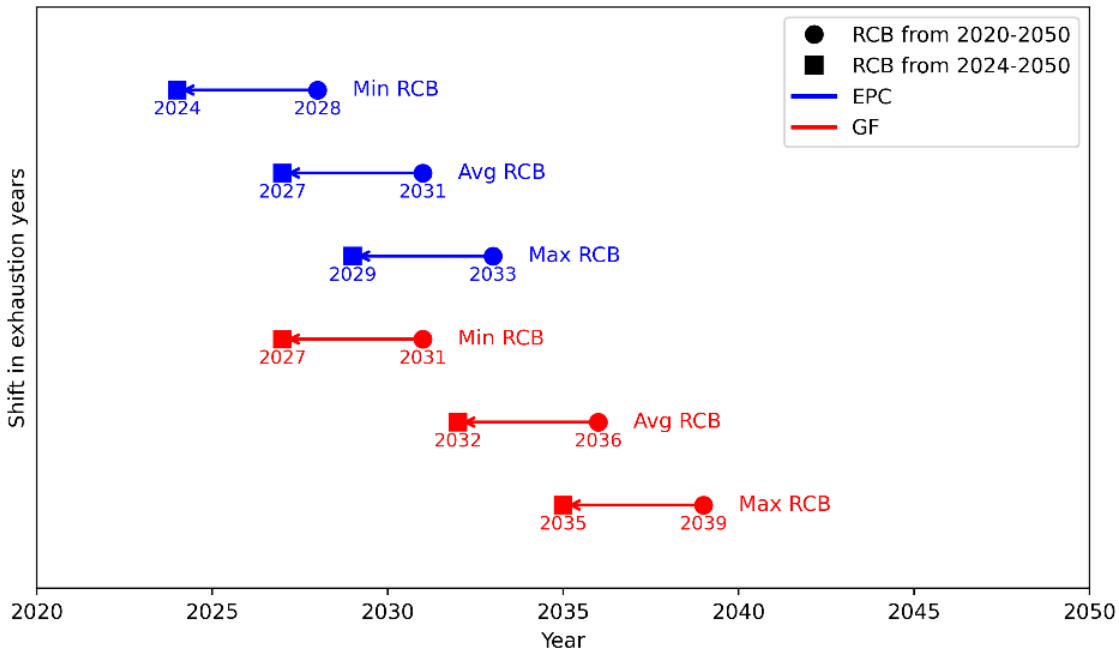


Figure 7.2 Possible exhaustion years of remaining carbon budgets and their shifts due to the emissions from 2020-2023 in Aotearoa New Zealand

The national dynamic RCB allocations are presented in Figure 7.3, illustrating how the previously calculated RCBs for 2024-2050 have been distributed over the years. The results show the EPC and GF principles yield distinctly different budgets at year 2024 but converge towards year 2050 with overlapping ranges. For the EPC, the dynamic RCB gradually increases due to the population growth forecast (UNPD, 2024). For the GF, the dynamic RCB decreases reflecting ANZ forecasted emission pathway towards net-zero emissions (Ministry for the Environment, 2024d).

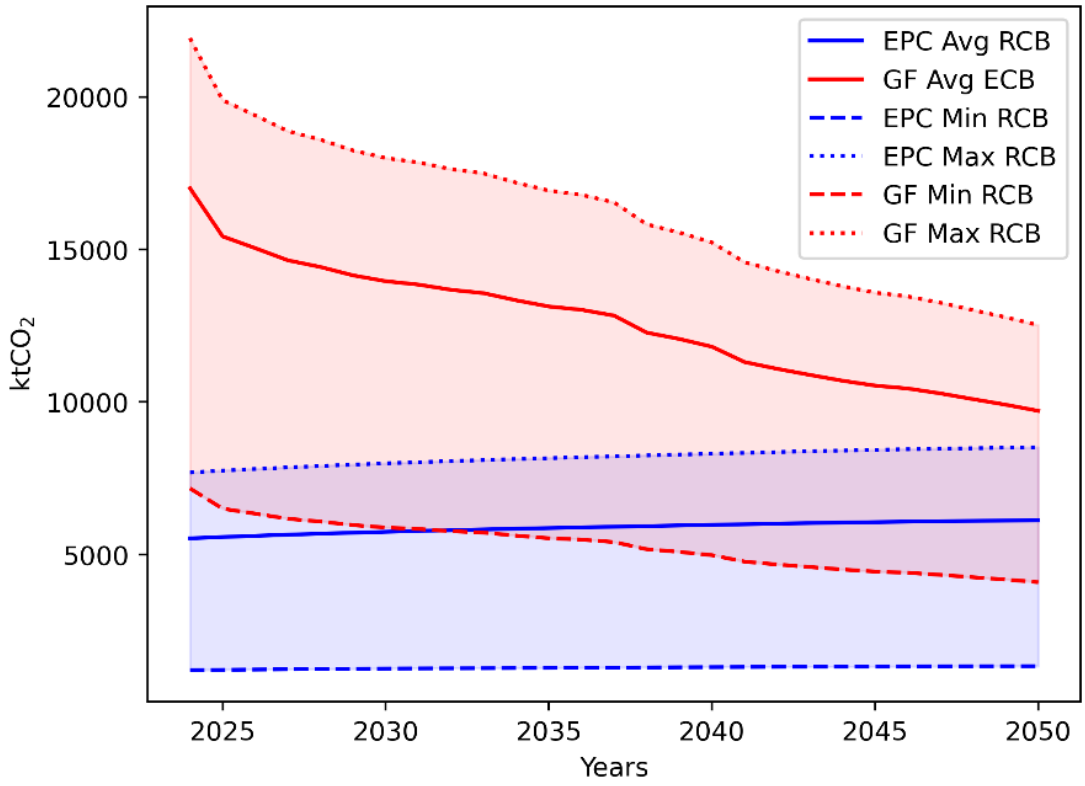


Figure 7.3 National dynamic remaining carbon budgets from 2024-2050 using equal per capita and grandfathering sharing principles (Same as Figure 6.1)

Dynamic RCBs allocated to ANZ building sector throughout 2024-2050 and the actual sectoral emissions in year 2022 are illustrated in Figure 7.4. The RCBs are shown using the four principles described in Section 7.3.1. The results show that the sectoral dynamic RCBs are significantly lower compared to the actual sectoral consumption-based emissions in year 2022. For all the RCBs derived from the four approaches, none are achievable in the near term if sectoral emissions continue to be same as in 2022. To achieve at least the maximum RCB using GF+GF approach, a 41% reduction from the year 2022 emissions is required. Similarly, for the minimum RCB using EPC+EVA approach, a 99% reduction is necessary. These findings suggest that the current sectoral

emission levels are significantly above target, making it exceptionally challenging for ANZ building sector to operate within 1.5 °C.

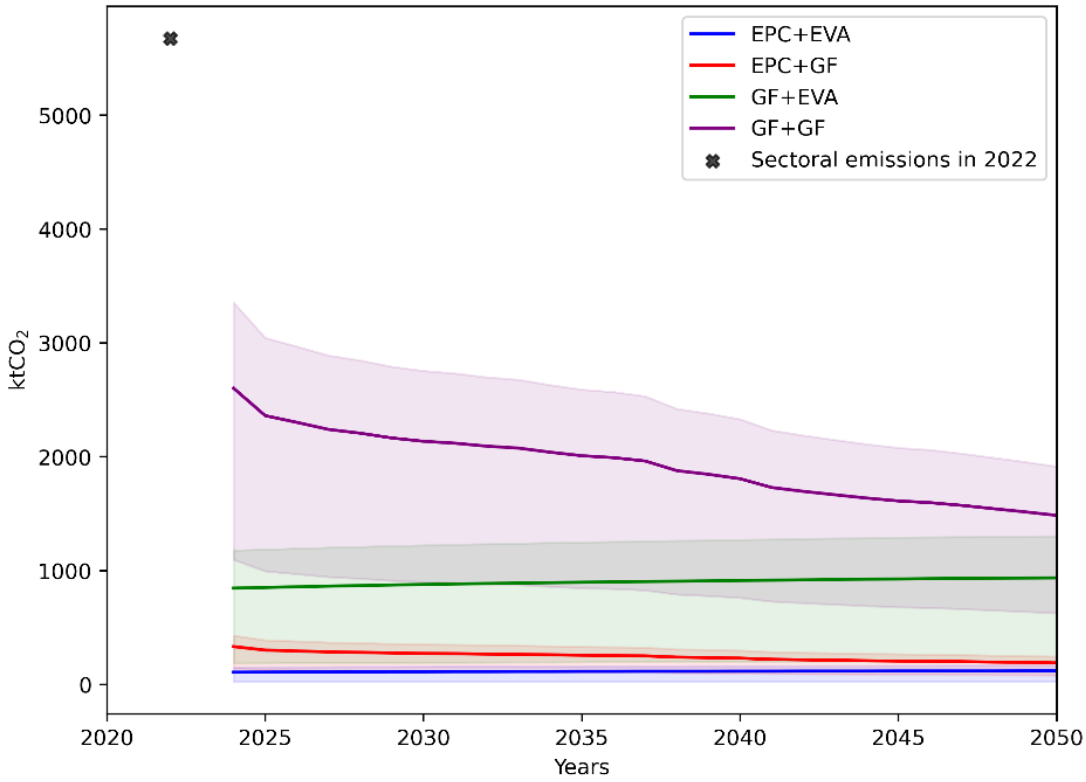


Figure 7.4 Sectoral annual remaining carbon budgets from 2024-2050 using different approaches and actual emissions in year 2022

7.4.2 National and Sectoral Carbon Debts

National dynamic RCBs, carbon debts and the forecasted emission pathways are shown in Figure 7.5(a). Our analysis suggests that ANZ needs to remove a total of 283.2-685.8 $MtCO_2$ during 2024-2050 to align with the 1.5 °C target. The results were derived based on EPC and GF principles, with a minimum and maximum range over years 2024-2050. For EPC, the higher carbon debts are due to lower allocated RCBs, and for GF the lower carbon debts are due to higher allocated RCBs. For all the results, Figure 7.5(a) shows that, initially, the carbon debts are relatively high due to current emissions. However,

carbon debts reduce over time as the forecasted emissions gradually reduce, requiring fewer offset efforts to stay within the budgetary limits.

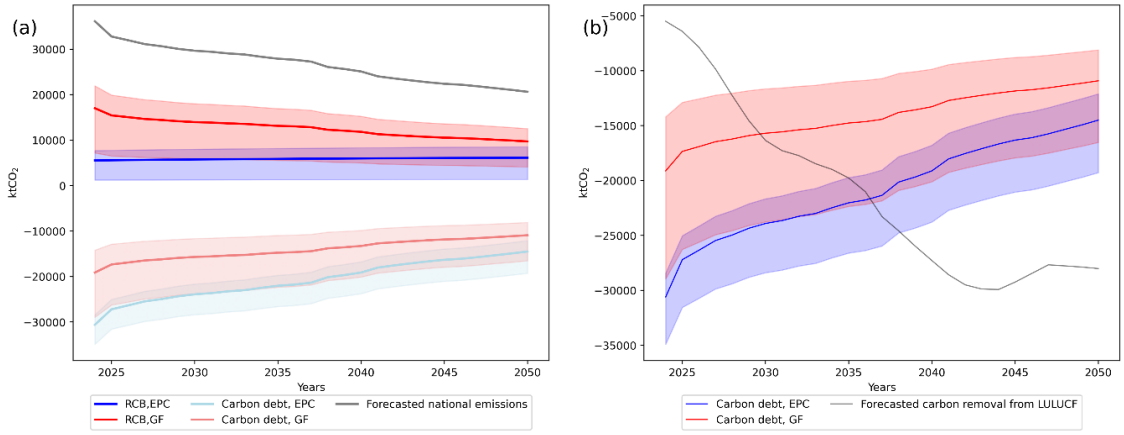


Figure 7.5 (a) National dynamic remaining carbon budgets and dynamic carbon debts from 2024-2050 to stay below 1.5 ºC warming and forecasted national emissions (b) National dynamic carbon debts and forecasted carbon removal from land use, land use change and forest

Figure 7.5(b) presents the calculated national dynamic carbon debts alongside the forecasted carbon removal from LULUCF as projected by the Ministry for the Environment (2024d) for NDC calculations. During 2024-2050, the total carbon removal forecasted by the ANZ Ministry for the Environment is 574.2 $MtCO_2$. Based on the allocated national RCBs and forecasted national CO_2 emissions, there needs to be a total carbon removal of 283.2 $MtCO_2$ based on upper bound and 685.8 $MtCO_2$ based on lower bound estimations during the same period; this amount can be interpreted as the additional mitigation requirement. However, use of the dynamic approach has allowed for a more precise identification of the required timing and magnitude of these mitigation activities. For example, Figure 7.5(b) shows the annual credit from forecasted removals due to afforestation (grey line) goes below the annual carbon debt after 2028 (lower bound based on GF) and after 2038 (higher bound based on EPC); in other words, this is the year when the national carbon removal via afforestation starts to offset the lower bound of the carbon debt to align with the 1.5 °C target. This highlights that national carbon removal via afforestation is not sufficient until 2028 even for the lower bound carbon debt. It

highlights the urgent need for near-term mitigation actions, as delays will mean that ANZ is not aligned with the 1.5 °C target.

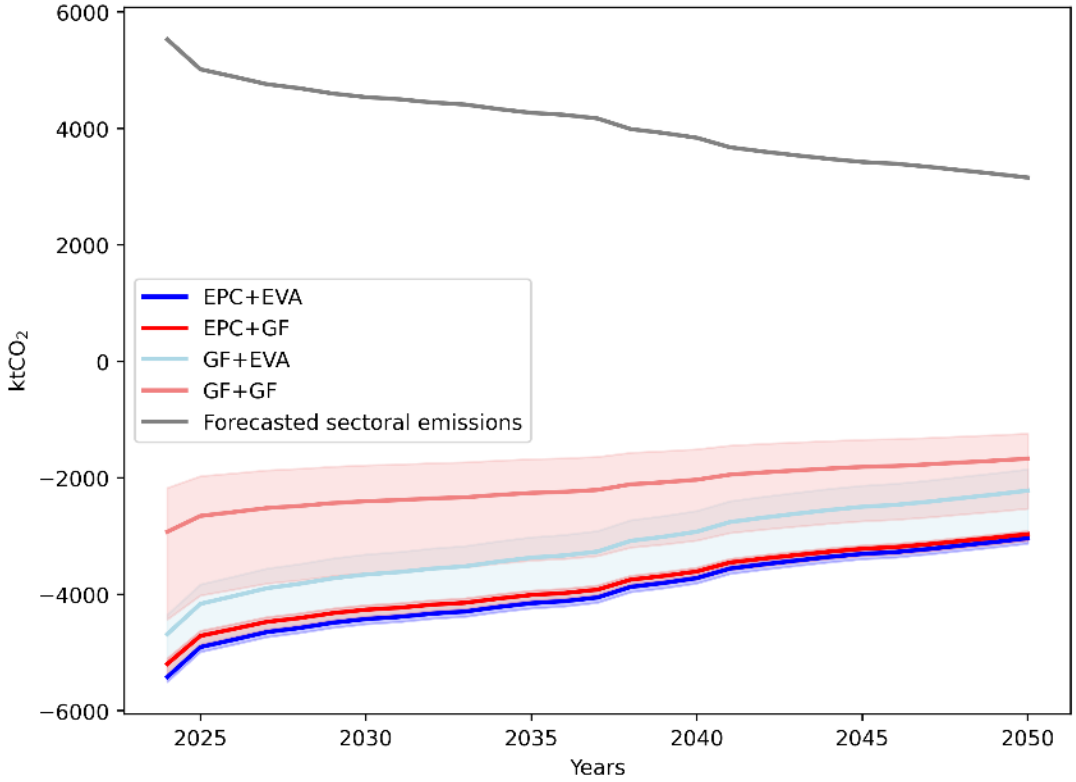


Figure 7.6 Building sector annual carbon debts during 2024-2050 and forecasted sectoral emission pathway with existing measures

Due to the substantial gap between forecasted building sectoral emission levels and RCBs, our analysis shows that the building sector needs to remove a total of 43.3-109.6 $MtCO_2$ (lower and upper bounds) during 2024-2050 to align with the 1.5 °C target. The timing and annual carbon debts that need to be addressed during 2024-2050 are presented in Figure 7.6 for each approach. The four approaches result in different carbon debts; the lower bound is associated with the GF+GF approach and the upper bound is associated with the EPC+EVA approach. Moreover, Figure 7.6 shows that, although annual emissions in the building sector are forecasted to decline over time, the corresponding carbon debts continue up to 2050. This indicates that the importance of defining additional and continuing mitigation strategies in the building sector over future years.

7.4.3 Sensitivity Analysis Results

The sensitivity analysis examined the influence of future changes in three dynamic parameters (population growth rate, EVA for the building sector as a proportion of the national GDP, and CO_2 emission projection) (see Section 7.3.3.) on the estimated RCBs for 2024-2050 and on cumulative carbon debts until 2050. The scenarios were developed assuming that other policies and measures remain the same as those in the baseline calculations. Table 7.2 presents the percentage change in the national RCB from 2024-2050 relative to the baseline for each sensitivity analysis for both EPC and GF sharing principles.

Table 7.2 Impact of parameter variation on the national remaining carbon budgets for 2024-2050 under the EPC and GF sharing principles

	EPC			GF		
Sensitivity Analysis	Min	Avg	Max	Min	Avg	Max
SA 1.1 (+25% population growth)	17.06%	6.22%	5.36%	-	-	-
SA 1.2 (-10% population growth)	-67.75%	-24.68%	-21.30%	-	-	-
SA 2.1 (+10% EVA to GDP)	-	-	-	-	-	-
SA 2.2 (-10% EVA to GDP)	-	-	-	-	-	-
SA 3.1 (High emission forecast)	-0.08%	-0.02%	-0.01%	-0.02%	-0.01%	-0.01%
SA 3.2 (Low emission forecast)	2.40%	0.52%	0.38%	0.58%	0.25%	0.19%

The results indicate that population forecast exert the biggest influence on the RCB when calculated using the EPC sharing principle. In particular, a +25% increase in the population growth rate results in a RCB increase ranging from 5% to 17% while a -10% decrease in the population growth results in a RCB decline ranging from 21-67% compared to the baseline results. Conversely, variations in population growth rate have no effect on the RCB when derived using GF sharing principle. National CO_2 emissions forecasts have a relatively small influence on national RCBs under both sharing principles. Lower CO_2 emissions estimates lead to an increase in RCB, whereas higher emissions estimates reduce the available budget. As expected, changes in the relative

contribution of the building sector's EVA to national GDP demonstrates no measurable effect on RCB outcomes for either sharing principle, as the relevant national parameters are not changed.

The influence of these parameters on the cumulative carbon debts is shown in Table 7.3. It shows the percentage change in the carbon debt until 2050 relative to the baseline carbon debt for each sensitivity case for both the EPC and GF sharing principles.

Table 7.3 Impact of parameter variation on national cumulative carbon debts until 2050 under EPC and GF sharing principles

Sensitivity Analysis	EPC			GF		
	Min	Avg	Max	Min	Avg	Max
SA 1.1	-0.86%	-1.76%	-2.37%	-	-	-
SA 1.2	3.43%	6.98%	9.42%	-	-	-
SA 2.1	-	-	-	-	-	-
SA 2.2	-	-	-	-	-	-
SA 3.1	4.81%	5.87%	6.60%	5.71%	8.64%	11.64%
SA 3.2	-6.96%	-8.50%	-9.56%	-8.27%	-12.52%	-16.86%

The sensitivity analysis for carbon debts gives results that inversely mirror the patterns observed for the sensitivity analysis of the RCBs, although the magnitude of change does not correspond exactly to the percentage variations in the RCB. The inverse mirroring effect arises because an increased RCB reduces the carbon debt that must be addressed to meet 1.5 °C warming. Conversely, a reduction in RCB results in a higher carbon debt for the given forecasted emissions, thereby requiring greater mitigation efforts to achieve the required targets. However, the magnitude of the changes varies because carbon debts depend on both RCBs and the removals from LULUCF.

For the building sector RCB sensitivity analysis, the results were evaluated using the same four sharing approaches as used for the national analysis (EPC+EVA, EPC+GF, GF+EVA and GF+GF). The sectoral RCBs for the EPC+GF and GF+GF sharing approaches exhibit change patterns similar to the corresponding national change patterns. However, where EVA formed part of the sharing approach (SA2.1 and SA2.2), it resulted in a ±10% change in RCBs (i.e. for the EPC+EVA and GF+EVA sharing approaches).

Similarly, the influence of emissions projections on sectoral RCBs (SA 3.1 and SA 3.2) revealed the same proportional changes in national RCBs. For instance, sectoral RCBs derived from EPC+EVA and GF+EVA responded in a manner comparable to the national RCBs from the EPC sharing principle, while sectoral RCBs from EPC+GF and GF+GF reflected change patterns similar to those of the national RCBs derived from the GF sharing principle.

7.5 Discussion

7.5.1 Communication of the Urgency to Undertake Near-Term Mitigation Actions

The importance of near-term rapid emissions reduction at both national and sectoral levels is highlighted using the dynamic approach described in this research. Regardless of the sharing principles employed, the projected possible exhaustion years shift closer to the present as each year passes, indicating a more rapid depletion of the available RCB. This is primarily driven by the current emission trajectories, which accelerate the RCB reduction rate. Also, the results suggest a high probability that the average RCB derived using EPC and minimum RCB derived using GF may have already been exhausted or is at imminent risk of being exhausted based on current emissions. Although the maximum RCB is also declining rapidly, similar to the minimum and average budget scenarios, its projected exhaustion under current emission trends is expected around the year 2029 and 2035 based on the EPC and GF sharing principles respectively (Figure 7.2). This shows a comparatively extended timeline for mitigation under the maximum RCB which is based on scenarios where climate change due to non-CO_2 GHG emissions are limited to approximately 0.05°C (IPCC, 2023; Rogelj & Lamboll, 2024). Conversely, failure to achieve significant reductions in non-CO_2 GHG emissions will lead to a substantially smaller RCB, thereby necessitating the near-term implementation of additional mitigation measures to remain within the 1.5 °C target. However, government emission projections such as those calculated for emission reduction plans, the national GHG inventory, and LULUCF are subject to change, potentially altering carbon budgets, exhaustion timelines and carbon debts. Therefore, the most recent emissions projections need to be accounted

when communicating the degree of urgency for mitigation measures in the medium to long term.

The results highlight the necessity of timely mitigation strategies instead of relying on long-term recovery to avoid the overshoot (Reisinger et al., 2025). The dynamic carbon debt framework based on forecasted emissions pathways and dynamic RCBs described in this research can inform development of quantitative and time-sensitive strategies to mitigate climate change. Particularly at the building sector level, the dynamic carbon debts suggest the sector's urgent requirement for additional mitigation measures to address climate change to stay within the 1.5 °C target. A time-phased decarbonisation strategy for the ANZ's building sector can align with national legislated climate targets under the Climate Change Response Act (New Zealand Legislation, 2019). For short-term strategies (2025-2030), government procurement rules and Green Building Star rating frameworks could require low carbon construction materials for designing new buildings and refurbishing existing buildings (Ministry of Business Innovation and Employment, 2020). As ANZ plans to achieve 100% renewable electricity generation by 2030 (Ministry of Business Innovation and Employment, 2023), Building Code updates could mandate net-zero operational emissions for all new buildings. Other short-term additional measures include the promotion of circular economy principles through programme to support the reuse and recycling of building components, refurbishment of existing buildings rather than constructing new buildings, design for disassembly and reuse, and more efficient use of existing buildings (Zimmermann et al., 2020). In the medium-term (2030-2040), as ANZ plans to develop a road map for the ANZ Building Code, it could include mandatory requirements to achieve net-zero for whole life embodied carbon for building materials, processes and disposal of materials (Ministry of Business Innovation and Employment, 2020). In addition to that, the ANZ Building Code could introduce legally binding whole-life carbon limit values for new buildings (Tozan et al., 2024) and introduce roadmaps for limit values of new buildings and refurbishments of existing buildings aligning with international best practices (e.g.OECD (2025)). In the long-term (2040-2050), policies could be strategically aligned across relevant industries (e.g. aluminium and steel), the energy sector, and the building sector to achieve net-zero by 2050 (Ministry for the Environment, 2024c). This could also extend to address the role of the New Zealand Emission Trading Scheme (NZ ETS) in supporting cross-sectoral emission strategies (Ministry for the Environment, 2024c).

Furthermore, this research suggests that a critical reassessment of national mitigation pathways needs to be conducted in order to show alignment - or not - with dynamic RCBs. It should include, where appropriate, integration of dynamic parameters into the investigated mitigation pathways (Forster et al., 2024; Reisinger et al., 2025). Delays in implementing low-carbon measures will accelerate carbon budget depletion (as observed under high-emission projections in the sensitivity analysis, Section 7.3.3). Therefore, future research on alternative policy interventions should include sensitivity analysis of the timing of policy interventions as a dynamic parameter. This could also include how the NZ ETS can be used to support sectoral decarbonisation aligned with advanced policies like carbon taxes (Du et al., 2025; Jia et al., 2025; OECD, 2025).

7.5.2 Use of a Dynamic Approach for Setting Budgets

A key contribution of this study is the use of a dynamic modelling approach, in which the main parameters used to downscale budgets are modelled as time-dependent in order to calculate national and sectoral RCBs and debts. At the national level, population growth projections up to 2050 were integrated into the population calculations for the EPC principle, and forecasted CO_2 emissions up to 2050 were used for the GF principle, to reflect their influence on the share of future national budgets. However, it should be noted that these forecasts are inherently uncertain due to the influence of parameters such as future socio-economic conditions, weather patterns, pandemics, technology advancements, and national and international politics. For example, the Ministry for the Environment (2024d) emphasises that forecasting of future electricity GHG emissions is particularly uncertain due to the changing weather conditions affecting hydroelectricity generation in ANZ. Moreover, in ANZ, there is significant potential for emission reductions driven by technological advancements in wind and solar energy systems, which could alter future energy scenarios if there is accelerated renewable energy deployment (Pimentel Pincelli et al., 2024).

In addition to the use of dynamic parameters for calculating future population and CO_2 emissions, this study allocates annual budgets across future years up to 2050. The results emphasise the need for additional mitigation efforts beyond those projected in ANZ government forecasts (Ministry for the Environment, 2024d). The annual national RCBs enable a time-differentiated comparison with forecasted removals, and identify the timing

and magnitude of any shortfalls that require additional interventions. At the building sectoral level, this approach exposes unrealistic budget allocations, thereby emphasising the urgent need to implement realistic mitigation measures to address near-term annual carbon debts. From a policy perspective, this dynamic approach enables policymakers to identify critical time-differentiated intervention points so that they can prioritise time-differentiated mitigation strategies.

This study focused on a limited number of dynamic parameters in setting RCBs and carbon debts. However, future research could address additional dynamic parameters affecting the RCB such as atmospheric CO_2 concentrations (Bennedsen et al., 2023), the influence of land and ocean CO_2 uptake (Bennedsen et al., 2023; Silvy et al., 2024), the influence of non-CO_2 radiative agents (Silvy et al., 2024), the country's GDP forecasts, and sectoral economic contribution forecasts. For carbon debt calculations, it was assumed that removals due to exotic forest expansion could proceed without any external constraints over future years - but future studies could account for how dynamics in agricultural, urban and conservation practices might influence this intervention. Additionally, for carbon debts, future research could explore how the rate of technology diffusion for alternative CDR technologies might influence the timing of carbon removals in the ANZ context. Finally, future research could assess the intersectoral dynamics - in particular, activities in the energy, transport, and material extraction and processing sectors - may contribute to mitigating the building sector's carbon debt. For example, climate change mitigation strategies in ANZ concrete industry (Concrete NZ, 2023) and steel industry (Ministry for the Environment, 2023c), and low-carbon innovations in the building sector (Du et al., 2023; Zhong et al., 2024) will influence the embodied GHG emissions of future construction materials.

7.5.3 Provision of a Range of RCBs

The choice of sharing principle directly influences the magnitude of RCBs, which in turn affects decision-making processes and the formulation of long-term strategies. Consequently, relying solely on one single sharing principle to determine RCBs and carbon budgets could lead to overly or insufficiently restricted climate change mitigation policy (Alaux et al., 2025). The use of two sharing principles, chosen to provide upper and lower bounds for allocating global RCBs among nations, reflects an appropriate level

of accuracy for informing policymaking given the uncertainties in forecasting population sizes, GHG emissions, technology development, economic trajectories, etc. up to 2050.

The sharing approaches are based on different sharing principles. As such, choice of a sharing approach is associated with an implicit value judgment that may advantage certain countries by aligning with their specific socio-economic or demographic characteristics (Williges et al., 2022). For example, the EPC principle inherently prioritises distributive equality, whereas the GF principle advantages countries with relatively higher historic GHG emissions, providing a relative carbon accounting advantage to countries with higher populations and higher GHG emissions respectively. This fairness concern is relevant not only for national level policies but also for political acceptability and legitimacy at a global scale. Therefore, future research could investigate the setting of dynamic RCBs and carbon debts by incorporating a responsibility-capability-based allocation guiding principle (e.g. common but differentiated responsibilities (CBDR) which is recognised by the UNFCCC (1992)).

In addition, this study is also limited by the assumptions used in setting the global RCB (IPCC, 2023). This has been addressed to a certain extent by incorporating RCBs with maximum and minimum values to account for uncertainties related to the assumption that future non-CO_2 warming aligns with stringent mitigation pathways (where non-CO_2 GHG and aerosols contribute approximately 0.1°C of additional warming above the 2010-2019 baseline). Minimum and maximum global RCB values were used as calculated by the IPCC (2023), i.e. accounting for the situation where actual non-CO_2 emissions are either higher or lower than the projected contribution of non-CO_2 GHG emissions.

7.6 Conclusion

This study addresses the limitations of conventional static carbon budget allocation methods by explicitly integrating dynamic parameters into calculation of national and sectoral dynamic RCBs over time. A dynamic carbon debt framework is proposed that can inform the development of additional strategies needed to achieve climate targets. The dynamic carbon budget framework described in this study facilitates a greater appreciation of the urgency of implementing rapid mitigation strategies at national and economic sector levels. This is achieved by: (i) integrating temporal dynamics into

parameters that affect forecasted GHG emissions and RCBs, (ii) calculating dynamic carbon debt results that show the shortfall between forecasted mitigation measures and GHG emissions, (iii) presenting time-differentiated results, and (iv) representing modelling uncertainties through use of ranges based on two sharing approaches as upper and lower bounds for the assessment, and use of minimum and maximum values for the RCB to account for the uncertainties in non-CO_2 GHG emissions.

For Aotearoa New Zealand, the dynamic carbon debt framework facilitates understanding of the magnitude and need for timely interventions for CDR. At the building sectoral level, the study results using this framework highlight that the downscaled RCBs are unrealistic and currently unachievable for this sector. There is therefore an urgent need for development of an immediate building sector time-differentiated decarbonisation pathway in order to stay below the 1.5 °C target. Furthermore, as the dynamic carbon debt framework shows the range of downscaled RCBs and carbon debts depend upon future non-CO_2 GHG emissions, it highlights the importance of additionally limiting non-CO_2 GHG emissions in the wider ANZ economy.

In summary, use of the dynamic carbon debt framework can inform translation of ambitious carbon targets (such as alignment with the 1.5 °C target by 2050) into time-differentiated milestones with associated mitigation strategies to support climate policymaking at national and sectoral levels.

References

Acosta, S. C., Grimes, A. L., & Leining, C. (2020). *Decision trees: Forestry in the New Zealand Emissions Trading Scheme post-2020*. Motu Economic and Public Policy Research.

Alaux, N., Steubing, B., Habert, G., Ruschi Mendes Saade, M., & Passer, A. (2025). Future Life-Cycle Greenhouse Gas Emission Scenarios for the Austrian Building Stock: A Systematic Approach. *Environmental Science & Technology*, *59*(10), 4962-4973.

Algunaibet, I. M., Pozo, C., Galán-Martín, Á., Huijbregts, M. A., Mac Dowell, N., & Guillén-Gosálbez, G. (2019). Powering sustainable development within planetary boundaries. *Energy & Environmental Science*, *12*(6), 1890-1900.

Bai, X., Hasan, S., Andersen, L. S., Bjørn, A., Kilkiş, Ş., Ospina, D., Liu, J., Cornell, S. E., Sabag Muñoz, O., de Bremond, A., Crona, B., DeClerck, F., Gupta, J., Hoff, H., Nakicenovic, N., Obura, D., Whiteman, G., Broadgate, W., Lade, S. J., . . . Zimm, C. (2024). Translating Earth system boundaries for cities and businesses. *Nature Sustainability*, *7*(2), 108-119. https://doi.org/10.1038/s41893-023-01255-w

Bednar, J., Obersteiner, M., Baklanov, A., Thomson, M., Wagner, F., Geden, O., Allen, M., & Hall, J. W. (2021). Operationalizing the net-negative carbon economy. *Nature*, *596*(7872), 377-383. https://doi.org/10.1038/s41586-021-03723-9

Bednar, J., Obersteiner, M., & Wagner, F. (2019). On the financial viability of negative emissions. *Nature Communications*, *10*(1), 1783. https://doi.org/10.1038/s41467-019-09782-x

Bennedsen, M., Hillebrand, E., & Koopman, S. J. (2023). A multivariate dynamic statistical model of the global carbon budget 1959–2020. *Journal of the Royal Statistical Society Series A: Statistics in Society*, *186*(1), 20-42.

Bjørn, A., Chandrakumar, C., Boulay, A.-M., Doka, G., Fang, K., Gondran, N., Hauschild, M. Z., Kerkhof, A., King, H., Margni, M., McLaren, S., Mueller, C., Owsianiak, M., Peters, G., Roos, S., Sala, S., Sandin, G., Sim, S., Vargas-Gonzalez, M., & Ryberg, M. (2020). Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. *Environmental Research Letters*, *15*(8), 1-23. https://doi.org/10.1088/1748-9326/ab89d7

Bullen, L., McLaren, S. J., & Dowdell, D. (2021). *Carbon budget of New Zealand buildings: A sensitivity assessment*. BRANZ.

Bullen, L., McLaren, S. J., Dowdell, D., & Chandrakumar, C. (2021). Absolute sustainability of New Zealand office buildings in the context of climate targets. *Building and Environment*, *205*. https://doi.org/10.1016/j.buildenv.2021.108186

Cabeza, L. F., Bai, Q., Bertoldi, P., Kihila, J. M., Lucena, A. F., Mata, É., Mirasgedis, S., Novikova, A., & Saheb, Y. (2022). Buildings. in IPCC, 2022: climate change 2022: mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. In: Cambridge University Press Cambridge, UK and New York, NY, USA) doi.

Chandrakumar, C., Malik, A., McLaren, S. J., Owsianiak, M., Ramilan, T., Jayamaha, N. P., & Lenzen, M. (2020). Setting Better-Informed Climate Targets for New Zealand: The Influence of Value and Modeling Choices. *Environ Sci Technol*, *54*(7), 4515-4527. https://doi.org/10.1021/acs.est.9b06991

Chandrakumar, C., McLaren, S. J., Dowdell, D., & Jaques, R. (2020). A science-based approach to setting climate targets for buildings: The case of a New Zealand

detached house. *Building and Environment*, *169*, 106560. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106560

Concrete NZ. (2023). *Roadmap to Net-Zero Carbon for Aotearoa New Zealand's Concrete Industry*. Retrieved May 29 from https://concretenz.org.nz/page/2050_roadmap

Crippa, M., Guizzardi D., Banja M., Solazzo E., Muntean M., Schaaf E., Pagani F., Monforti-Ferrario F., Olivier, J. G. J., Quadrelli, R., Grassi, G., Rossi, S., Oom, D., Branco, A., San-Miguel, J., & Vignati, E. (2022). *CO2 emissions of all world countries*

Dao, H., Peduzzi, P., & Friot, D. (2018). National environmental limits and footprints based on the Planetary Boundaries framework: The case of Switzerland. *Global Environmental Change*, *52*, 49-57. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2018.06.005

Dooley, K., & Kartha, S. (2018). Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *International Environmental Agreements: Politics, Law and Economics*, *18*(1), 79-98. https://doi.org/10.1007/s10784-017-9382-9

Du, Q., Ma, M., Lu, C., Wang, X., & Bai, L. (2025). Assessing the impact of emission trading scheme and carbon tax in the building sector: An embodied carbon perspective. *Environmental Impact Assessment Review*, *111*, 107732. https://doi.org/https://doi.org/10.1016/j.eiar.2024.107732

Du, Q., Wang, Y., Pang, Q., Hao, T., & Zhou, Y. (2023). The dynamic analysis on low-carbon building adoption under emission trading scheme. *Energy*, *263*, 125946. https://doi.org/https://doi.org/10.1016/j.energy.2022.125946

Evison, D., & Mason, E. (2017). The role of forestry in helping New Zealand reduce carbon emissions to the atmosphere.

Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Hall, B., Hauser, M., Ribes, A., Rosen, D., & Gillett, N. P. (2024). Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data*, *16*(6), 2625-2658.

Ghose, A., McLaren, S. J., & Dowdell, D. (2020). Upgrading New Zealand's existing office buildings – An assessment of life cycle impacts and its influence on 2050 climate change mitigation target. *Sustainable Cities and Society*, *57*, 102134. https://doi.org/https://doi.org/10.1016/j.scs.2020.102134

Gueret, A., Malliet, P., Saussay, A., & Timbeau, X. (2018). *An explorative evaluation of the climate debt* OFCE; OFCE].

Horup, L. H., Birgisdóttir, H., & Ryberg, M. W. (2023). Defining dynamic science-based climate change budgets for countries and absolute sustainable building targets. *Building and Environment*, *230*. https://doi.org/10.1016/j.buildenv.2022.109936

IPCC. (2023). *Climate Change 2023: Synthesis Report*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

Jia, Z., Wen, S., & Wu, R. (2025). Synergistic effect of emission trading scheme and carbon tax: A CGE model-based study in China. *Environmental Impact Assessment Review*, *110*, 107699. https://doi.org/https://doi.org/10.1016/j.eiar.2024.107699

Lahn, B. (2020). A history of the global carbon budget. *WIREs Climate Change*, *11*(3), e636. https://doi.org/https://doi.org/10.1002/wcc.636

Li, M., Pelz, S., Lamboll, R., Wang, C., & Rogelj, J. (2025). A principle-based framework to determine countries' fair warming contributions to the Paris Agreement. *Nature Communications*, *16*(1), 1043. https://doi.org/10.1038/s41467-025-56397-6

Lucas, P. L., Wilting, H. C., Hof, A. F., & van Vuuren, D. P. (2020). Allocating planetary boundaries to large economies: Distributional consequences of alternative perspectives on distributive fairness. *Global Environmental Change*, *60*, 102017. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2019.102017

Matthews, H. D. (2016). Quantifying historical carbon and climate debts among nations. *Nature Climate Change*, *6*(1), 60-64. https://doi.org/10.1038/nclimate2774

Matthews, H. D., Tokarska, K. B., Nicholls, Z. R. J., Rogelj, J., Canadell, J. G., Friedlingstein, P., Frölicher, T. L., Forster, P. M., Gillett, N. P., Ilyina, T., Jackson, R. B., Jones, C. D., Koven, C., Knutti, R., MacDougall, A. H., Meinshausen, M., Mengis, N., Séférian, R., & Zickfeld, K. (2020). Opportunities and challenges in using remaining carbon budgets to guide climate policy. *Nature Geoscience*, *13*(12), 769-779. https://doi.org/10.1038/s41561-020-00663-3

Matthews, H. D., Tokarska, K. B., Rogelj, J., Smith, C. J., MacDougall, A. H., Haustein, K., Mengis, N., Sippel, S., Forster, P. M., & Knutti, R. (2021). An integrated approach to quantifying uncertainties in the remaining carbon budget. *Communications Earth & Environment*, *2*(1), 7. https://doi.org/10.1038/s43247-020-00064-9

McLaren, S. J., Chandrakumar, C., Dowdell, D., Bullen, L., & Jaques, R. (2020). Application of Absolute Sustainability Assessment to New Zealand Residential Dwellings. *IOP Conference Series: Earth and Environmental Science*, *588*(2). https://doi.org/10.1088/1755-1315/588/2/022064

Mengis, N., & Matthews, H. D. (2020). Non-CO2 forcing changes will likely decrease the remaining carbon budget for 1.5 °C. *npj Climate and Atmospheric Science*, *3*(1), 19. https://doi.org/10.1038/s41612-020-0123-3

Ministry for the Environment. (2023a). *Carbon removals strategy*. Ministry for the Environment,. https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/carbon-removals-strategy/

Ministry for the Environment. (2023b). *Developing a carbon removals strategy*. Ministry for the Environment,. https://environment.govt.nz/news/developing-a-carbon-removals-strategy/

Ministry for the Environment. (2023c, 22 May 2023). *Government partnership with NZ Steel set to unlock massive emissions reductions*. https://environment.govt.nz/news/government-partnership-with-nz-steel-set-to-unlock-massive-emissions-reductions/

Ministry for the Environment. (2024a). *New Zealand's Greenhouse Gas Inventory 1990–2022: Snapshot*. Ministry for the Environment, Retrieved from https://environment.govt.nz/assets/publications/GHG-inventory-2024-Snapshot.pdf

Ministry for the Environment. (2024b). *New Zealand's second emission reduction plan 2026-2030: Technical annex*.

Ministry for the Environment. (2024c). *New Zealand's projected greenhouse gas emissions to 2050*. Retrieved from https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/emissions-reductions/emissions-reduction-targets/new-zealands-projected-greenhouse-gas-emissions-to-2050/

Ministry for the Environment. (2024d). *New Zealand's second emissions reduction plan 2026–30* https://environment.govt.nz/assets/publications/climate-change/ERP2/New-Zealands-second-emissions-reduction-plan-202630.pdf
Ministry for the Environment. (2024e). *Time series emissions data in AR5 1990 to 2022 from New Zealand's Greenhouse Gas Inventory published in 2024*.
Ministry of Business Innovation and Employment. (2020). *Building for Climate Change: Transforming the Building and Construction Sector to reduce emissions and improve climate resilience*. https://www.mbie.govt.nz/dmsdocument/11522-building-for-climate-change
Ministry of Business Innovation and Employment. (2023). *Measures for Transition to an Expanded and Highly Renewable Electricity System*. https://www.mbie.govt.nz/dmsdocument/26909-measures-for-transition-to-an-expanded-and-highly-renewable-electricity-system-pdf
Ministry of Business Innovation and Employment. (2024). *Building and Construction Sector Trends-Annual Report 2023*. https://www.mbie.govt.nz/assets/building-and-construction-sector-trends-annual-report-2023.pdf
New Zealand Legislation. (2019). *Climate Change Response (Zero Carbon) Amendment Act 2019*. Retrieved 15 08 from https://www.legislation.govt.nz/act/public/2019/0061/latest/whole.html#LMS183736
OECD. (2025). *Zero-Carbon Buildings in Cities- A Whole Life-Cycle Approach*. https://www.oecd.org/content/dam/oecd/en/publications/support-materials/2025/02/zero-carbon-buildings-in-cities_f926bc0b/WLC-Policy-Highlights-ENG.pdf
Peters, G. P., & Geden, O. (2017). Catalysing a political shift from low to negative carbon. *Nature Climate Change*, *7*(9), 619-621. https://doi.org/10.1038/nclimate3369
Pilorgé, H., Kolosz, B., Wu, G. C., Freeman, J., & Wilcox, J. (2021). Global mapping of CDR opportunities. *CDR Primer*.
Pimentel Pincelli, I., Brent, A. C., Hinkley, J. T., & Sutherland, R. (2024). Scaling up solar and wind electricity: empirical modelling and a disruptive scenario for their deployments in Aotearoa New Zealand. *Journal of the Royal Society of New Zealand*, 1-23.
Priore, Y. D., Habert, G., & Jusselme, T. (2023). Exploring the gap between carbon-budget-compatible buildings and existing solutions – A Swiss case study. *Energy and Buildings*, *278*, 112598. https://doi.org/https://doi.org/10.1016/j.enbuild.2022.112598
Reisinger, A., Fuglestvedt, J. S., Pirani, A., Geden, O., Jones, C. D., Maharaj, S., Poloczanska, E. S., Morelli, A., Johansen, T. G., & Adler, C. (2025). Overshoot: A Conceptual Review of Exceeding and Returning to Global Warming of 1.5° C. *Annual Review of Environment and Resources*, *50*.
Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J., & Seferian, R. (2019). Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, *571*(7765), 335-342. https://doi.org/10.1038/s41586-019-1368-z
Rogelj, J., & Lamboll, R. D. (2024). Substantial reductions in non-CO2 greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget. *Communications Earth & Environment*, *5*(1), 35. https://doi.org/10.1038/s43247-023-01168-8
Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., . .

. Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, *8*(4), 325-332. https://doi.org/10.1038/s41558-018-0091-3

Ryberg, M. W., Andersen, M. M., Owsianiak, M., & Hauschild, M. Z. (2020). Downscaling the planetary boundaries in absolute environmental sustainability assessments – A review. *Journal of Cleaner Production*, *276*. https://doi.org/10.1016/j.jclepro.2020.123287

Sandin, G., Peters, G. M., & Svanström, M. (2015). Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts. *The International Journal of Life Cycle Assessment*, *20*(12), 1684-1700. https://doi.org/10.1007/s11367-015-0984-6

Schenuit, F., Brutschin, E., Geden, O., Guo, F., Mohan, A., Oliveira Fiorini, A. C., Saluja, S., Schaeffer, R., & Riahi, K. (2025). Taking stock of carbon dioxide removal policy in emerging economies: developments in Brazil, China, and India. *Climate Policy*, *25*(1), 89-108.

Schenuit, F., Colvin, R., Fridahl, M., McMullin, B., Reisinger, A., Sanchez, D. L., Smith, S. M., Torvanger, A., Wreford, A., & Geden, O. (2021). Carbon dioxide removal policy in the making: assessing developments in 9 OECD cases. *Frontiers in Climate*, *3*, 638805.

Shukla, P. R., Skea, J., Slade, R., Al Khourdajie, A., Van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., & Fradera, R. (2022). Climate change 2022: Mitigation of climate change. *Contribution of working group III to the sixth assessment report of the Intergovernmental Panel on Climate Change*, *10*, 9781009157926.

Silvy, Y., Frölicher, T. L., Terhaar, J., Joos, F., Burger, F. A., Lacroix, F., Allen, M., Bernardello, R., Bopp, L., & Brovkin, V. (2024). AERA-MIP: emission pathways, remaining budgets, and carbon cycle dynamics compatible with 1.5 and 2° C global warming stabilization. *Earth System Dynamics*, *15*(6), 1591-1628.

Smith, S., Geden, O., Gidden, M., Lamb, W., Nemet, G., Minx, J., Buck, H., Burke, J., Cox, E., & Edwards, M. (2024). The state of carbon dioxide removal.

Stats NZ. (2023). *Greenhouse gas emissions (consumption-based): Year ended 2021 (provisional)*. https://www.stats.govt.nz/information-releases/greenhouse-gas-emissions-consumption-based-year-ended-2021-provisional/#text-alt

Stats NZ. (2024). *National accounts (industry production and investment): Year ended March 2023*. https://www.stats.govt.nz/information-releases/national-accounts-industry-production-and-investment-year-ended-march-2023/

Steininger, K. W., Williges, K., Meyer, L. H., Maczek, F., & Riahi, K. (2022). Sharing the effort of the European Green Deal among countries. *Nature Communications*, *13*(1), 3673.

thinkstep Ltd. (2018). *The carbon footprint of New Zealand's built environment: Hotspot or not?* https://www.thinkstep-anz.com/resrc/reports/the-carbon-footprint-of-new-zealands-built-environment/

Tilsted, J. P., & Bjørn, A. (2023). Green frontrunner or indebted culprit? Assessing Denmark's climate targets in light of fair contributions under the Paris Agreement. *Climatic Change*, *176*(8), 103. https://doi.org/10.1007/s10584-023-03583-4

Tokarska, K. B., Zickfeld, K., & Rogelj, J. (2019). Path Independence of Carbon Budgets When Meeting a Stringent Global Mean Temperature Target After an Overshoot. *Earth's Future*, *7*(12), 1283-1295. https://doi.org/https://doi.org/10.1029/2019EF001312

Tozan, B., Hoxha, E., Olsen, C. O., Rose, J., Kragh, J., Andersen, C. E., Sørensen, C. G., Garnow, A., & Birgisdóttir, H. (2024). A novel approach to establishing bottom-up LCA-based limit values for new construction. *Building and Environment*, *263*, 111891. https://doi.org/https://doi.org/10.1016/j.buildenv.2024.111891

United Nations Framework Convention on Climate Change, (1992). https://unfccc.int/sites/default/files/convention_text_with_annexes_english_for_posting.pdf

UNFCCC. (2015). The Paris Agreement. In.

United Nations Environment Programme. (2024). *Global Status Report for Buildings and Construction*. https://www.unep.org/resources/report/global-status-report-buildings-and-construction

UNPD. (2024). *World Population Prospects 2024*. New York Retrieved from https://population.un.org/wpp/

Williges, K., Meyer, L. H., Steininger, K. W., & Kirchengast, G. (2022). Fairness critically conditions the carbon budget allocation across countries. *Global Environmental Change*, *74*, 102481. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2022.102481

Wilson, N., Grout, L., Summers, J., Nghiem, N., & Baker, M. (2020). Health and economic impacts of the COVID-19 response: NZ compared to OECD countries. *Public Health Expert Briefing*.

World Bank. (2025). *World Development Indicators (WDI)*.

Zhong, Y., Qin, Z., Feng, R., & Liu, Y. (2024). Low-carbon design: Building optimization considering carbon emission, material utilization, and daylighting. *Journal of Cleaner Production*, *434*, 140087.

Zimmermann, R. K., Kanafani, K., Rasmussen, F. N., Andersen, C., & Birgisdóttir, H. (2020). LCA-framework to evaluate circular economy strategies in existing buildings. IOP Conference Series: Earth and Environmental Science,

This page is intentionally left blank

Chapter 8

Conclusion

8.1 Introduction

This chapter summarises how the RQs have been addressed through the research reported in this thesis (Section 8.2) with the integrated conclusion from the main themes (Section 8.3). The chapter further summarises the conceptual and methodological contributions to knowledge (Section 8.4.1), implications for research and practice (Section 8.4.2), key policy recommendation (Section 8.5), international transferability (Section 8.6), study limitations (Section 8.7) and directions for future research (Section 8.8).

8.2 Summary of the Key Findings

8.2.1 Differences Between Static and Time-Differentiated Emission Accounting Approaches (RQ1)

sLCA does not distinguish when emissions occur or represent how their relative climate significance change over time. This limitation is particularly important in buildings, where emissions arise at multiple life cycle stages across extended time horizons. In particular, sLCA provides limited capacity to assess CE strategies because the benefits of implementing these strategies are realised over extended time horizons (Section 2.3).

Application of the dLCA approach used in this thesis (Section 3.2.2) shows how incorporating emission timing and time-dependent characterisation factors enable explicit representation of RF associated with GHG emissions over a defined time horizon. The findings show that upfront emissions associated with construction-related activities and material production exert a disproportionately high influence on near-term climate outcomes; this is driven by the time-dependent behaviour of GHGs due to their unique atmospheric lifetimes and GWPs. This insight enables a more context-relevant understanding of emissions and potential improvement decisions (i.e. the relative

importance of early-stage design and material choices) which is missing from sLCA results. In this sense, dLCA functions as a "message-oriented" LCA application, supporting policymakers and building sector stakeholders in evaluating the timeliness of mitigation strategies.

While the appropriateness of dLCA remains debated in the literature, particularly due to its use of temporally resolved emission profiles, increased data requirements, and time-dependent characterisation factors (Jørgensen & Hauschild, 2013; Levasseur et al., 2016; Lueddeckens et al., 2020; Ventura, 2023), this research shows its practical applicability at the product system level. Importantly, representing emissions along a timeline does not introduce conceptual complexity for stakeholders, as it aligns with an intuitive understanding of cause and effect over time. The time-dependent emission profiles derived from dLCA can be readily interpreted through graphical representations that show when emissions occur and how long their impacts persist (e.g. Figures 3.5 and 3.6). This makes explicit, for example, that long-lived gases such as CO_2 continue to contribute to warming for centuries after the initial emission. Therefore, the use of dLCA allows the representation of emissions over specific time horizons that are aligned with the time-differentiated carbon budgets found in the national climate change policies for many countries.

However, a key limitation arises from the difference in impact metrics, as dLCA expresses climate impacts in terms of RF (W/m^2) whereas carbon budgets are generally defined in mass-based units (tCO_2 or tCO_2eq). This creates a challenge in directly translating dLCA outputs into existing budget-based policy frameworks, as results expressed in terms of RF require additional conversion steps to be reconciled with mass-based carbon budget metrics (Zieger et al., 2025). An alternative and more pragmatic approach is to retain conventional GWP-based emission metrics while explicitly representing emissions along timelines according to when they occur throughout the building life cycle (McLaren et al., 2025). In this approach, emissions are presented as temporally distributed GWP values through timeline-based representations, enabling stakeholders to visualise the sequencing and timing of emissions without requiring the additional complexity associated with RF-based dLCA modelling. This has been suggested as a practically transferable pathway for incorporating temporal

differentiation into building emission assessments while maintaining compatibility with existing mass-based carbon accounting and policy frameworks.

Overall, time-differentiated emission accounting approaches enable a more comprehensive understanding of how emissions evolve over time. Collectively, the research presented in Chapter 3, answers RQ1 and fulfils Objective 1.1 by investigating the differences in outcomes and representations between static versus dynamic LCA approaches, particularly in relation to their temporal distribution and climate relevance.

8.2.2 Influence of Temporal Dynamics on Whole-of-Life Building Emissions (RQ2)

This research shows that whole-of-life GHG emissions of buildings are inherently dynamic, evolving over time rather than remaining fixed at the point of design and construction. Emissions occur as temporally distributed pathways shaped by both technological and socio-economic developments across the building life cycle (Section 2.3). In particular, the results in Chapter 5 demonstrate that building-related emissions should be understood as evolving trajectories, reflecting interactions between life cycle stages and broader temporal dynamics in the background system, rather than static totals based on fixed assumptions.

Existing research has shown that future temporal dynamics tend to reduce the relative contribution of operational emissions over time, while recurring cycles - such as office fit-outs - introduce repeated embodied emission flows that accumulate throughout the service life (Section 5.1). Thus, the emission profiles of buildings become increasingly shaped by future temporal dynamics over their lifetimes.

The office fit-out case study (Chapter 5) demonstrates how recurring refurbishment cycles introduce periodic emission flows that become a significant component of whole-of-life impacts over time. The case study further shows that the magnitude of these emissions is influenced by the technologies associated with decarbonisation of energy systems and material production, which alter both operational and embodied emission intensities in future recurring cycles. In addition, EOL emissions are shaped by evolving CE related technologies (Section 3.3.3 and Section 5.3.3), affecting the long-term mitigation potential of materials and components in buildings.

In addition to technology developments, the findings demonstrate that future socio-economic and policy conditions significantly influence long-term building emission pathways. This is demonstrated by the case study results presented in Section 5.3.3.2, where alternative global climate policy pathways produce substantially different long-term emission trajectories. Although all pathways assessed in Chapter 5 benefit from ongoing technological and socio-economic transitions, stronger mitigation scenarios - such as the NDC and PkBudg1000 pathways - accelerate decarbonisation across energy, material production, transport, and EOL systems, thereby amplifying cumulative emission reductions over time. This confirms that emission profiles are not only sensitive to building-level interventions in the foreground system, but also to broader policy-driven system transitions that shape future background conditions.

The prospective LCA (pLCA) modelling approach, introduced in Section 2.2.1.2 was developed to assess environmental impacts under potential future conditions by modifying foreground and/or background systems to reflect anticipated technological, socio-economic, and policy changes. Conventionally, pLCA is generally implemented as an attributional sLCA model situated at a defined future point in time; however, it can be further extended by representing the temporal distribution of emissions and their time-dependent climate impacts. In this thesis, the conventional application of pLCA was further extended through the assessment of recurring office fit-out cycles across the service life of a building under alternative future climate policy pathways (Chapter 5). Rather than assessing a single future snapshot, the approach evaluated how repeated refurbishment activities interact with evolving background systems over time. This enables the analysis of how future technological developments, socio-economic transitions, and policy-driven decarbonisation pathways influence cumulative whole-of-life emissions across recurring intervention cycles. The findings demonstrate that stronger mitigation pathways accelerate reductions in GHG emissions through decarbonisation of energy, material production, transport, and EOL systems, thereby reshaping long-term building emission trajectories. Accordingly, integrating temporal resolution into emission accounting enhances the robustness of decision-support tools by aligning methodological representation with the inherently evolving nature of building systems.

Overall, the office fitout case study reported in Chapter 5 highlights the limitations of static emission accounting and aggregated indicators in the building sector, and demonstrates the value of pLCA in representing both foreground and background system temporal dynamics related to whole-of-life GHG emissions of buildings. This answers RQ2 and fulfils Objective 1.2.

8.2.3 Role of Construction 4.0 in Shaping the Magnitude and Timing of Building Emissions (RQ3)

Recent studies show that Construction 4.0 can provide a critical enabling context for building sector decarbonisation, but its potential is not fully realised in current practice. To date, Construction 4.0 has predominantly focused on improving efficiency and productivity at the design and construction stages, with limited attention to whole-of-life emissions or their temporal distribution. As a result, its contribution to climate change mitigation has often been assessed in terms of immediate or upfront benefits, rather than its capacity to influence long-term emission trajectories.

The result of this research demonstrates the role of Construction 4.0 beyond this narrow focus by showing that it can shape both the magnitude and timing of emissions across the building life cycle. In particular, the findings highlight that, technological advancements, when considered alongside broader socio-economic and policy developments, substantially influence how emissions are generated, mitigated, and distributed over time. This positions Construction 4.0 not only as a set of enabling technologies, but as part of a wider system transition that determines the effectiveness and timing of decarbonisation strategies.

Evidence from the two case studies show how this influence is operationalised in practice. For steel EBF in building structural systems (Chapter 3), the results show that decarbonisation strategies - such as use of reused/reconditioned materials, DfD strategies, proper EOL management - substantially influence emissions. The use of reused/reconditioned steel at the design stage significantly reduces climate change impacts compared with the use of primary steel, reinforcing the mitigation potential of circular material flows in building steel structures. Furthermore, when temporal dynamics such as seismic events occur during the use phase, climate change impacts increase

markedly due to additional demolition and reconstruction activities. Under such scenarios, DfD strategies demonstrate clear mitigation benefits by facilitating component recovery, reducing reconstruction related burdens, and lowering the cumulative impact associated with such disruptive events. At the EOL stage, reuse strategies have lower climate change impacts than recycling or landfilling, highlighting the importance of embedding CE strategies over the life cycle of structural systems. These findings indicate that early-stage structural design decisions influence not only initial embodied emissions but also the buildings' resilience and adaptive capacity under temporal dynamics.

Similarly, the results from the recurring office fit-outs case study shows (Chapter 5) that the decarbonisation potential of CE interventions is closely linked to future technological and socio-economic developments. The effectiveness of reuse, design optimisation, and low-impact material selection improves over time as supporting systems in the background systems evolve. This demonstrates that Construction 4.0 enables not only immediate emission reductions, but also the progressive enhancement of mitigation potential across multiple intervention cycles.

Chapter 4 further investigates how advanced technologies such as digitalisation, additive manufacturing, BIM, GIS, AI can operationalise sustainability principles in the built environment (Çetin et al., 2021; Markou et al., 2025). The alignment between CE principles and Construction 4.0 is evident in their shared standing on life cycle thinking, stakeholder integration, and systemic coordination where advancements in technologies can facilitate decarbonisation strategies. Both paradigms challenge the traditional linear construction model and reframe buildings as a climate change mitigation potential.

Overall, the findings answer RQ3 and fulfil Objective 1.3 by evidencing that the evolution of Construction 4.0 influences building decarbonisation not simply through point-based emission reductions, but by fundamentally reshaping emission trajectories over time and enabling their systematic emission accounting under alternative future scenarios. Moreover, by integrating technological innovation with CE principles and life cycle thinking, Construction 4.0 provides a framework through which both the magnitude and timing of emissions can be strategically managed.

8.2.4 Development of Time-Differentiated Carbon Budgets for the Building Sector (RQ4)

The findings from Chapter 6 confirm that carbon budgeting is essential for translating global climate targets into actionable emission limits at national and sectoral levels. Existing approaches have provided a basis for such translation; however, they are typically grounded in static assumptions and cumulative emission metrics, offering limited insight into how emissions should evolve over time to meet time-bound climate targets.

The results show that carbon budgets can be developed as dynamic budgets by explicitly embedding temporal dynamics within allocation approaches. In this study, key variables underpinning common sharing principles were treated as time-dependent, including population change for equal per capita (EPC) allocation, emission forecasts for grandfathering, and sectoral economic growth for economic value added (EVA) approaches. By integrating these variables, this approach generates temporally explicit remaining carbon budgets (RCBs), enabling the representation of how allowable emissions evolve over time. This temporal approach reveals a critical insight that conventional static carbon budgeting approaches fail to capture: the urgency of near-term mitigation actions.

To address methodological bias and uncertainty, the study further introduces bounded carbon budget ranges rather than relying on single point estimates. This is achieved by combining multiple sharing approaches to define upper and lower bounds, thereby reducing the risk of over- or under-constraining mitigation pathways. In addition, uncertainty associated with future non-CO_2 GHG warming is incorporated using minimum and maximum estimates from the IPCC, expanding the range of RCBs and reflecting variability in climate change mitigation strategies. This transparent treatment of uncertainty enhances the robustness of the results, supporting informed decision-making under conditions of evolving scientific understanding.

The application of this approach demonstrates that incorporating temporal dynamics into carbon budget allocation provides critical insight into the timing and distribution of allowable emissions by answering RQ4 and fulfilling Objective 2.1 and 2.2. In particular,

it reveals the increased risk of overshooting carbon budgets and the urgency of mitigation requirements.

8.2.5 Alignment of Building Sector Emissions with Climate Targets and the Concept of Dynamic Carbon Debt (RQ5)

Assessing alignment between current and projected emissions versus carbon budgets is critical for evaluating the effectiveness of decarbonisation pathways in the building sector. While emission projections and carbon budgets are often analysed independently, existing approaches provide limited insight into how deviations from climate-aligned pathways evolve over time or the implications of delayed mitigation. Chapter 7 addresses this gap by integrating projected emission trajectories for Aotearoa New Zealand's building sector with the dynamic carbon budgets developed in this thesis. This enables a direct comparison between forecasted emissions and allowable emission pathways (i.e. dynamic RCBs) aligned with international climate targets, thereby providing a temporally differentiated assessment of alignment.

The findings in Section 7.4.1 indicate that the downscaled RCBs consistent with 1.5 ºC warming level are currently unrealistic and unachievable under existing emission trajectories. This misalignment becomes more pronounced over time, as delayed mitigation leads to the accumulation of excess emissions relative to allowable limits. To capture this dynamic, the research introduces the concept of dynamic carbon debt in Section 7.4.2, which quantifies the cumulative gap between projected emissions and dynamic RCBs over time.

Applied to the Aotearoa New Zealand context, the framework enables a clear understanding of the scale of dynamic carbon debt and the associated need for timely deployment of national CDR measures mainly through LULUCF. This highlights a critical disconnection between international climate commitments and national sectoral mitigation capacity. The results show that carbon debt increases significantly under delayed mitigation scenarios, indicating that postponing emission reductions imposes disproportionately higher future mitigation requirements. This highlights that alignment with climate targets is not solely determined by cumulative emissions, but by the timing

and rate of emission reductions. Early and sustained mitigation is therefore critical to avoid escalating carbon debt and the associated burden on future decarbonisation efforts. Overall, the findings answer RQ5 and fulfil Objective 2.2 and 2.3 by integrating dynamic carbon budgets with emission projections, providing a robust framework for evaluating alignment with climate targets. The introduction of dynamic carbon debt offers a novel and policy-relevant metric for quantifying the consequences of delayed action, thereby supporting more timely and effective decision-making in national and sectoral levels.

8.3 Integrated Conclusion from Main Themes

The findings of this thesis collectively show that aligning building sector emissions with international carbon budgets is necessary, requiring approaches that account for when emissions occur, how they evolve, and how they interact with time-bound carbon budgets. By systematically integrating time-differentiated emission accounting, prospective assessment, and dynamic carbon budgeting, this research establishes an approach for linking building-level decisions with sectoral pathways and national climate commitments.

The findings reinforce that achieving effective decarbonisation in the building sector requires a shift from static, aggregate forms of assessment towards temporally resolved frameworks that engage with evolving technological advancements, socio-economic changes, and policy landscapes. Within this framing, buildings are reconceptualised as dynamic, embedded systems within broader transitions. The interplay between building designs, construction, use phase, and EOL treatments together with temporal dynamics shape long-term emission pathways and their alignment with time-bound carbon budgets. Therefore, this study advances time-differentiated emission accounting and dynamic carbon budgeting approaches as a coherent basis for supporting climate-aligned decarbonisation under evolving temporal dynamics. This perspective offers a scalable foundation for advancing building sector decarbonisation in Aotearoa New Zealand and beyond.

8.4 Contribution to Knowledge

The existing research gaps identified in Section 1.2, including the predominance of static approaches in building-related GHG emission assessment and carbon budget setting, are addressed through this research, which makes several contributions to the field of building sector decarbonisation. These contributions advance current understanding of how temporal dynamics, future technological and socio-economic transitions, and time-differentiated climate targets can be incorporated into building emission assessment and decision-making frameworks. The key contributions can be broadly categorised into: (i) methodological contributions related to time-differentiated emission accounting approaches and their applicability in the implications within building-sector case studies; and (ii) policy and industry-oriented contributions related to climate target alignment, carbon budgeting, and prospective decarbonisation pathways.

8.4.1 Methodological and Conceptual Contributions

This study advances the state of the art of building sector decarbonisation by **introducing temporal resolution** into both GHG accounting and carbon budget setting. First, by applying dLCA and pLCA the research moves beyond static representations to explicitly model how emissions evolve across time. In contrast to conventional sLCA, the methods applied in this thesis enable the impact of emissions to be traced along defined time horizons, thereby revealing insights that remain obscured in conventional static assessments. However, this research does not position dynamic and/or prospective LCA as replacements for static approaches, but rather as a complementary and decision-oriented extension that provide additional temporal insights to the decision-making process in building decarbonisation. By demonstrating their application at building and component levels, the research pioneers a transferable methodological foundation for incorporating temporal dynamics into climate-aligned assessment and policy-relevant analysis.

Secondly, this study challenges the prevailing static, cumulative carbon budget allocation by reframing emissions within a temporal context. Existing research on carbon budgeting in the building sector aggregates emissions over the life cycle of buildings. It primarily assesses the current emissions in terms of whether, and by how much, current carbon budgets are exceeded. This approach obscures the temporal distribution of emissions and

neglects the time-bound nature of carbon budgets. As a result, prevailing approaches offer limited insight into the urgency, sequencing and timing of mitigation actions, and risk underestimating the climate significance of delayed interventions. Therefore, in this research, **carbon budgets are reconceptualised as evolving constraints** shaped by the timing and effectiveness of mitigation actions. The **introduction of dynamic carbon debt** operationalises overshoot by quantifying the cumulative gap between projected emissions and climate targets, providing a clear signal for policy intervention at national and sectoral scales.

This thesis advances the conceptual shift by **reframing buildings as temporally dynamic systems** embedded within climate aligned pathways. By explicitly accounting for the timing of emissions arising from life cycle stages, the research conceptualises building emissions as evolving trajectories rather than static totals. This temporal lens enables a better understanding of how design stage decisions, recurring interventions, and long service life interact with climate targets.

Moreover, the thesis positions Construction 4.0 not merely as a technological evolution, but as a **conceptual enabler of temporally informed decarbonisation initiatives**, linking technological developments, CE strategies, and digital tools with time-differentiated emission accounting. This integration establishes a conceptual foundation for aligning technological innovation with climate aligned governance, extending the role of Construction 4.0 beyond technological advancements and towards enabling timely, evidence-based mitigation strategies in the building sector.

8.4.2 Industry and Practitioner Contributions

This thesis offers practical contributions to multiple stakeholder groups by operationalising time-differentiated emission accounting within LCA and carbon budgeting approaches, thereby enabling more forward-looking and climate-aligned decision-making in the building sector.

For LCA practitioners, the research demonstrates how integrating temporal dynamics into LCA enables emissions to be modelled and interpreted over extended time horizons rather

than through periodic static updates. This information can be used support development of more efficient mitigation strategies in the building sector.

For building designers, contractors and owners, the application of dynamic and prospective LCA enables assessment of climate change impacts in a manner that explicitly accounts for future uncertainties, such as refurbishment cycles and disruptive events over long building service lives. This supports design strategies that minimise embodied emissions and enhance resilience to future dynamics. Such insights support low carbon building delivery from a whole-of-life and whole-of-building perspective.

For technology developers and digital solution providers, the findings identify priority areas where innovation can most effectively support building sector decarbonisation. These include the development of pLCA tools to modify inventories, advanced software platforms capable of handling time-differentiated LCA modelling, digital product passports, and enhanced BIM applications that integrate life cycle and emissions data. By highlighting the importance of temporal resolution and scenario-based analysis, the research informs the direction of Construction 4.0 aligned technological advancement.

For cross-sectoral stakeholders, including cement, steel, glass, and timber industries, the thesis provides insights into how building sector decarbonisation pathways interact with upstream manufacturing systems. The dynamic assessment of building sector emissions enables suppliers to better align production strategies, material innovations, and investment decisions with evolving demand from a climate aligned building sector.

For policymakers and governance institutions, the dynamic carbon budgeting approach enables time-differentiated monitoring of emissions relative to climate targets, which supports adaptive, forward-looking policy design. By linking emissions trajectories, carbon debt, and carbon budgets, the approach has potential to enhance national and sectoral reporting, and improve the credibility (or not) of long-term mitigation strategies. Importantly, the approach is transferable beyond the building sector, providing a foundation for dynamic budget setting and policy development in other emissions-intensive sectors, such as agriculture.

8.5 Key Policy Recommendations

The findings of this thesis have implications for the development of building sector climate policy, carbon accounting frameworks and decarbonisation strategies. Although the primary contribution of the research is methodological, the results identify several areas in which policy and practice could progressively incorporate the temporal dimension of building-related GHG emissions and decarbonising the building sector. Based on the findings, three main policy actions are proposed which are intended to provide a pathway for translating the methodological findings of this research into policy and practice, rather than constituting a comprehensive evaluation of existing policy instruments.

Integrate emission timing and future scenarios into building carbon accounting and regulation

Building emissions accounting should move beyond static assessments by incorporating the timing of emissions and plausible temporal dynamics in background systems. The findings of this thesis support the progressive introduction of whole-of-life carbon requirements into the Building Code, including legally binding whole-of-life carbon limit values for new buildings and progressively tightening limit value roadmaps for both new construction and refurbishment. Such requirements would provide a regulatory pathway towards net-zero whole-of-life carbon while recognising that the magnitude and timing of building emissions change over time.

Accelerate circular economy practices through enabling infrastructure and secondary markets

The findings from Chapter 3-5 support greater emphasis on retaining and reusing existing building assets and components, alongside design for disassembly, reuse and recycling. This should be supported by the development of infrastructure for secondary material markets, including material banks, trading platforms, and systems for tracking and verifying the condition, composition and reuse potential of building components. Establishing digital product passports could provide the information infrastructure needed to trace materials and components throughout their life cycles and facilitate their recovery and subsequent reuse. Government programmes could therefore support refurbishment

rather than replacement or new construction where appropriate, more efficient utilisation of existing buildings, and components.

Align economic incentives with building sector dynamic carbon budgets and carbon debts

The dynamic carbon budget and carbon debt framework developed in this thesis provides a basis for assessing whether building sector emissions remain compatible with time-bound climate targets. The New Zealand Emissions Trading Scheme (NZ ETS) could be used to support sectoral decarbonisation, complemented by policy instruments such as carbon pricing that strengthen incentives for emissions reductions. Aligning these instruments with time-differentiated building sector carbon budgets would shift decarbonisation from a focus on cumulative targets towards managing both the magnitude and timing of emissions and avoiding the accumulation of sectoral carbon debt.

Overall, these policy recommendations translate the findings of this thesis into a coordinated approach to Aotearoa New Zealand building sector decarbonisation, linking emission accounting, circular economy practices and economic mechanisms with time-bound climate targets.

8.6 International Transferability

Although Aotearoa New Zealand provides the empirical and policy context for this research, the methodological contribution of the thesis extends beyond the national context. The research integrates time-differentiated emission accounting, time-differentiated carbon budgeting, circular economy and Construction 4.0 perspectives to examine building emissions across both building and sectoral scales. This integrated framework provides a basis for considering not only the magnitude of building-related emissions, but also their timing, future evolution and alignment with time-bounded climate targets.

The numerical results and policy implications presented in this thesis are specific to Aotearoa New Zealand and should not be directly generalised to other countries. However, the underlying methodological approaches can be adapted to different contexts by incorporating country-specific building characteristics, background systems, future

scenarios, climate pathways and carbon budget allocation assumptions. The research therefore supports methodological and analytical generalisation rather than statistical generalisation.

This transferability provides a basis for applying the framework to other national and other economic sectors and for future comparative research examining how differences in energy systems, technological transitions and climate policies influence building sector emission trajectories and their alignment with climate targets.

8.7 Limitations

The empirical analysis undertaken of the two case studies (steel EBF building structure and an office fit-out) does not capture the full diversity of materials and components utilised in the building sector, but they were intentionally selected to represent different stages of the building life cycle. This focus enabled in-depth exploration of emission timing, decarbonisation strategies, and future technology pathways within system boundaries. The findings should be interpreted as methodological demonstrations, as the research prioritised methodological depth over statistical representativeness of the full diversity of the building sector.

The application of dynamic and prospective LCA approaches involves higher modelling complexity than conventional sLCA. The need to specify temporal emission distributions, dynamic characterisation factors, and future technology pathways increase data requirements and computational effort. However, this reflects the current state of methodological development rather than a unique limitation of the conceptual framework itself. At present, the practical application of time-differentiated LCA is relatively resource- and time-intensive, particularly due to the additional expertise and learning required to develop temporally resolved emission inventories. This highlights an important opportunity for future advancement through the development of simplified tools, practitioner guidance, and educational initiatives that could improve accessibility and facilitate broader industry adoption of time-differentiated emission assessment approaches.

The study focuses solely on climate change impacts, and thus excludes consideration of other environmental impact categories. In addition, biogenic carbon emissions associated with timber-based materials were not explicitly assessed, as the methodological focus was GWP-fossil and time-differentiated emission modelling. Modelling biogenic carbon storage, delayed emissions, and land-use change effects introduces additional complexity that fall outside the core objectives of this study. Future work could extend the proposed frameworks to incorporate biogenic carbon flows in a time-differentiated manner.

The use of multiple sharing approaches as upper and lower bounds to downscale global RCB to national and building sectoral level captures a range of plausible outcomes, and reinforces that no single allocation method can be considered definitive. Moreover, the uncertainties associated with non-CO_2 GHG are addressed by using minimum and maximum RCB values. These approaches enhance robustness, but also highlight that methods on downscaling carbon budgets are inherently sensitive to methodological choices. The resulting budgets should therefore be interpreted as decision support tools rather than fixed thresholds.

Finally, the research is linked to the broader transition towards Construction 4.0. The analysis prioritises decarbonisation strategies that are directly linked to emission timing, LCA, and future-oriented decision-making. Other dimensions, such as the effect on digitisation, automation, robotics, and organisational transformation, are acknowledged but not examined empirically. Instead, the focus was on developing quantitative, time-differentiated climate mitigation frameworks to achieve the main aim of the study.

8.8 Future Work

Building on the findings and the limitations of the thesis, several future research directions are suggested to advance time-differentiated emission accounting and carbon budgeting for the building sector:

1. Extend the application of dLCA and pLCA approaches to different building typologies, components and materials with priority given to the detailed assessment of operational and use phase emissions through integration with future energy system modelling.

2. An explicit assessment of biogenic carbon under different temporal assumptions would support comparative analysis and contribute to a more comprehensive understanding of how biogenic emission interact under temporal dynamics.
3. Explore methods and tools to reduce the modelling complexity of dLCA and pLCA to enhance their practical usability. This includes the development of streamlined datasets, user friendly tools for LCA modelling, and integration with digital design environments such as BIM.
4. Integrate localised cross-sectoral forecasts such as demand for building materials, energy utilisation and technology advancements for EOL processing into pLCA. Such integration would strengthen the policy relevance of prospective assessments and enable more robust exploration of alternative decarbonisation pathways at sectoral and national scales.
5. Extend the dynamic carbon budget and carbon debt concepts to other economic sectors (e.g. transport, agriculture, manufacturing) to support development of integrated, cross-sectoral climate mitigation strategies.
6. Integrate behavioural change and governance mechanisms relevant to the different stakeholders in the building sector with time-differentiated emission modelling. This should include examining how institutional capacity, stakeholder behaviour, market structures, and regulatory frameworks influence the timing and effectiveness of mitigation actions in the building sector.

These future research directions highlight the potential of time-differentiated emission accounting and dynamic carbon budgeting to evolve into a comprehensive decision-support paradigm, capable of guiding climate-aligned transformation of the building sector and beyond.

References

Abtahi, S. (2006). *Embodied energy of a UK office fit-out* (Publication Number U593828) [M.Sc., University of London, University College London (United Kingdom)]. ProQuest Dissertations & Theses Global. England.

Abu-Ghaida, H., Hollberg, A., Ritzen, M., Wöhler, A., & Lizin, S. (2025). Assessing the environmental benefits of design for disassembly in buildings with a time-resolved prospective LCA approach. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-025-02526-8

Acosta, S. C., Grimes, A. L., & Leining, C. (2020). *Decision trees: Forestry in the New Zealand Emissions Trading Scheme post-2020*. Motu Economic and Public Policy Research.

Akanbi, L., Oyedele, L., Davila Delgado, J. M., Bilal, M., Akinade, O., Ajayi, A., & Mohammed-Yakub, N. (2019). Reusability analytics tool for end-of-life assessment of building materials in a circular economy. *World Journal of Science, Technology and Sustainable Development*, *16*(1), 40-55. https://doi.org/10.1108/WJSTSD-05-2018-0041

Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Davila Delgado, M., Bilal, M., & Bello, S. A. (2018). Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation and Recycling*, *129*, 175-186. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.10.026

Alaux, N., Steubing, B., Habert, G., Ruschi Mendes Saade, M., & Passer, A. (2025). Future Life-Cycle Greenhouse Gas Emission Scenarios for the Austrian Building Stock: A Systematic Approach. *Environmental Science & Technology*, *59*(10), 4962-4973.

Alcorn, J. A. (2021). *Global Sustainability and the New Zealand House* Open Access Te Herenga Waka-Victoria University of Wellington]. https://openaccess.wgtn.ac.nz/articles/thesis/Global_Sustainability_and_the_New_Zealand_House/16992619

Algunaibet, I. M., Pozo, C., Galán-Martín, Á., Huijbregts, M. A., Mac Dowell, N., & Guillén-Gosálbez, G. (2019). Powering sustainable development within planetary boundaries. *Energy & Environmental Science*, *12*(6), 1890-1900.

AlJaber, A., Martinez-Vazquez, P., & Baniotopoulos, C. (2025). Exploring Circular Economy Strategies in Buildings: Evaluating Feasibility, Stakeholders Influence, and the Role of the Building Lifecycle in Effective Adoption. *Applied Sciences*, *15*(3), 1174.

Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *The International Journal of Life Cycle Assessment*, *22*(9), 1441-1458. https://doi.org/10.1007/s11367-016-1244-0

Andisheh, K., Hasanali, M., Jármai, K., Taheri, H., Mago, N., ShahMohammadi, A., Karpenko, M., Dong, P., Clifton, G. C., & MacRae, G. A. (2024). *EVALUATING SEISMIC RESPONSE OF INNOVATIVE REUSABLE ECCENTRIC BRACED FRAMES (EBF)* World Conference on Earthquake Engineering Milan.

Antwi-Afari, P., Ng, S. T., Chen, J., Oluleye, B. I., Antwi-Afari, M. F., & Ababio, B. K. (2023). Enhancing life cycle assessment for circular economy measurement of different case scenarios of modular steel slab. *Building and Environment*, *239*, 110411. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110411

Armeni, I., Raghu, D., & De Wolf, C. (2024). Artificial Intelligence for Predicting Reuse Patterns. *A Circular Built Environment in the Digital Age*, 57-78.

Arredondo, C., & Miguel, J. (2021). *Circular economy and office fit-out: an analysis for office fit-out processes based on material flows* UCL (University College London)].

ARUP. (2025). *Unlocking value in buildings: developing the business case for building circular*. https://www.arup.com/insights/unlocking-value-in-buildings-developing-the-business-case-for-building-circular/

Arvidsson, R., Tillman, A. M., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D., & Molander, S. (2018). Environmental assessment of emerging technologies: recommendations for prospective LCA. *Journal of Industrial Ecology*, *22*(6), 1286-1294.

Bagheri, M., Shirzadi, N., Bazdar, E., & Kennedy, C. A. (2018). Optimal planning of hybrid renewable energy infrastructure for urban sustainability: Green Vancouver. *Renewable and Sustainable Energy Reviews*, *95*, 254-264. https://doi.org/https://doi.org/10.1016/j.rser.2018.07.037

Bai, X., Hasan, S., Andersen, L. S., Bjørn, A., Kilkiş, Ş., Ospina, D., Liu, J., Cornell, S. E., Sabag Muñoz, O., de Bremond, A., Crona, B., DeClerck, F., Gupta, J., Hoff, H., Nakicenovic, N., Obura, D., Whiteman, G., Broadgate, W., Lade, S. J., . . . Zimm, C. (2024). Translating Earth system boundaries for cities and businesses. *Nature Sustainability*, *7*(2), 108-119. https://doi.org/10.1038/s41893-023-01255-w

Balasubramanian, S., Shukla, V., Islam, N., & Manghat, S. (2024). Construction Industry 4.0 and Sustainability: An Enabling Framework. *IEEE Transactions on Engineering Management*, *71*, 1-19. https://doi.org/10.1109/TEM.2021.3110427

Balouktsi, M., & Lützkendorf, T. (2016). Energy efficiency of buildings: the aspect of embodied energy. *Energy Technology*, *4*(1), 31-43.

Baumstark, L., Bauer, N., Benke, F., Bertram, C., Bi, S., Gong, C., Dietrich, J., Dirnaichner, A., Giannousakis, A., Hilaire, J., Klein, D., Koch, J., Leimbach, M., Levesque, A., Madeddu, S., Malik, A., Merfort, A., Merfort, L., Odenweller, A., & Luderer, G. (2021). *REMIND2.1: Transformation and innovation dynamics of the energy-economic system within climate and sustainability limits*. https://doi.org/10.5194/gmd-2021-85

Bednar, J., Obersteiner, M., Baklanov, A., Thomson, M., Wagner, F., Geden, O., Allen, M., & Hall, J. W. (2021). Operationalizing the net-negative carbon economy. *Nature*, *596*(7872), 377-383. https://doi.org/10.1038/s41586-021-03723-9

Bednar, J., Obersteiner, M., & Wagner, F. (2019). On the financial viability of negative emissions. *Nature Communications*, *10*(1), 1783. https://doi.org/10.1038/s41467-019-09782-x

Bennedsen, M., Hillebrand, E., & Koopman, S. J. (2023). A multivariate dynamic statistical model of the global carbon budget 1959–2020. *Journal of the Royal Statistical Society Series A: Statistics in Society*, *186*(1), 20-42.

Better Buildings Partnership. (2023). *Circular fitouts toolkit for offices*. https://www.betterbuildingspartnership.com.au/circular-fitout-toolkit-for-offices/

Bjørn, A., Chandrakumar, C., Boulay, A.-M., Doka, G., Fang, K., Gondran, N., Hauschild, M. Z., Kerkhof, A., King, H., Margni, M., McLaren, S., Mueller, C., Owsianiak, M., Peters, G., Roos, S., Sala, S., Sandin, G., Sim, S., Vargas-Gonzalez, M., & Ryberg, M. (2020). Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. *Environmental Research Letters*, *15*(8), 1-23. https://doi.org/10.1088/1748-9326/ab89d7

BlueScope Steel Limited. (2020a). *Steel – Welded Beams and Columns Environmental Product Declaration*.
BlueScope Steel Limited. (2020b). *XLERPLATE® steel Environmental Product Declaration*.
Bocken, N. M., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of industrial and production engineering*, *33*(5), 308-320.
Boothroyd, G., & Alting, L. (1992). Design for Assembly and Disassembly. *CIRP Annals*, *41*(2), 625-636. https://doi.org/https://doi.org/10.1016/S0007-8506(07)63249-1
Brandão, R., & Verissimo, L. (2024). Circular Economy Adoption in Construction: A Pathway to Sustainable Development and UN SDG 11 Achievement. In W. Leal Filho, A. L. Salvia, & C. R. Portela de Vasconcelos (Eds.), *An Agenda for Sustainable Development Research* (pp. 213-230). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-65909-6_13
Broadbent, C. (2016). Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy. *The International Journal of Life Cycle Assessment*, *21*(11), 1658-1665. https://doi.org/10.1007/s11367-016-1081-1
Broughton, J. (2023). 20 - Disassembly. In L. Harper & M. Clifford (Eds.), *Design and Manufacture of Structural Composites* (pp. 499-526). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-0-12-819160-6.00017-2
Bruhn, S., Sacchi, R., Cimpan, C., & Birkved, M. (2023). Ten questions concerning prospective LCA for decision support for the built environment. *Building and Environment*, *242*, 110535. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110535
Bruhn, S., Sacchi, R., Horup, L. H., Zindel, A., & Birkved, M. (2025). Historical and Future Lca Insights on Residential Buildings in Denmark. *Available at SSRN 5101422*.
BSI. (2011). PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. In. London: British Standards Institution.
Budiyani, A. G. (2023). Embodied carbon and waste generation of building refurbishment: Case studies of office fit out in Sweden. In.
Bui, T. T. P., Wilkinson, S., MacGregor, C., & Domingo, N. (2023). Decision making in reducing carbon emissions for building refurbishment: Case studies of university buildings in New Zealand. *Building and Environment*, *242*, 110557. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110557
Bullen, L., & Dowdell, D. (2022). Embodied carbon of New Zealand office and residential building services. *Study Report SR479. BRANZ Ltd*.
Bullen, L., McLaren, S. J., & Dowdell, D. (2021). *Carbon budget of New Zealand buildings: A sensitivity assessment*. BRANZ.
Bullen, L., McLaren, S. J., Dowdell, D., & Chandrakumar, C. (2021). Absolute sustainability of New Zealand office buildings in the context of climate targets. *Building and Environment*, *205*. https://doi.org/10.1016/j.buildenv.2021.108186
Butler, J. (2024). Carbon-friendly office fit-outs. *Build Magazine*, *JUN/JUL 2024*, 56-57.
Cabeza, L. F., Bai, Q., Bertoldi, P., Kihila, J. M., Lucena, A. F., Mata, É., Mirasgedis, S., Novikova, A., & Saheb, Y. (2022). Buildings. in IPCC, 2022: climate change 2022: mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. In: Cambridge University Press Cambridge, UK and New York, NY, USA) doi.
Cabeza, L. F., Barreneche, C., Miró, L., Morera, J. M., Bartolí, E., & Inés Fernández, A. (2013). Low carbon and low embodied energy materials in buildings: A review.

Renewable and Sustainable Energy Reviews, *23*, 536-542. https://doi.org/https://doi.org/10.1016/j.rser.2013.03.017

Camilleri, M. J., & Jaques, R. A. (2001). *Implications of Climate Change for the Construction Sector: Office Buildings*. https://d39d3mj7qio96p.cloudfront.net/media/documents/SR96_Implications_of_climate_change_for_the_construction_sector_-_office_buildings.pdf

Carbon Leadership Forum. (2019). *LCA for low carbon construction: Estimates of embodied carbon for mechanical, electrical, plumbing and tenant improvement* (Summary document, Issue. https://carbonleadershipforum.org/download/3123/

Casas-Arredondo, M., Croxford, B., & Domenech, T. (2018). Material and decision flows in non-domestic building fit-outs. *Journal of Cleaner Production*, *204*, 916-925. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.08.328

CBRE Inc. (2024). *Office occupier bennchmark report*.

CBRE Inc. (2025). *2024-2025 CBRE Global Workspace & Occupancy Insight*.

CEN. (2012). Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method. In *EN 15978:2011*. Dublin, Ireland: NSAI Standard.

CEN. (2019). EN 15804:2012+A2:2019 Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products. In. Brussels: European Committee for Standardization.

Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular digital built environment: An emerging framework. *Sustainability*, *13*(11), 6348.

Çetin, S., Raghu, D., Honic, M., Straub, A., & Gruis, V. (2023). Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. *Sustainable Production and Consumption*, *40*, 422-437. https://doi.org/https://doi.org/10.1016/j.spc.2023.07.011

Chandrakumar, C., Malik, A., McLaren, S. J., Owsianiak, M., Ramilan, T., Jayamaha, N. P., & Lenzen, M. (2020). Setting Better-Informed Climate Targets for New Zealand: The Influence of Value and Modeling Choices. *Environ Sci Technol*, *54*(7), 4515-4527. https://doi.org/10.1021/acs.est.9b06991

Chandrakumar, C., McLaren, S. J., Dowdell, D., & Jaques, R. (2020). A science-based approach to setting climate targets for buildings: The case of a New Zealand detached house. *Building and Environment*, *169*, 106560. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106560

Chandrakumar, C., McLaren, S. J., Jayamaha, N. P., & Ramilan, T. (2018). Absolute Sustainability-Based Life Cycle Assessment (ASLCA): A Benchmarking Approach to Operate Agri-food Systems within the 2°C Global Carbon Budget. *Journal of Industrial Ecology*, *23*(4), 906-917. https://doi.org/10.1111/jiec.12830

Chandrakumar, C., McLaren, S. J., Malik, A., Ramilan, T., & Lenzen, M. (2019). Understanding New Zealand's consumption-based greenhouse gas emissions: an application of multi-regional input-output analysis. *The International Journal of Life Cycle Assessment*, *25*(7), 1323-1332. https://doi.org/10.1007/s11367-019-01673-z

Charef, R., & Emmitt, S. (2021). Uses of building information modelling for overcoming barriers to a circular economy. *Journal of Cleaner Production*, *285*, 124854. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.124854

CIL Masterspec. (2025). *National Embodied Carbon Repository*.

Collinge, W. O., Landis, A. E., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2013). Dynamic life cycle assessment: framework and application to an institutional

building. *The International Journal of Life Cycle Assessment*, *18*(3), 538-552. https://doi.org/10.1007/s11367-012-0528-2

Collinge, W. O., Liao, L., Xu, H., Saunders, C. L., Bilec, M. M., Landis, A. E., Jones, A. K., & Schaefer, L. A. (2011, 16-18 May 2011). Enabling dynamic life cycle assessment of buildings with wireless sensor networks. Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology,

Collinge, W. O., Rickenbacker, H. J., Landis, A. E., Thiel, C. L., & Bilec, M. M. (2018). Dynamic Life Cycle Assessments of a Conventional Green Building and a Net Zero Energy Building: Exploration of Static, Dynamic, Attributional, and Consequential Electricity Grid Models. *Environmental Science & Technology*, *52*(19), 11429-11438. https://doi.org/10.1021/acs.est.7b06535

Concrete NZ. (2023). *Roadmap to Net-Zero Carbon for Aotearoa New Zealand's Concrete Industry*. Retrieved May 29 from https://concretenz.org.nz/page/2050_roadmap

Crippa, M., Guizzardi D., Banja M., Solazzo E., Muntean M., Schaaf E., Pagani F., Monforti-Ferrario F., Olivier, J. G. J., Quadrelli, R., Grassi, G., Rossi, S., Oom, D., Branco, A., San-Miguel, J., & Vignati, E. (2022). *CO2 emissions of all world countries*

Crowther, P. (2005). Design for disassembly–themes and principles. *Environment design guide*, 1-7.

Cucurachi, S., Steubing, B., Siebler, F., Navarre, N., Caldeira, C., & Sala, S. (2022). Prospective LCA methodology for Novel and Emerging Technologies for BIO-based products. *Publications Office of the European Union, Luxembourg*.

Dao, H., Peduzzi, P., & Friot, D. (2018). National environmental limits and footprints based on the Planetary Boundaries framework: The case of Switzerland. *Global Environmental Change*, *52*, 49-57. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2018.06.005

Davenport, P. (2003). Instrumental measures of earthquake intensity in New Zealand. Proceedings of the 7th Pacific conference on earthquake engineering, Christchurch, New Zealand, paper,

Davis, S. J., & Caldeira, K. (2010). Consumption-based accounting of CO2 emissions. *Proceedings of the National Academy of Sciences*, *107*(12), 5687-5692. https://doi.org/10.1073/pnas.0906974107

de Almeida Barbosa Franco, J., Domingues, A. M., de Almeida Africano, N., Deus, R. M., & Battistelle, R. A. (2022). Sustainability in the Civil Construction Sector Supported by Industry 4.0 Technologies: Challenges and Opportunities. *Infrastructures*, *7*(3).

Diemer, A., Nedelciu, C. E., Morales, M. E., Batisse, C., & Cantuarias-Villessuzanne, C. (2022). Waste Management and Circular Economy in the French Building and Construction Sector. *Frontiers in Sustainability*, *3*. https://doi.org/10.3389/frsus.2022.840091

Dixit, M. K. (2019). Life cycle recurrent embodied energy calculation of buildings: A review. *Journal of Cleaner Production*, *209*, 731-754. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.10.230

Dooley, K., & Kartha, S. (2018). Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *International Environmental Agreements: Politics, Law and Economics*, *18*(1), 79-98. https://doi.org/10.1007/s10784-017-9382-9

Du, Q., Ma, M., Lu, C., Wang, X., & Bai, L. (2025). Assessing the impact of emission trading scheme and carbon tax in the building sector: An embodied carbon

perspective. *Environmental Impact Assessment Review*, *111*, 107732. https://doi.org/https://doi.org/10.1016/j.eiar.2024.107732
Du, Q., Wang, Y., Pang, Q., Hao, T., & Zhou, Y. (2023). The dynamic analysis on low-carbon building adoption under emission trading scheme. *Energy*, *263*, 125946. https://doi.org/https://doi.org/10.1016/j.energy.2022.125946
Durmisevic, E., & Noort, N. (2003). Re-use potential of steel in building construction. CIB Publication,
Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019a). Dynamic Benchmarking of Building Strategies for a Circular Economy. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012027. https://doi.org/10.1088/1755-1315/323/1/012027
Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019b). Life cycle assessment of a Danish office building designed for disassembly. *Building Research & Information*, *47*(6), 666-680. https://doi.org/10.1080/09613218.2018.1517458
Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019c). Potential of Circular Economy in Sustainable Buildings. *IOP Conference Series: Materials Science and Engineering*, *471*(9), 092051. https://doi.org/10.1088/1757-899X/471/9/092051
Eberhardt, L., Birkved, M., & Birgisdottir, H. (2022). Building design and construction strategies for a circular economy. *Architectural Engineering and Design Management*, *18*(2), 93-113. https://doi.org/10.1080/17452007.2020.1781588
Eboh, F. C., Andersson, B.-Å., & Richards, T. (2019). Economic evaluation of improvements in a waste-to-energy combined heat and power plant. *Waste Management*, *100*, 75-83. https://doi.org/https://doi.org/10.1016/j.wasman.2019.09.008
ecoinvent. (2023). *Allocation, cut-off, EN15804 (EN15804)*.
EEA. (2022). *Investigating Europe's secondary raw material markets*.
Ellen MacArthur Foundation. (2024). *Building Prosperity: Unlocking the potential of a nature-positive, circular economy for Europe*. https://content.ellenmacarthurfoundation.org/m/62e7613596a2d12f/original/Building-Prosperity-July-2024.pdf
EMR Group. (2022). *Environmental Product Declaration Reusable Steel*.
Energy Efficiency & Conservation Authority. (2025). *New Zealand Energy Scenarios TIMES-NZ 2.0*. Energy Efficiency & Conservation Authority,. https://www.eeca.govt.nz/insights/data-tools/new-zealand-energy-scenarios-times-nz/
European Commission. (2002). *Life-cycle assessment (LCA) for steel construction – Final report*. Publications Office.
European Commission. (2022). *Green Deal: New proposals to make sustainable products the norm and boost Europe's resource independence*
European Union. (2024). *REGULATION (EU) 2024/1781 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL*. Retrieved from https://eur-lex.europa.eu/eli/reg/2024/1781/oj
Evison, D., & Mason, E. (2017). The role of forestry in helping New Zealand reduce carbon emissions to the atmosphere.
Fei, W., Opoku, A., Agyekum, K., Oppon, J. A., Ahmed, V., Chen, C., & Lok, K. L. (2021). The critical role of the construction industry in achieving the sustainable development goals (SDGs): Delivering projects for the common good. *Sustainability*, *13*(16), 9112.

Fieldson, R., & Rai, D. (2009). An assessment of carbon emissions from retail fit-out in the United Kingdom. *Journal of Retail & Leisure Property*, *8*(4), 243-258. https://doi.org/10.1057/rlp.2009.16

Fierens, T. (2024). *Bridging the fit-out gap* Delft University of Technology].

Fini, A. A. F., & Forsythe, P. (2020). Barriers to reusing and recycling office fit-out: An exploratory analysis of demolition processes and product features. *Construction Economics and Building*, *20*(4), 42-62.

Finkbeiner, M., Roche, L., & Holzapfel, P. (2025). From analysis-LCA to message-LCA: a lost cause? *The International Journal of Life Cycle Assessment*, 1-8.

Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Hall, B., Hauser, M., Ribes, A., Rosen, D., & Gillett, N. P. (2024). Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data*, *16*(6), 2625-2658.

Forsythe, P. (2010). Office Buildings-The Importance Of" Make Good", Fitout and Recurring Embodied Energy. SB10: Innovation and Transformation, New Zealand Sustainable Building Conference,

Forsythe, P. (2017). Quantifying the recurring nature of fitout to assist LCA studies in office buildings. *International Journal of Building Pathology and Adaptation*, *35*(3), 233-246.

Forsythe, P., & Ding, K. (2017). Increasing wood based office fitout for sustainable life cycle benefits.

Forsythe, P., & Wilkinson, S. (2015). Measuring office fit-out changes to determine recurring embodied energy in building life cycle assessment. *Facilities*, *33*(3/4), 262-274.

Fouquet, M., Levasseur, A., Margni, M., Lebert, A., Lasvaux, S., Souyri, B., Buhé, C., & Woloszyn, M. (2015). Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. *Building and Environment*, *90*, 51-59. https://doi.org/10.1016/j.buildenv.2015.03.022

Gallagher, J., Basu, B., Browne, M., Kenna, A., McCormack, S., Pilla, F., & Styles, D. (2017). Adapting Stand-Alone Renewable Energy Technologies for the Circular Economy through Eco-Design and Recycling. *Journal of Industrial Ecology*, *23*(1), 133-140. https://doi.org/10.1111/jiec.12703

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757-768. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.048

Ghose, A., McLaren, S. J., & Dowdell, D. (2020). Upgrading New Zealand's existing office buildings – An assessment of life cycle impacts and its influence on 2050 climate change mitigation target. *Sustainable Cities and Society*, *57*, 102134. https://doi.org/https://doi.org/10.1016/j.scs.2020.102134

Ghose, A., McLaren, S. J., Dowdell, D., & Phipps, R. (2017). Environmental assessment of deep energy refurbishment for energy efficiency-case study of an office building in New Zealand. *Building and Environment*, *117*, 274-287. https://doi.org/https://doi.org/10.1016/j.buildenv.2017.03.012

Ghose, A., Pizzol, M., McLaren, S. J., Vignes, M., & Dowdell, D. (2019). Refurbishment of office buildings in New Zealand: identifying priorities for reducing environmental impacts. *The International Journal of Life Cycle Assessment*, *24*(8), 1480-1495. https://doi.org/10.1007/s11367-018-1570-5

Goldstein, B., & Rasmussen, F. N. (2018). LCA of Buildings and the Built Environment. *Life cycle assessment: theory and practice*, 695-722.

Gondaliya, A., Ong, E., Wu, J., Jepsen, S., & Saatchi, S. (2023). Towards Zero Waste: An Environmental Life Cycle Analysis of New Furniture vs Participation in the Furniture Reuse Program.

Goubran, S. (2019). On the role of construction in achieving the SDGs. *Journal of sustainability research*, *1*(2).

Gueret, A., Malliet, P., Saussay, A., & Timbeau, X. (2018). *An explorative evaluation of the climate debt* OFCE; OFCE].

Guy, B., Shell, S., & Esherick, H. (2006). Design for deconstruction and materials reuse. *Proceedings of the CIB Task Group*, *39*(4), 189-209.

Harčárová, K., Vilčeková, S., & Balintova, M. (2020). Building materials as potential emission sources of VOC in the indoor environment of buildings. Key Engineering Materials,

Hart, J., D'Amico, B., & Pomponi, F. (2021). Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. *Journal of Industrial Ecology*, *25*(2), 403-418. https://doi.org/10.1111/jiec.13139

Hasanali, M., Andisheh, K., Mago, N., Taheri, H., ShahMohammadi, A., Karpenko, M., Jármai, K., Dong, P., Clifton, G. C., & MacRae, G. A. (2024). *Seismic response of sustainable, resilient eccentrically braced frames* New Zealand Society for Earthquake Engineering 2024 Annual Conference, Auckland.

Hawkins, W., Cooper, S., Allen, S., Roynon, J., & Ibell, T. (2021). Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure. *Structures*, *33*, 90-98. https://doi.org/https://doi.org/10.1016/j.istruc.2020.12.013

Heisel, F., & Rau-Oberhuber, S. (2020). Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. *Journal of Cleaner Production*, *243*, 118482. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.118482

Hemmati, M., Messadi, T., Gu, H., & Hemmati, M. (2024). LCA Operational Carbon Reduction Based on Energy Strategies Analysis in a Mass Timber Building. *Sustainability*, *16*(15).

Hensher, D. A., Wei, E., & Beck, M. J. (2023). The impact of COVID-19 and working from home on the workspace retained at the main location office space and the future use of satellite offices. (0967-070X (Print)).

HERA. (2021). *Steel Recycling Report*. New Zealand Heavy Engineering Research Association. https://www.hera.org.nz/wp-content/uploads/R5-89-Steel-Recycling-Report-v2.pdf

Hildebrandt, J., Hagemann, N., & Thrän, D. (2017). The contribution of wood-based construction materials for leveraging a low carbon building sector in europe. *Sustainable Cities and Society*, *34*, 405-418. https://doi.org/https://doi.org/10.1016/j.scs.2017.06.013

Holappa, L. (2020). A General Vision for Reduction of Energy Consumption and CO2 Emissions from the Steel Industry. *Metals*, *10*(9).

Holøs, S. B., Yang, A., Lind, M., Thunshelle, K., Schild, P., & Mysen, M. (2019). VOC emission rates in newly built and renovated buildings, and the influence of ventilation–a review and meta-analysis. *International Journal of Ventilation*, *18*(3), 153-166.

Horup, L., Bruhn, S., Hoxha, E., Birgisdottir, H., Secher, A. Q., Ohms, P., & Hauschild, M. (2025). Absolute sustainability assessment of the Danish building sector through prospective LCA. *Science of The Total Environment*, *966*, 178780. https://doi.org/https://doi.org/10.1016/j.scitotenv.2025.178780

Horup, L. H., Birgisdóttir, H., & Ryberg, M. W. (2023). Defining dynamic science-based climate change budgets for countries and absolute sustainable building targets. *Building and Environment*, *230*. https://doi.org/10.1016/j.buildenv.2022.109936

Hoxha, E., Passer, A., Saade, M. R. M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., & Habert, G. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. *Buildings and Cities*, *1*(1), 504-524.

Huang, M., Simonen, K., Ditto, J. (2018). *Life Cycle Assessment (LCA) for Low Carbon Construction: Tenant Improvements in Commercial Office Buildings, Final Report*.

Huang, Z., Zhou, H., Miao, Z., Tang, H., Lin, B., & Zhuang, W. (2024). Life-Cycle Carbon Emissions (LCCE) of Buildings: Implications, Calculations, and Reductions. *Engineering*. https://doi.org/https://doi.org/10.1016/j.eng.2023.08.019

InfraBuild Australia Pty Ltd. (2024). *Environmental Product Declaration Reinforcing Rod, Bar, Wire and SENSE 600®*.

Interface Inc. (2025). *REENTRY*. https://www.interface.com/AU/en-AU/sustainability/recycling.html

IPCC. (2001). *Climate change 2001: the scientific basis. Intergovernmental Panel on Climate Change*. UK: Cambridge University Press.

IPCC. (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4_syr_full_report.pdf

IPCC. (2013). *Climate Change 2013: The Physical Science Basis*. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf

IPCC. (2014). *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol*. https://www.ipcc-nggip.iges.or.jp/public/kpsg/pdf/KP_Supplement_Entire_Report.pdf

IPCC. (2023). *Climate Change 2023: Synthesis Report*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

Ishaq, M., Ghouse, G., Fernández-González, R., Puime-Guillén, F., Tandir, N., & Santos de Oliveira, H. M. (2022). From Fossil Energy to Renewable Energy: Why is Circular Economy Needed in the Energy Transition? *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.941791

ISO. (2006a). *ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework*. ISO.

ISO. (2006b). ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines. In.

ISO. (2017). ISO 21930:2017. In *Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services* (pp. 80).

Itanola, M., Griffiths, P., & Motawa, I. (2025). Closing the loop in building services: A systematic review of circular economy applications. *Building Services Engineering Research and Technology*, *46*(3), 293-315. https://doi.org/10.1177/01436244241296762

Jemal, K. M., Kabzhassarova, M., Shaimkhanov, R., Dikhanbayeva, D., Turkyilmaz, A., Durdyev, S., & Karaca, F. (2023). Facilitating Circular Economy Strategies Using Digital Construction Tools: Framework Development. *Sustainability*, *15*(1).

Jia, Z., Wen, S., & Wu, R. (2025). Synergistic effect of emission trading scheme and carbon tax: A CGE model-based study in China. *Environmental Impact Assessment Review*, *110*, 107699. https://doi.org/https://doi.org/10.1016/j.eiar.2024.107699

JLL Inc. (2025). *Circular design cuts carbon and transforms office fit-outs*. https://www.jll.com/en-uk/guides/circular-design-choices-are-cutting-carbon-and-transforming-office-fit-outs

Jørgensen, S. V., & Hauschild, M. Z. (2013). Need for relevant timescales when crediting temporary carbon storage. *The International Journal of Life Cycle Assessment*, *18*(4), 747-754. https://doi.org/10.1007/s11367-012-0527-3

Kanters, J. (2020). Circular building design: An analysis of barriers and drivers for a circular building sector. *Buildings*, *10*(4), 77.

Kılıç Bakırhan, E., & Tuna, M. (2025). Mitigating fit-out waste in rentable offices: The role of flexible design strategies. *Journal of Construction Engineering, Management & Innovation*, *8*, 521-541. https://doi.org/10.31462/jcemi.2025.04521541

Knoth, K., Fufa, S. M., & Seilskjær, E. (2022). Barriers, success factors, and perspectives for the reuse of construction products in Norway. *Journal of Cleaner Production*, *337*, 130494. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.130494

Lahn, B. (2020). A history of the global carbon budget. *WIREs Climate Change*, *11*(3), e636. https://doi.org/https://doi.org/10.1002/wcc.636

Lan, K., & Yao, Y. (2022). Dynamic Life Cycle Assessment of Energy Technologies under Different Greenhouse Gas Concentration Pathways. *Environmental Science & Technology*, *56*(2), 1395-1404. https://doi.org/10.1021/acs.est.1c05923

Larsen, V. G., Tollin, N., Sattrup, P. A., Birkved, M., & Holmboe, T. (2022). What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. *Journal of Building Engineering*, *50*, 104203. https://doi.org/https://doi.org/10.1016/j.jobe.2022.104203

Lausselet, C., Dahlstrøm, O. A., Thyholt, M., Eghbali, A., & Schneider-Marin, P. (2023). Methods to Account for Design for Disassembly: Status of the Building Sector. *Buildings*, *13*(4).

Lenzen, M., Geschke, A., Wiedmann, T., Lane, J., Anderson, N., Baynes, T., Boland, J., Daniels, P., Dey, C., Fry, J., Hadjikakou, M., Kenway, S., Malik, A., Moran, D., Murray, J., Nettleton, S., Poruschi, L., Reynolds, C., Rowley, H., . . . West, J. (2014). Compiling and using input-output frameworks through collaborative virtual laboratories. *Sci Total Environ*, *485-486*, 241-251. https://doi.org/10.1016/j.scitotenv.2014.03.062

Lenzen, M., Kanemoto, K., Moran, D., & Geschke, A. (2012). Mapping the structure of the world economy. *Environ Sci Technol*, *46*(15), 8374-8381. https://doi.org/10.1021/es300171x

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics*, *52*(3), 262-271. https://doi.org/10.2307/1926294

Levasseur, A., Cavalett, O., Fuglestvedt, J. S., Gasser, T., Johansson, D. J. A., Jørgensen, S. V., Raugei, M., Reisinger, A., Schivley, G., Strømman, A., Tanaka, K., & Cherubini, F. (2016). Enhancing life cycle impact assessment from climate science: Review of recent findings and recommendations for application to LCA. *Ecological Indicators*, *71*, 163-174. https://doi.org/https://doi.org/10.1016/j.ecolind.2016.06.049

Levasseur, A., Lesage, P., Margni, M., Deschênes, L., & Samson, R. (2010). Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environmental Science & Technology*, *44*(8), 3169-3174. https://doi.org/10.1021/es9030003

Li, M., Pelz, S., Lamboll, R., Wang, C., & Rogelj, J. (2025). A principle-based framework to determine countries' fair warming contributions to the Paris Agreement. *Nature Communications*, *16*(1), 1043. https://doi.org/10.1038/s41467-025-56397-6

Liljenström, C., & Malmqvist, T. (2016, 2016). *Resource use and greenhouse gas emissions of office fit-outs - A case study* Central Europe Towards Sustainable Building 2016: Innovations for Sustainable Future, CESB 2016, 22 June 2016 through 24 June 2016, http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-195453

Lima, A. T., Kirkelund, G. M., Lu, Z., Mao, R., Kunther, W., Rode, C., Slabik, S., Hafner, A., Sameer, H., Dürr, H. H., Flörke, M., Lowe, B. H., Aloini, D., Zerbino, P., & Simoes, S. G. (2024). Mapping circular economy practices for steel, cement, glass, brick, insulation, and wood – A review for climate mitigation modeling. *Renewable and Sustainable Energy Reviews*, *202*, 114697. https://doi.org/https://doi.org/10.1016/j.rser.2024.114697

Liu, K., Guhathakurta, S., Han, C., Hittinger, E., Phoung, S., & Williams, E. (2024). How much is US office building space reduced per teleworker? *Findings*.

López Ruiz, L. A., Roca Ramón, X., & Gassó Domingo, S. (2020). The circular economy in the construction and demolition waste sector – A review and an integrative model approach. *Journal of Cleaner Production*, *248*, 119238. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.119238

Lucas, P. L., Wilting, H. C., Hof, A. F., & van Vuuren, D. P. (2020). Allocating planetary boundaries to large economies: Distributional consequences of alternative perspectives on distributive fairness. *Global Environmental Change*, *60*, 102017. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2019.102017

Lueddeckens, S., Saling, P., & Guenther, E. (2020). Temporal issues in life cycle assessment—a systematic review. *The International Journal of Life Cycle Assessment*, *25*(8), 1385-1401. https://doi.org/10.1007/s11367-020-01757-1

Lundgren, R., Kyrö, R., Toivonen, S., & Tähtinen, L. (2024). Enabling circular futures of workspaces through facility management: a backcasting approach. 23rd EuroFM Research Symposium,

Lützkendorf, T., & Balouktsi, M. (2022). Embodied carbon emissions in buildings: explanations, interpretations, recommendations. *Buildings and Cities*. https://doi.org/10.5334/bc.257

MacArthur, E. (2013). Towards the circular economy. *Journal of Industrial Ecology*, *2*(1), 23-44.

Markou, I., Sinnott, D., & Thomas, K. (2025). Current methodologies of creating material passports: A systematic literature review. *Case Studies in Construction Materials*, *22*, e04267. https://doi.org/https://doi.org/10.1016/j.cscm.2025.e04267

Martínez, I., Zalba, B., Trillo-Lado, R., Blanco, T., Cambra, D., & Casas, R. (2021). Internet of Things (IoT) as Sustainable Development Goals (SDG) Enabling Technology towards Smart Readiness Indicators (SRI) for University Buildings. *Sustainability*, *13*(14).

Mathew, P., Regnier, C., Shackelford, J., & Walter, T. (2020). Energy Efficiency Package for Tenant Fit-Out: Laboratory Testing and Validation of Energy Savings and Indoor Environmental Quality. *Energies*, *13*(20).

Matthews, H. D. (2016). Quantifying historical carbon and climate debts among nations. *Nature Climate Change*, *6*(1), 60-64. https://doi.org/10.1038/nclimate2774

Matthews, H. D., Tokarska, K. B., Nicholls, Z. R. J., Rogelj, J., Canadell, J. G., Friedlingstein, P., Frölicher, T. L., Forster, P. M., Gillett, N. P., Ilyina, T., Jackson, R. B., Jones, C. D., Koven, C., Knutti, R., MacDougall, A. H., Meinshausen, M., Mengis, N., Séférian, R., & Zickfeld, K. (2020). Opportunities and challenges in using remaining carbon budgets to guide climate policy. *Nature Geoscience*, *13*(12), 769-779. https://doi.org/10.1038/s41561-020-00663-3

Matthews, H. D., Tokarska, K. B., Rogelj, J., Smith, C. J., MacDougall, A. H., Haustein, K., Mengis, N., Sippel, S., Forster, P. M., & Knutti, R. (2021). An integrated approach to quantifying uncertainties in the remaining carbon budget. *Communications Earth & Environment*, *2*(1), 7. https://doi.org/10.1038/s43247-020-00064-9

MBIE. (2020). *Whole-of-Life Embodied Carbon Emissions Reduction Framework*. https://www.mbie.govt.nz/dmsdocument/11794-whole-of-life-embodied-carbon-emissions-reduction-framework

McDonough, W., & Braungart, M. (2003). Towards a sustaining architecture for the 21st century: the promise of cradle-to-cradle design. *Industry and environment*, *26*(2), 13-16.

McDonough, W., & Braungart, M. (2010). *Cradle to cradle: Remaking the way we make things*. North point press.

McLaren, S., Elliot, T., Dowdell, D., Wakelin, S., Kouchaki-Penchah, H., Levasseur, A., & Hoxha, E. (2025). Policy implications of time-differentiated climate change analysis in life cycle assessment of building elements in Aotearoa New Zealand. *The International Journal of Life Cycle Assessment*, 1-23. https://doi.org/10.1007/s11367-025-02444-9

McLaren, S. J. (2021). Linking Life Cycle Assessment to the wider circular economy. In A. Borrion & O. Mwabonje (Eds.), *Life Cycle Assessment: a metric for the circular economy,* . Royal Society of Chemistry.

McLaren, S. J., Chandrakumar, C., Dowdell, D., Bullen, L., & Jaques, R. (2020). Application of Absolute Sustainability Assessment to New Zealand Residential Dwellings. *IOP Conference Series: Earth and Environmental Science*, *588*(2). https://doi.org/10.1088/1755-1315/588/2/022064

Mengis, N., & Matthews, H. D. (2020). Non-CO2 forcing changes will likely decrease the remaining carbon budget for 1.5 °C. *npj Climate and Atmospheric Science*, *3*(1), 19. https://doi.org/10.1038/s41612-020-0123-3

Mequignon, M., Adolphe, L., Thellier, F., & Ait Haddou, H. (2013). Impact of the lifespan of building external walls on greenhouse gas index. *Building and Environment*, *59*, 654-661.

Mestre, A., & Cooper, T. (2017). Circular Product Design. A Multiple Loops Life Cycle Design Approach for the Circular Economy. *The Design Journal*, *20*(sup1), S1620-S1635. https://doi.org/10.1080/14606925.2017.1352686

Ministry for the Environment. (2020). *Interface ReEntry Programme*. https://environment.govt.nz/what-you-can-do/stories/interface-reentry-programme/

Ministry for the Environment. (2022a). *Measuring emissions: a guide for organisations: 2022 detailed guide*. https://environment.govt.nz/publications/measuring-emissions-a-guide-for-organisations-2022-detailed-guide/

Ministry for the Environment. (2022b). *New Zealand's Greenhouse Gas Inventory 1990–2020*. https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-1990-2020/

Ministry for the Environment. (2022c). *Towards a productive, sustainable and inclusive economy: Aotearoa New Zealand's first emissions reduction plan*. Retrieved 15 08 from https://environment.govt.nz/publications/aotearoa-new-zealands-first-emissions-reduction-plan/

Ministry for the Environment. (2023a). *Carbon removals strategy*. Ministry for the Environment,. https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/carbon-removals-strategy/

Ministry for the Environment. (2023b). *Developing a carbon removals strategy*. Ministry for the Environment,. https://environment.govt.nz/news/developing-a-carbon-removals-strategy/

Ministry for the Environment. (2023c, 22 May 2023). *Government partnership with NZ Steel set to unlock massive emissions reductions*. https://environment.govt.nz/news/government-partnership-with-nz-steel-set-to-unlock-massive-emissions-reductions/

Ministry for the Environment. (2024a). *Measuring emissions: A guide for organisations: 2024 detailed guide*.

Ministry for the Environment. (2024b). *New Zealand's Greenhouse Gas Inventory 1990–2022: Snapshot*. Ministry for the Environment, Retrieved from https://environment.govt.nz/assets/publications/GHG-inventory-2024-Snapshot.pdf

Ministry for the Environment. (2024c). *New Zealand's second emission reduction plan 2026-2030: Technical annex*.

Ministry for the Environment. (2024d). *New Zealand's projected greenhouse gas emissions to 2050*. Retrieved from https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/emissions-reductions/emissions-reduction-targets/new-zealands-projected-greenhouse-gas-emissions-to-2050/

Ministry for the Environment. (2024e). *New Zealand's second emissions reduction plan 2026–30* https://environment.govt.nz/assets/publications/climate-change/ERP2/New-Zealands-second-emissions-reduction-plan-202630.pdf

Ministry for the Environment. (2024f). *Time series emissions data in AR5 1990 to 2022 from New Zealand's Greenhouse Gas Inventory published in 2024*.

Ministry of Business Innovation and Employment. (2020). *Building for Climate Change: Transforming the Building and Construction Sector to reduce emissions and improve climate resilience*. https://www.mbie.govt.nz/dmsdocument/11522-building-for-climate-change

Ministry of Business Innovation and Employment. (2023). *Measures for Transition to an Expanded and Highly Renewable Electricity System*. https://www.mbie.govt.nz/dmsdocument/26909-measures-for-transition-to-an-expanded-and-highly-renewable-electricity-system-pdf

Ministry of Business Innovation and Employment. (2024). *Building and Construction Sector Trends-Annual Report 2023*. https://www.mbie.govt.nz/assets/building-and-construction-sector-trends-annual-report-2023.pdf

Minunno, R., O'Grady, T., Morrison, G. M., Gruner, R. L., & Colling, M. (2018). Strategies for Applying the Circular Economy to Prefabricated Buildings. *Buildings*, *8*(9).

Morris & Spottiswood Limited. (2025). Modular Office Fit-Out Project Delivers Embodied Carbon Saving Equivalent to Circumnavigating the Glob. https://www.morrisandspottiswood.co.uk/blog/modular-office-fit-out-project-delivers-embodied-carbon-saving-equivalent-to-circumnavigating-the-glob

Mughrabi, O. (2026). In (Email ed., pp. 06-03-2026).
Mutel, C. (2017). Brightway: an open source framework for life cycle assessment. *Journal of Open Source Software*, *2*(12), 236.
Negishi, K., Lebert, A., Almeida, D., Chevalier, J., & Tiruta-Barna, L. (2019). Evaluating climate change pathways through a building's lifecycle based on Dynamic Life Cycle Assessment. *Building and Environment*, *164*, 106377. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106377
Negishi, K., Tiruta-Barna, L., Schiopu, N., Lebert, A., & Chevalier, J. (2018). An operational methodology for applying dynamic Life Cycle Assessment to buildings. *Building and Environment*, *144*, 611-621. https://doi.org/10.1016/j.buildenv.2018.09.005
New Zealand Green Building Council. (2023). *Green Star Case Studies*. https://nzgbc.org.nz/green-star-case-studies
New Zealand Legislation. (2019). *Climate Change Response (Zero Carbon) Amendment Act 2019*. Retrieved 15 08 from https://www.legislation.govt.nz/act/public/2019/0061/latest/whole.html#LMS183736
Nex-Architecture. (2021). *Interview: British Land's Circular Economy Workspace*. Nex-Architecture. https://www.nex-architecture.com/2021/09/case-study-british-lands-circular-economy-workspace/
Nilimaa, J. (2023). Smart materials and technologies for sustainable concrete construction. *Developments in the Built Environment*, *15*, 100177. https://doi.org/https://doi.org/10.1016/j.dibe.2023.100177
Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. *Journal of Building Engineering*, *44*, 102704. https://doi.org/https://doi.org/10.1016/j.jobe.2021.102704
OECD. (2025). *Zero-Carbon Buildings in Cities- A Whole Life-Cycle Approach*. https://www.oecd.org/content/dam/oecd/en/publications/support-materials/2025/02/zero-carbon-buildings-in-cities_f926bc0b/WLC-Policy-Highlights-ENG.pdf
Office Insight. (2025). Office fit-out cost guide.
Ogunmakinde, O. E., Egbelakin, T., & Sher, W. (2022). Contributions of the circular economy to the UN sustainable development goals through sustainable construction. *Resources, Conservation and Recycling*, *178*, 106023. https://doi.org/https://doi.org/10.1016/j.resconrec.2021.106023
Oluleye, B. I., Chan, D. W. M., Saka, A. B., & Olawumi, T. O. (2022). Circular economy research on building construction and demolition waste: A review of current trends and future research directions. *Journal of Cleaner Production*, *357*, 131927. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.131927
Ouellet-Plamondon, C., Ramseier, L., Balouktsi, M., Delem, L., Foliente, G., Francart, N., Garcia, A., Hoxha, E., Lützkendorf, T., Nygaard Rasmussen, F., Peuportier, B., Butler, J., Birgisdottir, H., Dowdell, D., Dixit, M., Silva, V., Silva, M., de Cózar, J., Kjendseth Wiik, M., & Frischknecht, R. (2022). *Carbon footprint assessment of a wood multi-residential building considering biogenic carbon*. https://doi.org/10.21203/rs.3.rs-2273783/v1
Ouellet-Plamondon, C. M., Ramseier, L., Balouktsi, M., Delem, L., Foliente, G., Francart, N., Garcia-Martinez, A., Hoxha, E., Lützkendorf, T., & Rasmussen, F. N. (2023). Carbon footprint assessment of a wood multi-residential building considering biogenic carbon. *Journal of Cleaner Production*, *404*, 136834.

Overbury. (2024). *Counting the upfront carbon in Cat B office fit-out*. https://d31fl6kv41tqjh.cloudfront.net/v2/accreditations/Counting-the-upfront-carbon-in-Cat-B-office-fit-out-Overbury-2024.pdf

Palacios-Munoz, B., Peuportier, B., Gracia-Villa, L., & López-Mesa, B. (2019). Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach. *Building and Environment*, *160*, 106203. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106203

Peters, G. P., & Geden, O. (2017). Catalysing a political shift from low to negative carbon. *Nature Climate Change*, *7*(9), 619-621. https://doi.org/10.1038/nclimate3369

Pilorgé, H., Kolosz, B., Wu, G. C., Freeman, J., & Wilcox, J. (2021). Global mapping of CDR opportunities. *CDR Primer*.

Pimentel Pincelli, I., Brent, A. C., Hinkley, J. T., & Sutherland, R. (2024). Scaling up solar and wind electricity: empirical modelling and a disruptive scenario for their deployments in Aotearoa New Zealand. *Journal of the Royal Society of New Zealand*, 1-23.

Pomponi, F., Farr, E. R. P., Piroozfar, P., & Gates, J. R. (2015). Façade refurbishment of existing office buildings: Do conventional energy-saving interventions always work? *Journal of Building Engineering*, *3*, 135-143. https://doi.org/https://doi.org/10.1016/j.jobe.2015.07.003

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710-718. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.055

Pomponi, F., & Moncaster, A. (2018). Scrutinising embodied carbon in buildings: The next performance gap made manifest. *Renewable and Sustainable Energy Reviews*, *81*, 2431-2442. https://doi.org/https://doi.org/10.1016/j.rser.2017.06.049

Pongiglione, M., Calderini, C., & Guy, G. B. (2017). A new demountable seismic-resistant joint to improve industrial building reparability. *International Journal of Disaster Resilience in the Built Environment*, *8*(3), 251-262. https://doi.org/10.1108/IJDRBE-06-2016-0026

Priore, Y. D., Habert, G., & Jusselme, T. (2023). Exploring the gap between carbon-budget-compatible buildings and existing solutions – A Swiss case study. *Energy and Buildings*, *278*, 112598. https://doi.org/https://doi.org/10.1016/j.enbuild.2022.112598

Reisinger, A., Fuglestvedt, J. S., Pirani, A., Geden, O., Jones, C. D., Maharaj, S., Poloczanska, E. S., Morelli, A., Johansen, T. G., & Adler, C. (2025). Overshoot: A Conceptual Review of Exceeding and Returning to Global Warming of 1.5° C. *Annual Review of Environment and Resources*, *50*.

Rey-Álvarez, B., Sánchez-Montañés, B., & García-Martínez, A. (2022). Building material toxicity and life cycle assessment: A systematic critical review. *Journal of Cleaner Production*, *341*, 130838. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.130838

RICS. (2024). Whole life carbon assessment for the built environment. In. London: Royal Institution of Chartered Surveyors (RICS),.

Rios, F. C., Chong, W. K., & Grau, D. (2015). Design for Disassembly and Deconstruction - Challenges and Opportunities. *Procedia Engineering*, *118*, 1296-1304. https://doi.org/https://doi.org/10.1016/j.proeng.2015.08.485

Robertson, N., & Hurren, K. (2021). *New Zealand Steel Economic Impact Assessment*. https://www.aucklandcouncil.govt.nz/ResourceConsentDocuments/18DIS60376538%20AppH%20EIA.pdf

Rodrigues, C., König, J., & Freire, F. (2023). Prospective life cycle assessment of a novel building system with improved foam glass incorporating high recycled content. *Sustainable Production and Consumption*, *36*, 161-170. https://doi.org/https://doi.org/10.1016/j.spc.2023.01.002

Rodrigues, C., Rodrigues, E., S. Fernandes, M., & Tadeu, S. (2024). Prospective life cycle approach to buildings' adaptation for future climate and decarbonization scenarios. *Applied Energy*, *372*, 123867. https://doi.org/https://doi.org/10.1016/j.apenergy.2024.123867

Rodriguez, B. X., Huang, M., Lee, H. W., Simonen, K., & Ditto, J. (2020). Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation. *Energy and Buildings*, *226*, 110324. https://doi.org/https://doi.org/10.1016/j.enbuild.2020.110324

Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J., & Seferian, R. (2019). Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, *571*(7765), 335-342. https://doi.org/10.1038/s41586-019-1368-z

Rogelj, J., & Lamboll, R. D. (2024). Substantial reductions in non-CO2 greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget. *Communications Earth & Environment*, *5*(1), 35. https://doi.org/10.1038/s43247-023-01168-8

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., . . . Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, *8*(4), 325-332. https://doi.org/10.1038/s41558-018-0091-3

Rosenbaum, R. K., Hauschild, M. Z., Boulay, A.-M., Fantke, P., Laurent, A., Núñez, M., & Vieira, M. (2018). Life cycle impact assessment. *Life cycle assessment: theory and practice*, 167-270.

Rotimi, J. O. B., & Rasheed, E. O. (2024). The “Other” Workplace Design Factors: An Insight into What New Zealand Workers Want. *Sustainability*, *16*(19), 8381.

Ryberg, M. W., Andersen, M. M., Owsianiak, M., & Hauschild, M. Z. (2020). Downscaling the planetary boundaries in absolute environmental sustainability assessments – A review. *Journal of Cleaner Production*, *276*. https://doi.org/10.1016/j.jclepro.2020.123287

Ryberg, M. W., Owsianiak, M., Clavreul, J., Mueller, C., Sim, S., King, H., & Hauschild, M. Z. (2018). How to bring absolute sustainability into decision-making: An industry case study using a Planetary Boundary-based methodology. *Sci Total Environ*, *634*, 1406-1416. https://doi.org/10.1016/j.scitotenv.2018.04.075

Ryberg, M. W., Owsianiak, M., Richardson, K., & Hauschild, M. Z. (2016). Challenges in implementing a Planetary Boundaries based Life-Cycle Impact Assessment methodology. *Journal of Cleaner Production*, *139*, 450-459. https://doi.org/10.1016/j.jclepro.2016.08.074

Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., & Luderer, G. (2022). PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renewable*

and Sustainable Energy Reviews, *160*, 112311. https://doi.org/https://doi.org/10.1016/j.rser.2022.112311

Sandin, G., Peters, G. M., & Svanström, M. (2015). Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts. *The International Journal of Life Cycle Assessment*, *20*(12), 1684-1700. https://doi.org/10.1007/s11367-015-0984-6

Sassanelli, C., Urbinati, A., Rosa, P., Chiaroni, D., & Terzi, S. (2020). Addressing circular economy through design for X approaches: A systematic literature review. *Computers in Industry*, *120*, 103245. https://doi.org/https://doi.org/10.1016/j.compind.2020.103245

Schenuit, F., Brutschin, E., Geden, O., Guo, F., Mohan, A., Oliveira Fiorini, A. C., Saluja, S., Schaeffer, R., & Riahi, K. (2025). Taking stock of carbon dioxide removal policy in emerging economies: developments in Brazil, China, and India. *Climate Policy*, *25*(1), 89-108.

Schenuit, F., Colvin, R., Fridahl, M., McMullin, B., Reisinger, A., Sanchez, D. L., Smith, S. M., Torvanger, A., Wreford, A., & Geden, O. (2021). Carbon dioxide removal policy in the making: assessing developments in 9 OECD cases. *Frontiers in Climate*, *3*, 638805.

Schützenhofer, S., Kovacic, I., Rechberger, H., & Mack, S. (2022). Improvement of Environmental Sustainability and Circular Economy through Construction Waste Management for Material Reuse. *Sustainability*, *14*(17).

Selvaraj, S., & Chan, T.-M. (2024). Recommendations for Implementing Circular Economy in Construction: Direct Reuse of Steel Structures. *Journal of Constructional Steel Research*, *214*, 108439. https://doi.org/https://doi.org/10.1016/j.jcsr.2023.108439

Sepanta, F., Sirati, M., & O'Brien, W. (2024). Quantifying the net impact of hybrid work on greenhouse gas emissions associated with workplace and residential energy consumption.

Shukla, P. R., Skea, J., Slade, R., Al Khourdajie, A., Van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., & Fradera, R. (2022). Climate change 2022: Mitigation of climate change. *Contribution of working group III to the sixth assessment report of the Intergovernmental Panel on Climate Change*, *10*, 9781009157926.

Silvy, Y., Frölicher, T. L., Terhaar, J., Joos, F., Burger, F. A., Lacroix, F., Allen, M., Bernardello, R., Bopp, L., & Brovkin, V. (2024). AERA-MIP: emission pathways, remaining budgets, and carbon cycle dynamics compatible with 1.5 and 2° C global warming stabilization. *Earth System Dynamics*, *15*(6), 1591-1628.

Singh, R., & Lazarus, I. J. (2018). Energy-efficient building construction and embodied energy. In *Sustainability through energy-efficient buildings* (pp. 89-107). CRC Press.

Smith, S., Geden, O., Gidden, M., Lamb, W., Nemet, G., Minx, J., Buck, H., Burke, J., Cox, E., & Edwards, M. (2024). The state of carbon dioxide removal.

Sonae Aruco. (2022). *Environmental Product Declaration of Oriented Strand Board*.

Spišáková, M., Mandičák, T., Mésároš, P., & Špak, M. (2022). Waste Management in a Sustainable Circular Economy as a Part of Design of Construction. *Applied Sciences*, *12*(9), 4553.

Stathaki, E. (2025). A whopping 92% of this slick London office fit-out came from reused materials. *Wallpaper*. https://www.wallpaper.com/architecture/plp-architecture-circular-office-design-london-uk

Stats NZ. (2023). *Greenhouse gas emissions (consumption-based): Year ended 2021 (provisional)*. https://www.stats.govt.nz/information-releases/greenhouse-gas-emissions-consumption-based-year-ended-2021-provisional/#text-alt

Stats NZ. (2024a). *National accounts (industry production and investment): Year ended March 2023*. https://www.stats.govt.nz/information-releases/national-accounts-industry-production-and-investment-year-ended-march-2023/

Stats NZ. (2024b). *New Zealand International Trade*. Retrieved 8/15 from https://statisticsnz.shinyapps.io/trade_dashboard/

Steininger, K. W., Williges, K., Meyer, L. H., Maczek, F., & Riahi, K. (2022). Sharing the effort of the European Green Deal among countries. *Nature Communications*, *13*(1), 3673.

Steubing, B., De Koning, D., Haas, A., & Mutel, C. L. (2020). The Activity Browser—An open source LCA software building on top of the brightway framework. *Software Impacts*, *3*, 100012.

Su, S., Li, X., Zhu, Y., & Lin, B. (2017). Dynamic LCA framework for environmental impact assessment of buildings. *Energy and Buildings*, *149*, 310-320. https://doi.org/10.1016/j.enbuild.2017.05.042

Su, S., Wang, Q., Han, L., Hong, J., & Liu, Z. (2020). BIM-DLCA: An integrated dynamic environmental impact assessment model for buildings. *Building and Environment*, *183*, 107218. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.107218

Tabrizikahou, A., Kuczma, M., Nowotarski, P., Kwiatek, M., & Javanmardi, A. (2021). Sustainability of Civil Structures through the Application of Smart Materials: A Review. *Materials*, *14*(17).

thinkstep Ltd. (2018). *The carbon footprint of New Zealand's built environment: Hotspot or not?* https://www.thinkstep-anz.com/resrc/reports/the-carbon-footprint-of-new-zealands-built-environment/

thinkstep Ltd. (2022). *The carbon benefits of working from home*. https://www.thinkstep-anz.com/resrc/case-studies/carbon-benefits-wfh/

Thonemann, N., Schulte, A., & Maga, D. (2020). How to conduct prospective life cycle assessment for emerging technologies? A systematic review and methodological guidance. *Sustainability*, *12*(3), 1192.

Tibaut, A., Rebolj, D., & Nekrep Perc, M. (2016). Interoperability requirements for automated manufacturing systems in construction. *Journal of Intelligent Manufacturing*, *27*(1), 251-262. https://doi.org/10.1007/s10845-013-0862-7

Tilsted, J. P., & Bjørn, A. (2023). Green frontrunner or indebted culprit? Assessing Denmark's climate targets in light of fair contributions under the Paris Agreement. *Climatic Change*, *176*(8), 103. https://doi.org/10.1007/s10584-023-03583-4

Tiruta-Barna, L., Pigné, Y., Navarrete Gutiérrez, T., & Benetto, E. (2016). Framework and computational tool for the consideration of time dependency in Life Cycle Inventory: proof of concept. *Journal of Cleaner Production*, *116*, 198-206. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.12.049

Tleuken, A., Torgautov, B., Zhanabayev, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2022). Design for Deconstruction and Disassembly: Barriers, Opportunities, and Practices in Developing Economies of Central Asia. *Procedia CIRP*, *106*, 15-20. https://doi.org/https://doi.org/10.1016/j.procir.2022.02.148

Tokarska, K. B., Zickfeld, K., & Rogelj, J. (2019). Path Independence of Carbon Budgets When Meeting a Stringent Global Mean Temperature Target After an Overshoot. *Earth's Future*, *7*(12), 1283-1295. https://doi.org/https://doi.org/10.1029/2019EF001312

Tomić, T., & Schneider, D. R. (2018). The role of energy from waste in circular economy and closing the loop concept – Energy analysis approach. *Renewable and Sustainable Energy Reviews*, *98*, 268-287. https://doi.org/https://doi.org/10.1016/j.rser.2018.09.029

Tozan, B., Hoxha, E., Olsen, C. O., Rose, J., Kragh, J., Andersen, C. E., Sørensen, C. G., Garnow, A., & Birgisdóttir, H. (2024). A novel approach to establishing bottom-up LCA-based limit values for new construction. *Building and Environment*, *263*, 111891. https://doi.org/https://doi.org/10.1016/j.buildenv.2024.111891

Tukker, A., Pollitt, H., & Henkemans, M. (2020). Consumption-based carbon accounting: sense and sensibility. *Climate Policy*, *20*(sup1), S1-S13. https://doi.org/10.1080/14693062.2020.1728208

UK Green Building Council. (2024). *Future Homes Standard*. https://ukgbc.org/policy-advocacy/new-build-standards/future-homes-standard/

UKGBC. (2022). *Insights on how circular economy principles can impact carbon and value*. https://ukgbc.org/wp-content/uploads/2022/08/Whole-Life-Carbon-Circular-Economy-Report.pdf

UKGBC. (2025). *Materials Passports Platforms*. UK Green Building Council. https://ukgbc.org/resources/materials-passports-platforms/

United Nations Framework Convention on Climate Change, (1992). https://unfccc.int/sites/default/files/convention_text_with_annexes_english_for_posting.pdf

UNFCCC. (2015). The Paris Agreement. In.

UNFCCC. (2021). *What is the Kyoto Protocol?* unfccc.int/kyoto_protocol

United Nations. (2017). *The sustainable development goals*. Stylus Publishing, LLC.

United Nations Environment Programme. (2020). 2020 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector - Executive Summary.

United Nations Environment Programme. (2023). *Building Materials and the Climate: Constructing a New Future*. https://wedocs.unep.org/20.500.11822/43293

United Nations Environment Programme. (2024). *Global Status Report for Buildings and Construction*. https://www.unep.org/resources/report/global-status-report-buildings-and-construction

UNPD. (2024). *World Population Prospects 2024*. New York Retrieved from https://population.un.org/wpp/

van der Heijden, J. (2023). Construction 4.0 in a narrow and broad sense: A systematic and comprehensive literature review. *Building and Environment*, *244*, 110788. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110788

van der Heijden, J. (2024). Public governance in the context of Construction 4.0: a systematic and comprehensive literature review. *Smart and Sustainable Built Environment*, *ahead-of-print*(ahead-of-print). https://doi.org/10.1108/SASBE-06-2023-0150

Vanegas, P., Peeters, J. R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., & Duflou, J. R. (2018). Ease of disassembly of products to support circular economy strategies. *Resources, Conservation and Recycling*, *135*, 323-334. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.06.022

Ventura, A. (2023). Conceptual issue of the dynamic GWP indicator and solution. *The International Journal of Life Cycle Assessment*, *28*(7), 788-799. https://doi.org/10.1007/s11367-022-02028-x

Verhagen, T. J., Sauer, M. L., van der Voet, E., & Sprecher, B. (2021). Matching demolition and construction material flows, an urban mining case study. *Sustainability*, *13*(2), 653.

Walden, J., Steinbrecher, A., & Marinkovic, M. (2021). Digital product passports as enabler of the circular economy. *Chemie Ingenieur Technik*, *93*(11), 1717-1727.

Walzberg, J., Lonca, G., Hanes, R. J., Eberle, A. L., Carpenter, A., & Heath, G. A. (2021). Do We Need a New Sustainability Assessment Method for the Circular Economy? A Critical Literature Review. *Frontiers in Sustainability*, *1*. https://doi.org/10.3389/frsus.2020.620047

Wang, K., & Guo, F. (2022). Towards Sustainable Development through the Perspective of Construction 4.0: Systematic Literature Review and Bibliometric Analysis. *Buildings*, *12*(10).

Wang, Y., Levis, J. W., & Barlaz, M. A. (2020). An Assessment of the Dynamic Global Warming Impact Associated with Long-Term Emissions from Landfills. *Environmental Science & Technology*, *54*(3), 1304-1313. https://doi.org/10.1021/acs.est.9b04066

Webster, M., & Costello, D. (2006). Designing structural systems for deconstruction. Proceedings, greenbuild conference,

Weerasinghe, S. N., McLaren, S. J., Dowdell, D., Boulic, M., & Chandrakumar, C. (2026). Dynamic carbon budgets and carbon debts for Aotearoa New Zealand and its building sector. *Building and Environment*, *287*, 113805. https://doi.org/https://doi.org/10.1016/j.buildenv.2025.113805

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218-1230. https://doi.org/10.1007/s11367-016-1087-8

Wiedmann, T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecological Economics*, *69*(2), 211-222. https://doi.org/https://doi.org/10.1016/j.ecolecon.2009.08.026

Wiedmann, T., Wilting, H. C., Lenzen, M., Lutter, S., & Palm, V. (2011). Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. *Ecological Economics*, *70*(11), 1937-1945. https://doi.org/10.1016/j.ecolecon.2011.06.014

Wilkinson, S., & Reed, R. (2006). Office buildings and the environment: the increasing importance of ESD.

Williges, K., Meyer, L. H., Steininger, K. W., & Kirchengast, G. (2022). Fairness critically conditions the carbon budget allocation across countries. *Global Environmental Change*, *74*, 102481. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2022.102481

Wilson, N., Grout, L., Summers, J., Nghiem, N., & Baker, M. (2020). Health and economic impacts of the COVID-19 response: NZ compared to OECD countries. *Public Health Expert Briefing*.

Workman LLP. (2024). *Embodied carbon: our office move delivers 95% savings*. Workman LLP. https://www.workman.co.uk/office-move-carbon-savings/

World Bank. (2025). *World Development Indicators (WDI)*.

World Steel Association. (2024). *Steel recycling: Attributes and benefits*. World Steel Association. https://worldsteel.org/wider-sustainability/circular-economy/#recycle

Wu, H., Liang, H., Roy, K., Harrison, E., Fang, Z., De Silva, K., Collins, N., & Lim, J. B. P. (2022). Analyzing the Climate Change Potential of Residential Steel Buildings

in New Zealand and Their Alignment in Meeting the 2050 Paris Agreement Targets. *Buildings*, *12*(3). https://doi.org/10.3390/buildings12030290

Xiao, J., Chen, Z., Ding, T., & Xia, B. (2021). Effect of recycled aggregate concrete on the seismic behavior of DfD beam-column joints under cyclic loading. *Advances in Structural Engineering*, *24*(8), 1709-1723. https://doi.org/10.1177/1369433220982729

You, J., Xu, X., Wang, Y., Xiang, X., & Luo, Y. (2023). Life cycle carbon emission assessment of large-span steel structures: A case study. *Structures*, *52*, 842-853. https://doi.org/https://doi.org/10.1016/j.istruc.2023.04.001

Zhang, Y., Sattar, S., Cook, D., Johnson, K., & Fung, J. (2024). *Systematic Review of Embodied Carbon Assessment and Reduction in Building Life Cycles*. US Department of Commerce, National Institute of Standards and Technology.

Zhong, Y., Qin, Z., Feng, R., & Liu, Y. (2024). Low-carbon design: Building optimization considering carbon emission, material utilization, and daylighting. *Journal of Cleaner Production*, *434*, 140087.

Zieger, V., Lecompte, T., Guihéneuf, S., Guevel, Y., Bazzana, M., Gasser, T., & He, Y. (2025). Climate change metrics: bridging IPCC AR6 updates and dynamic life cycle assessments. *Earth Syst. Dynam.*, *16*(6), 2003-2019. https://doi.org/10.5194/esd-16-2003-2025

Zimmermann, R. K., Kanafani, K., Rasmussen, F. N., Andersen, C., & Birgisdóttir, H. (2020). LCA-framework to evaluate circular economy strategies in existing buildings. IOP Conference Series: Earth and Environmental Science,

Appendix A

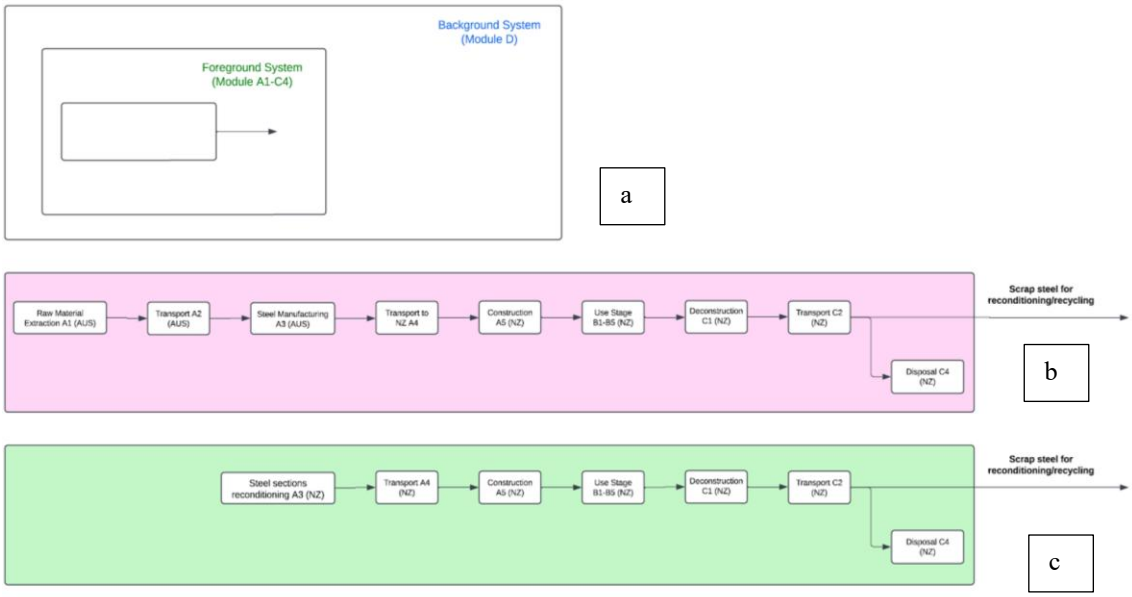


Figure A1. 1 a. Base diagram for all structures, b. Cradle to grave processes of Structure 1, 2 and 3, c. Cradle grave processes of Structures 4 and 5

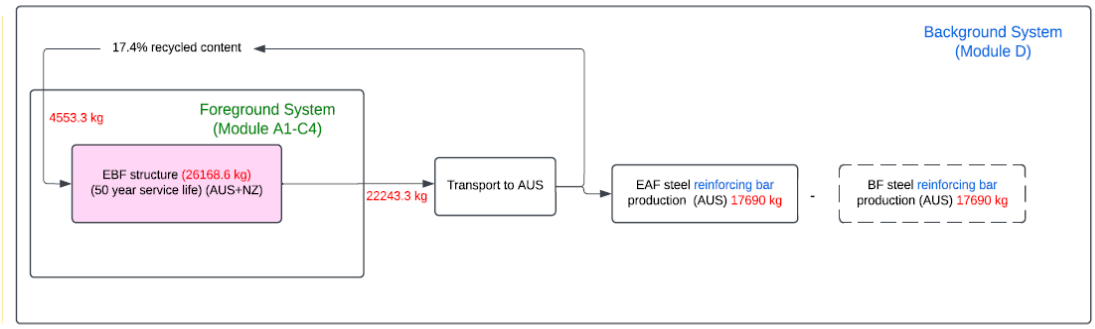


Figure A1. 2 Structure 1, Scenario 1

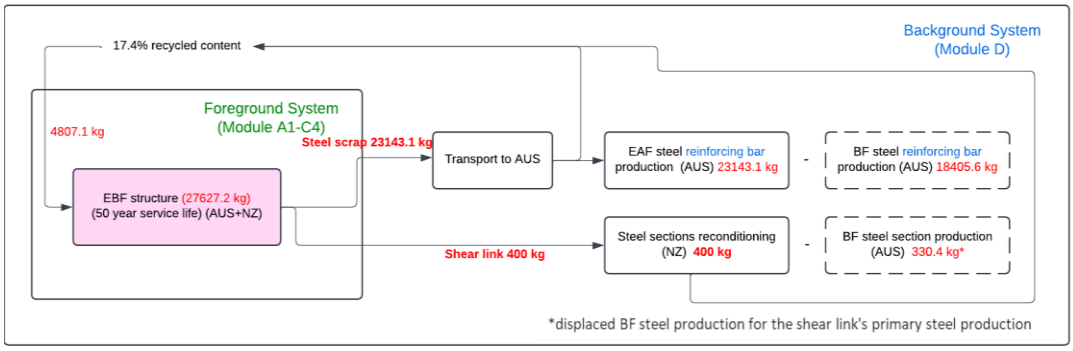


Figure A1. 3 Structure 2, Scenario 1

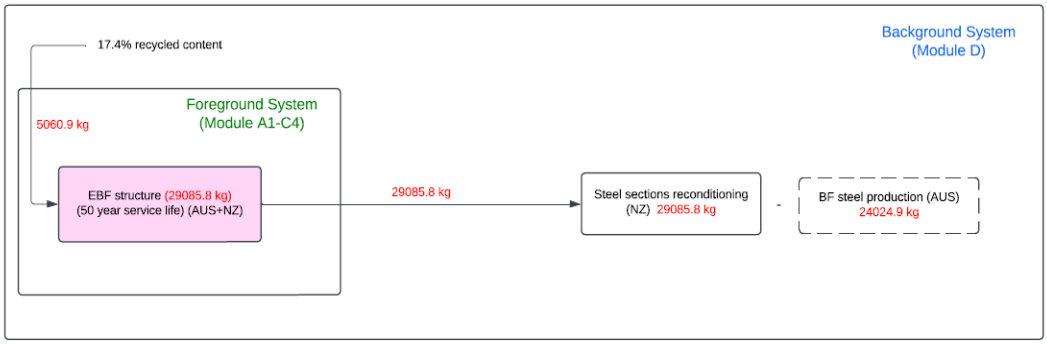


Figure A1. 4 Structure 3, Scenario 1

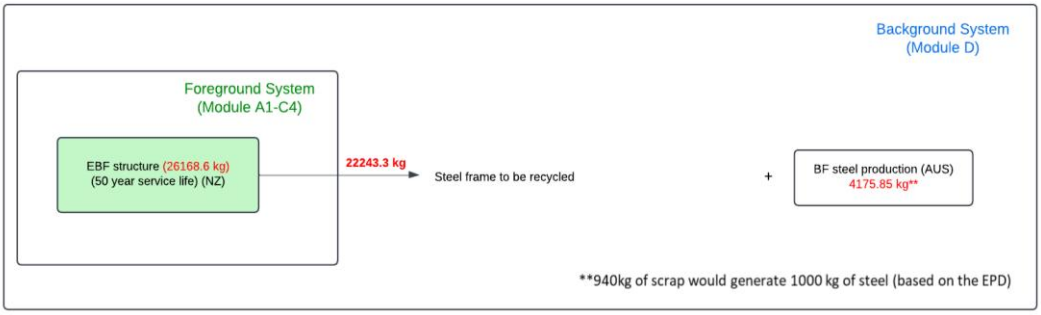


Figure A1. 5 Structure 4, Scenario 1

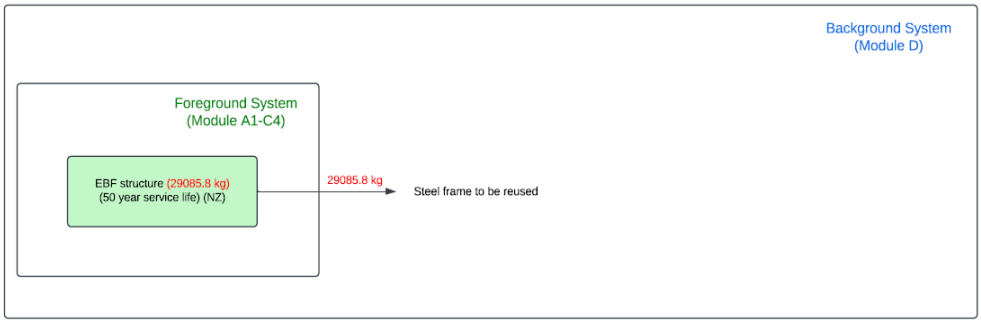


Figure A1. 6 Structure 5, Scenario 1

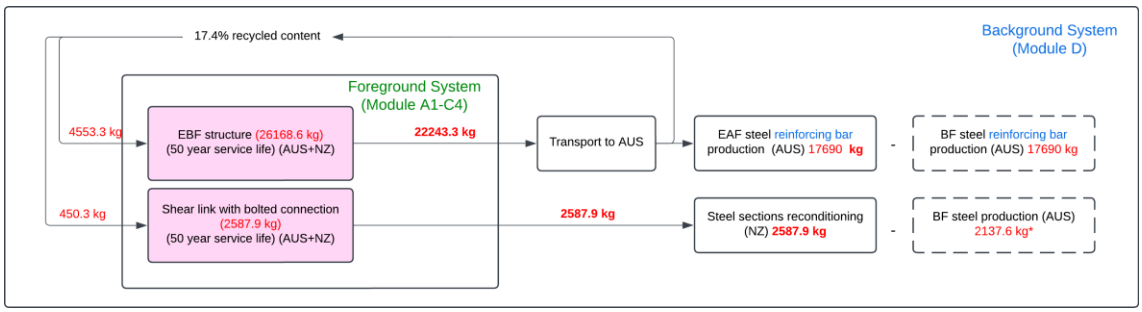


Figure A1. 7 Structure 1, Scenario 2

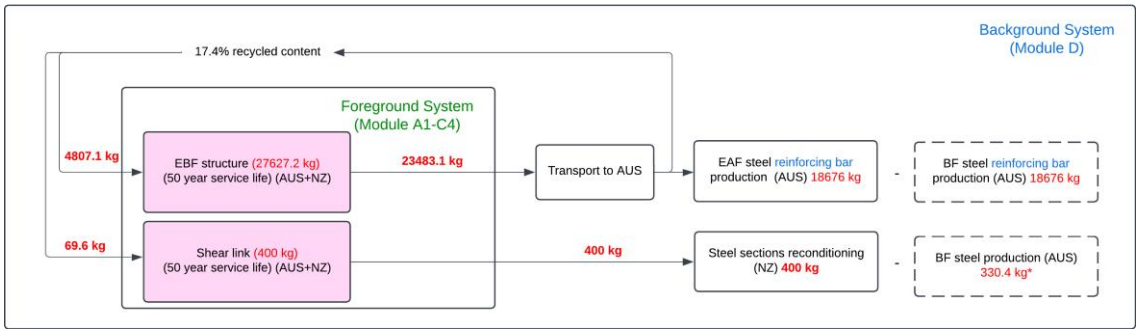


Figure A1. 8 Structure 2, Scenario 2

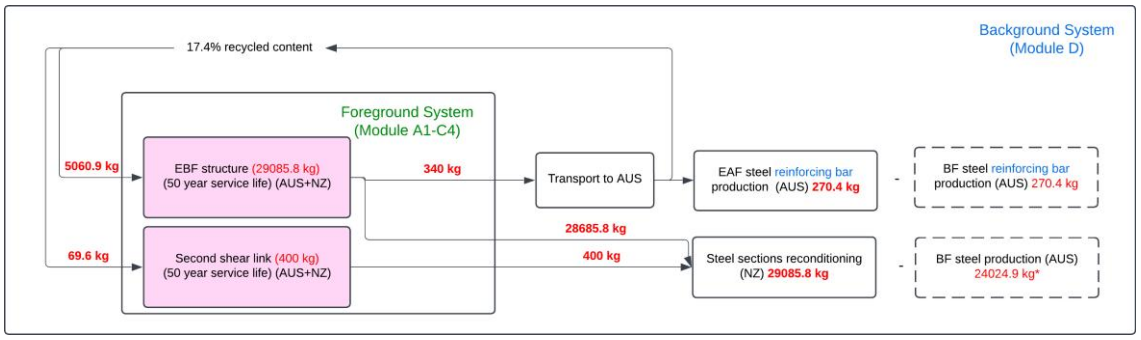


Figure A1. 9 Structure 3, Scenario 2

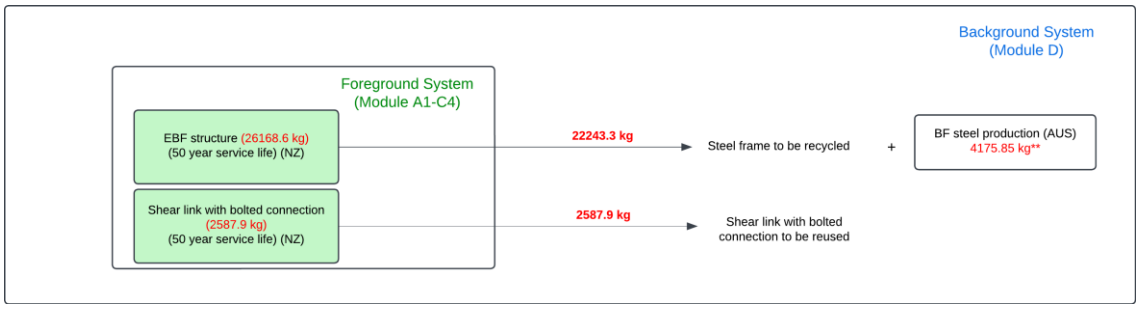


Figure A1. 10 Structure 4, Scenario 2

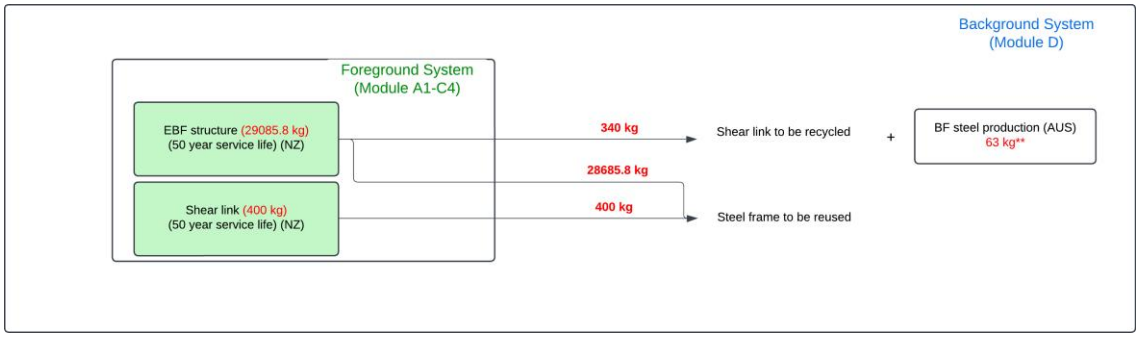


Figure A1. 11 Structure 5, Scenario 2

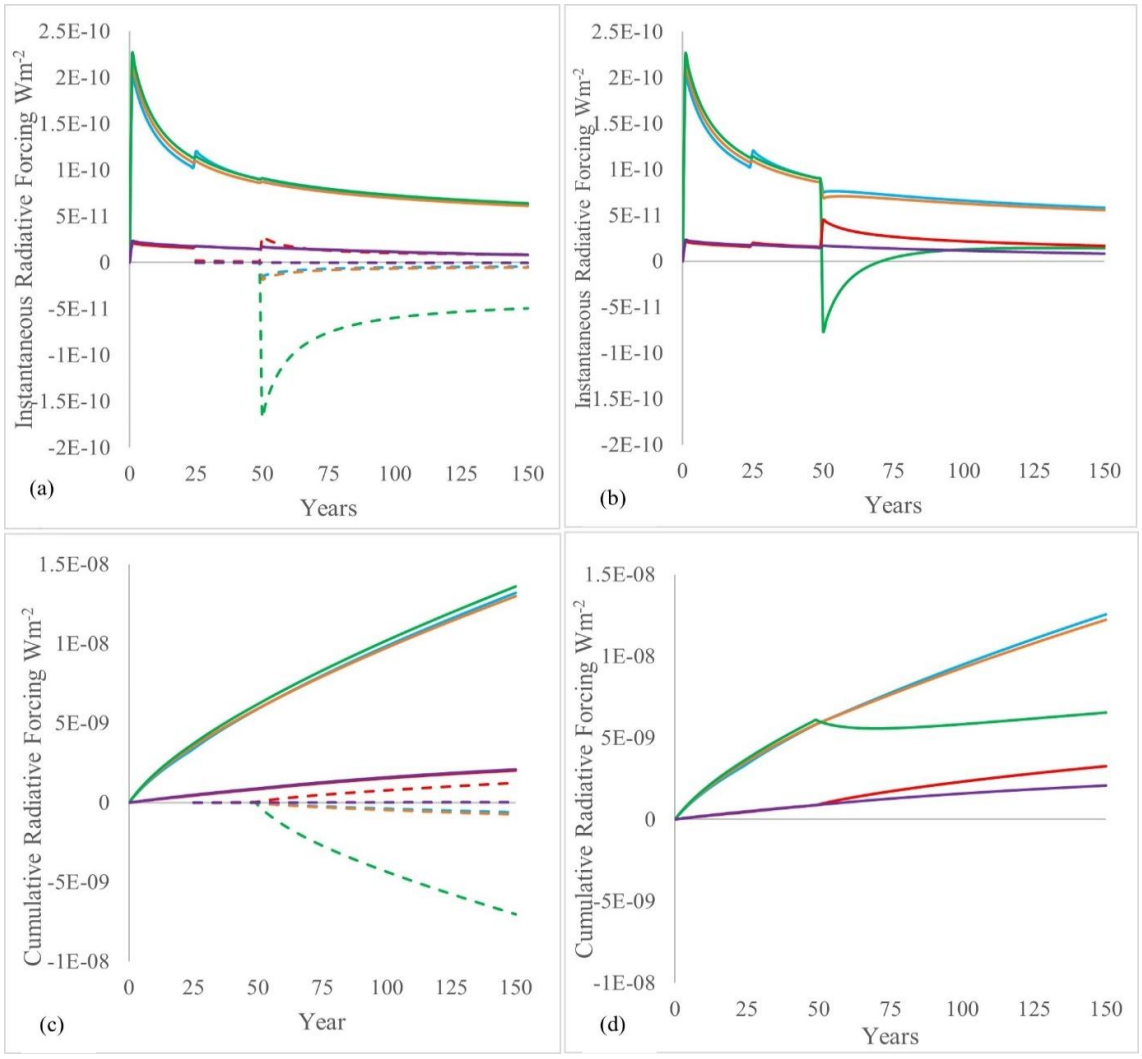


Figure A1. 12 Dynamic LCA results of EBF structure in scenario 2: Figure (a) and (c) show separate results with disaggregated module D. Thick lines show the results from module A-C and dotted lines show the module D. Figure (b) and (d) show results including module D

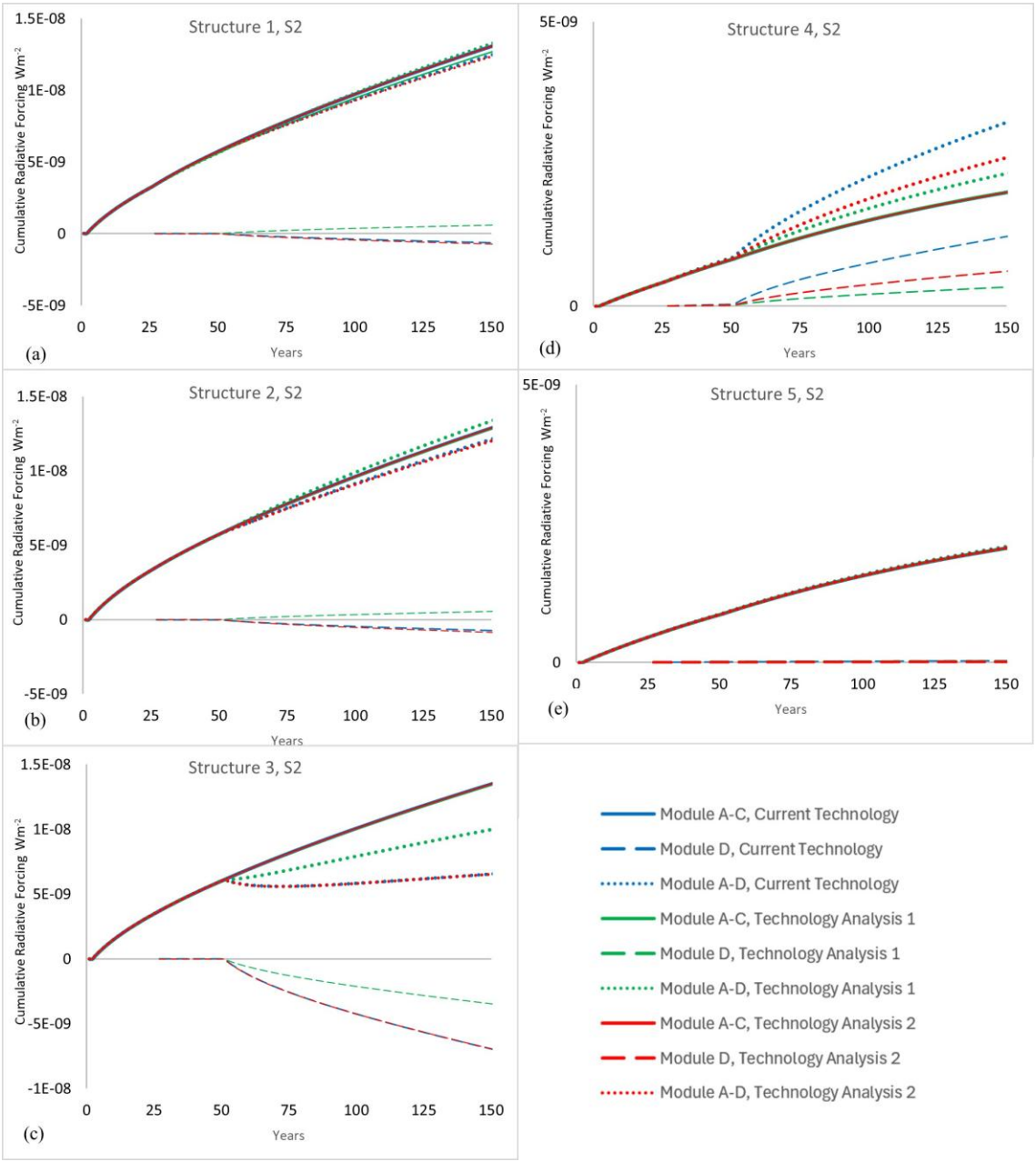


Figure A1. 13 Cumulative Radiative Forcing of all structures in scenario 2 with current technology and prospective technology scenarios: (TA1 and TA2 respectively). Figure (a), (b), (c), (d) and (e) show the Cumulative Radiative Forcing of Structures 1, 2, 3, 4 and 5. Blue, green and red colours indicate the results of the baseline technology, prospective technology 1 and prospective technology 2 respectively. Solid, dashed and dotted lines show the results of modules A-C, module D and modules A-D respectively

Appendix B

Table A2. 1 Climate change impact results of each circular economy strategy sensitivity scenarios and percentage reductions

CE Strategy	Module	Climate change impact $kgCO_2eq/ m^2$ NLA			Percentage reduction	
		Low	Medium	High	Low to High	Low to Medium
CE1.1	B5.1	196.3	196.3	196.3	0%	0%
	B5.2	13.82	13.82	13.82	0%	0%
	B5.3	1.72	1.72	1.72	0%	0%
	D	-49.87	-63.82	-77.76	-56%	-28%
	Net	161.98	148.03	134.08	17%	9%
	Gross (B5)	211.85	211.85	211.85	0%	0%
CE1.2	B5.1	196.3	196.3	196.3	0%	0%
	B5.2	13.82	13.82	13.82	0%	0%
	B5.3	1.72	1.68	1.65	4%	2%
	D	-49.87	-51.83	-53.8	-8%	-4%
	Net	161.98	159.98	157.97	2%	1%
	Gross (B5)	211.85	211.81	211.77	0%	0%
CE2.1	B5.1	183.39	171.24	158.34	14%	7%
	B5.2	13.82	13.82	13.82	0%	0%
	B5.3	1.7	1.68	1.67	2%	1%
	D	-48.58	-47.36	-46.07	5%	3%
	Net	150.34	139.39	127.75	15%	7%
	Gross (B5)	198.92	186.75	173.82	13%	6%
CE2.2	B5.1	196.3	195.04	193.77	1%	1%
	B5.2	13.82	13.82	13.82	0%	0%
	B5.3	1.72	1.63	1.54	10%	5%
	D	-49.87	-49.5	-49.13	1%	1%
	Net	161.98	160.99	160.01	1%	1%
	Gross (B5)	211.85	210.49	209.14	1%	1%
CE3.1	B5.1	196.3	188.63	187.47	4%	4%
	B5.2	13.82	16.99	12.49	10%	-23%
	B5.3	1.72	1.72	1.72	0%	0%
	D	-49.87	-49.87	-49.87	0%	0%
	Net	161.98	157.47	151.82	6%	3%
	Gross (B5)	211.85	207.34	201.69	5%	2%
CE3.2	B5.1	196.3	195.38	194.46	1%	0%
	B5.2	13.82	13.82	13.82	0%	0%
	B5.3	1.72	1.72	1.72	0%	0%
	D	-49.87	-49.78	-49.69	0%	0%
	Net	161.98	161.15	160.32	1%	1%
	Gross (B5)	211.85	210.93	210	1%	0%

Appendix C

Table A3. 1 Forecasts of dynamic parameters considered in the study from 2024-2050

Year	NZ Population Forecast'000	Global Population Forecast'000	NZ CO_2 Emissions forecasted by the MfE	Forecasted building sector CO_2 emissions contribution	NZ LULUCF forecast by the MfE	Net Emissions	Building construction EVA to GDP and forecast
2020	5,036.51	7,851,414.62	38,454.00	5,883.46	- 7,705.42	30,748.58	
2021	5,103.28	7,922,587.96	39,032.00	5,971.90	- 7,031.13	32,000.87	
2022	5,112.11	7,986,308.82	37,084.00	5,673.85	- 6,231.45	30,852.55	
2023	5,151.36	8,056,505.56	36,911.09	5,647.40	- 5,659.95	31,251.14	0.0196
2024	5,194.32	8,126,964.30	36,130.99	5,528.04	- 5,499.68	30,631.31	0.0196
2025	5,233.57	8,196,980.85	32,778.18	5,015.06	- 6,414.41	26,363.77	0.0196
2026	5,270.23	8,266,245.29	31,957.94	4,889.56	- 7,869.03	24,088.91	0.0196
2027	5,304.73	8,335,111.50	31,109.13	4,759.70	- 9,860.14	21,248.99	0.0196
2028	5,337.01	8,403,077.19	30,644.50	4,688.61	- 12,269.26	18,375.24	0.0196
2029	5,366.65	8,470,160.58	30,060.70	4,599.29	- 14,552.42	15,508.28	0.0196
2030	5,394.54	8,536,410.06	29,655.15	4,537.24	- 16,354.76	13,300.39	0.0196
2031	5,420.16	8,601,839.76	29,417.78	4,500.92	- 17,284.04	12,133.74	0.0196
2032	5,444.81	8,666,398.91	29,055.60	4,445.51	- 17,729.64	11,325.96	0.0196
2033	5,467.42	8,730,060.72	28,822.24	4,409.80	- 18,467.85	10,354.39	0.0196
2034	5,489.83	8,792,837.45	28,321.66	4,333.21	- 18,992.76	9,328.90	0.0196
2035	5,510.30	8,854,732.37	27,894.21	4,267.81	- 19,777.06	8,117.15	0.0196
2036	5,530.90	8,915,687.99	27,665.07	4,232.76	- 21,017.94	6,647.13	0.0196
2037	5,550.68	8,975,685.24	27,258.46	4,170.54	- 23,285.42	3,973.04	0.0196
2038	5,570.03	9,034,620.01	26,072.65	3,989.12	- 24,587.00	1,485.65	0.0196
2039	5,589.74	9,092,525.84	25,630.15	3,921.41	- 25,980.15	- 350.00	0.0196
2040	5,608.26	9,149,330.92	25,090.57	3,838.86	- 27,292.20	- 2,201.63	0.0196
2041	5,626.32	9,205,049.49	24,023.26	3,675.56	- 28,577.77	- 4,554.51	0.0196
2042	5,645.25	9,259,513.66	23,551.08	3,603.31	- 29,501.48	- 5,950.40	0.0196
2043	5,662.99	9,312,707.08	23,127.41	3,538.49	- 29,884.00	- 6,756.59	0.0196
2044	5,679.00	9,364,615.55	22,723.18	3,476.65	- 29,926.43	- 7,203.25	0.0196
2045	5,693.64	9,415,131.84	22,381.76	3,424.41	- 29,249.55	- 6,867.79	0.0196

2046	5,707.47	9,464,147.50	22,180.05	3,393.55	-	28,462.82	-6,282.77	0.0196
2047	5,719.43	9,511,631.71	21,838.14	3,341.24	-	27,676.33	-5,838.19	0.0196
2048	5,730.38	9,557,460.25	21,440.28	3,280.36	-	27,774.11	-6,333.83	0.0196
2049	5,741.17	9,601,611.84	21,053.23	3,221.14	-	27,877.89	-6,824.66	0.0196
2050	5,749.75	9,644,036.22	20,625.28	3,155.67	-	28,019.67	-7,394.39	0.0196

Appendix D: Statement of Contribution

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Sachini Nidusha Weerasinghe
Name and title of main supervisor:	Prof Sarah J McLaren
In which chapter is the manuscript/published work?	Chapter 2

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Sachini Weerasinghe: Conceptualisation, Writing - original draft
Sarah McLaren: Supervision, Writing - review & editing
David Dowdell: Supervision, Writing - review & editing

Please select one of the following three options:

- (●) **The manuscript/published work is published or in press**

  Please provide the full reference of the research output:

  Weerasinghe, S. N., McLaren, S. J., & Dowdell, D. (2025). Setting a new and novel research agenda for Construction 4.0 to include greenhouse gas emissions accounting and Indigenous perspectives on climate change mitigation. In K. Husted, T. Coyle, & R. Amor (Eds.), Building the future: Advancing Construction 4.0 in A

- ( ) **The manuscript is currently under review for publication**

  Please provide the name of the journal:

- ( ) **It is intended that the manuscript will be published, but it has not yet been submitted to a journal**

Student's signature:	Digitally signed by Sachini Weerasinghe Date: 2026.05.12 09:38:14 +12'00'	Main supervisor's signature:	Sarah McLaren Digitally signed by Sarah McLaren Date: 2026.05.27 16:11:30 +12'00'

This form should be placed at the beginning of each relevant thesis chapter.

[1] Refer to the Massey University Publishing and Authorship guidelines (OneMassey for staff, Stream for students) and/ or Contributor Roles Taxonomy (CRediT) guidelines for guidance.

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Sachini Nidusha Weerasinghe
Name and title of main supervisor:	Prof Sarah J McLaren
In which chapter is the manuscript/published work?	Chapter 3

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Sachini Weerasinghe: Conceptualisation, Formal analysis, Methodology, Visualisation, Writing-original draft
Sarah McLaren: Methodology, Funding acquisition, Supervision, Writing-review and editing
Mikael Boulic: Supervision, Writing-review and editing
David Dowdell: Supervision, Methodology, Writing-review and editing
Chanjief Chandrakumar: Supervision, Writing-review and editing

Please select one of the following three options:

- (●) **The manuscript/published work is published or in press**

  Please provide the full reference of the research output:

  Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2026). Design for Disassembly Strategies in Steel Eccentric Braced Frames: Climate Change Assessment Using Static and Dynamic Life Cycle Assessment Methods. International Journal of Life Cycle Assessment

- ( ) **The manuscript is currently under review for publication**

  Please provide the name of the journal:

- ( ) **It is intended that the manuscript will be published, but it has not yet been submitted to a journal**

Student's signature:	Digitally signed by Sachini Weerasinghe Date: 2026.05.12 09:44:47 +12'00'	Main supervisor's signature:	Sarah McLaren Digitally signed by Sarah McLaren Date: 2026.05.27 16:13:22 +12'00'

This form should be placed at the beginning of each relevant thesis chapter.

[1] Refer to the Massey University Publishing and Authorship guidelines (OneMassey for staff, Stream for students) and/ or Contributor Roles Taxonomy (CRediT) guidelines for guidance.

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Sachini Nidusha Weerasinghe
Name and title of main supervisor:	Prof Sarah J McLaren
In which chapter is the manuscript/published work?	Chapter 4

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Sachini Weerasinghe: Conceptualisation, Formal analysis, Visualisation, Writing-original draft
Sarah McLaren: Funding acquisition, Supervision, Writing-review and editing
Mikael Boulic: Supervision, Writing-review and editing
David Dowdell: Supervision, Writing-review and editing
Chanjief Chandrakumar: Supervision, Writing-review and editing

Please select one of the following three options:

- (●) **The manuscript/published work is published or in press**

  Please provide the full reference of the research output:

  Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2026). Enabling Circular Office Fit-Outs for a Sustainable Future. In S. M. E. Sepasgozar & R.J. Tumpa (Eds.), Circular Economy enabling the SDGs through assessment governance and multi-scale built environment strategies from waste to

- ( ) **The manuscript is currently under review for publication**

  Please provide the name of the journal:

- ( ) **It is intended that the manuscript will be published, but it has not yet been submitted to a journal**

Student's signature:	Digitally signed by Sachini Weerasinghe Date: 2026.05.12 09:51:28 +12'00'	Main supervisor's signature:	Sarah McLaren Digitally signed by Sarah McLaren Date: 2026.05.27 16:14:12 +12'00'

This form should be placed at the beginning of each relevant thesis chapter.

[1] Refer to the Massey University Publishing and Authorship guidelines (OneMassey for staff, Stream for students) and/ or Contributor Roles Taxonomy (CRediT) guidelines for guidance.

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Sachini Nidusha Weerasinghe
Name and title of main supervisor:	Prof Sarah J McLaren
In which chapter is the manuscript/published work?	Chapter 5

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Sachini Weerasinghe: Conceptualisation, Formal analysis, Methodology, Visualisation, Writing-original draft
Sarah McLaren: Methodology, Funding acquisition, Supervision, Writing-review and editing
Romain Sacchi: Methodology, Writing-review and editing
Mikael Boulic: Supervision, Writing-review and editing
David Dowdell: Supervision, Methodology, Writing-review and editing
Chanjief Chandrakumar: Supervision, Writing-review and editing

Please select one of the following three options:

○ The manuscript/published work is published or in press

Please provide the full reference of the research output:

◉ The manuscript is currently under review for publication

Please provide the name of the journal:
International Journal of Life Cycle Assessment

○ It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Student's signature:	Digitally signed by Sachini Weerasinghe Date: 2026.05.12 09:54:54 +12'00'	Main supervisor's signature:	Sarah McLaren Digitally signed by Sarah McLaren Date: 2026.05.27 16:15:09 +12'00'

This form should be placed at the beginning of each relevant thesis chapter.

[1] Refer to the Massey University Publishing and Authorship guidelines (OneMassey for staff, Stream for students) and/ or Contributor Roles Taxonomy (CRediT) guidelines for guidance.

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Sachini Nidusha Weerasinghe
Name and title of main supervisor:	Prof Sarah J McLaren
In which chapter is the manuscript/published work?	Chapter 6

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Sachini Weerasinghe: Conceptualisation, Methodology, Formal analysis, Visualisation, Writing-original draft
Sarah McLaren: Methodology, Funding acquisition, Supervision, Writing-review and editing
Mikael Boulic: Supervision, Writing-review and editing
David Dowdell: Supervision, Writing-review and editing
Chanjief Chandrakumar: Supervision, Writing-review and editing

Please select one of the following three options:

- (●) **The manuscript/published work is published or in press**

  Please provide the full reference of the research output:

  Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2025, 25.06.2025-27.06.2025). Towards Dynamic Carbon Budgets for Aotearoa New Zealand Building Sector. SBE Conference Series, Zurich, Switzerland.

- ( ) **The manuscript is currently under review for publication**

  Please provide the name of the journal:

- ( ) **It is intended that the manuscript will be published, but it has not yet been submitted to a journal**

Student's signature:	Digitally signed by Sachini Weerasinghe Date: 2026.05.12 10:00:49 +12'00'	Main supervisor's signature:	Sarah McLaren Digitally signed by Sarah McLaren Date: 2026.05.27 16:16:08 +12'00'

This form should be placed at the beginning of each relevant thesis chapter.

[1] Refer to the Massey University Publishing and Authorship guidelines (OneMassey for staff, Stream for students) and/ or Contributor Roles Taxonomy (CRediT) guidelines for guidance.

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Sachini Nidusha Weerasinghe
Name and title of main supervisor:	Prof Sarah J McLaren
In which chapter is the manuscript/published work?	Chapter 7

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Sachini Weerasinghe: Conceptualisation, Methodology, Formal analysis, Visualisation, Writing-original draft
Sarah McLaren: Methodology, Funding acquisition, Supervision, Writing-review and editing
Mikael Boulic: Supervision, Writing-review and editing
David Dowdell: Supervision, Writing-review and editing
Chanjief Chandrakumar: Supervision, Writing-review and editing

Please select one of the following three options:

- (●) **The manuscript/published work is published or in press**

  Please provide the full reference of the research output:

  Weerasinghe, S. N., McLaren, S. J., Boulic, M., Dowdell, D., & Chandrakumar, C. (2026). Dynamic carbon budgets and carbon debts for Aotearoa New Zealand and its building sector. Building and Environment, 287, 113805. https://doi.org/https://doi.org/10.1016/j.buildenv.2025.113805

- ( ) **The manuscript is currently under review for publication**

  Please provide the name of the journal:

- ( ) **It is intended that the manuscript will be published, but it has not yet been submitted to a journal**

Student's signature:	Digitally signed by Sachini Weerasinghe Date: 2026.05.12 10:02:01 +12'00'	Main supervisor's signature:	Sarah McLaren Digitally signed by Sarah McLaren Date: 2026.05.27 16:16:36 +12'00'

This form should be placed at the beginning of each relevant thesis chapter.

[1] Refer to the Massey University Publishing and Authorship guidelines (OneMassey for staff, Stream for students) and/ or Contributor Roles Taxonomy (CRediT) guidelines for guidance.